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Important Information

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Pabai & Anor v Commonwealth of Australia (VID622/2021)

Federal Court of Australia

Expert Report of Emeritus Professor John Church AO FAA FTSE

Climate Change Research Centre

University of New South Wales

I have prepared this report in response to an expert brief provided to me by Phi Finney McDonald who are acting on behalf of Pabai Pabai and Guy Paul Kabai.

I have been asked to prepare an expert report in relation to climate change and sea levels.

Annexure A is the letter of instruction provided to me by Phi Finney McDonald.
Annexure B is an abbreviated CV and list of publications.

I acknowledge that I have been provided with, read, complied with, and agree to be bound by the Federal Court of Australia Expert Evidence Practice Note (GPN-EXPT) and Harmonised Expert Witness Code of Conduct.

My opinions in this report are based wholly or substantially on specialised knowledge arising from my training, study or experience.

I have made all the inquiries which I believe are desirable and appropriate (save for any matters identified explicitly in this report) and confirm that no matters of significance which I regard as relevant have, to my knowledge, been withheld from the Court.

Yours Sincerely,

John Church.

John Church
23/06/2023

BASIS OF EXPERTISE

Question 1

Please describe your academic qualifications, professional background, and experience in the field of climate science, and any other training, study, or experience that is relevant to this brief (you may wish to do so by reference to a current curriculum vitae).

1. I am an Emeritus Professor in the Climate Change Research Centre, University of New South Wales. I have published across a broad range of topics in oceanography. My area of expertise is the role of the ocean in climate, particularly anthropogenic climate change, and the oceanic storage of increased heat in the world's oceans. I am recognised as a world leader in understanding historical and projected global and regional sea-level rise, having provided historical estimates of sea-level change since the late 19th century, robust explanations for the rise, its attribution to greenhouse gas emissions and improved projections of global and regional sea-level rise.

2. I am the author of over 190 refereed publications, over 110 other reports and I have co-edited three books. I was co-convening lead author for the Chapter on Sea Level in the Intergovernmental Panel on Climate Change (IPCC) Third and Fifth Assessment Reports.

3. My expertise has been recognised nationally and internationally by a number of significant awards: the Roger Revelle Medal by the Intergovernmental Oceanographic Commission (2006), a CSIRO Medal for Research Achievement (2006), the Eureka Prize for Scientific Research (2007), the Australian Meteorological and Oceanographic Society (AMOS) R.H. Clarke Lecture (2008), the AMOS Morton Medal (2017), joint winner of the BBVA Frontiers of Knowledge Climate Change Category Prize (2019), the Australian Academy of Science Jaeger Medal (2021), the Royal Society of NSW James Cook Medal (2022), the Prince Albert I Medal of the International Association for Physical Sciences of the Ocean (2023), and the Axford Medal of the Asia Oceania Geoscience Society (2023).

4. I am an Officer of the Order of Australia, a Fellow of the Australian Academy of Science, the Australian Academy of Technology and Engineering, the American Geophysical Union, the American Meteorological Society and the Australian Meteorological and Oceanographic Society.

5. Further details regarding my academic qualifications, professional background, experience and publications can be found in the brief CV and publication list provided at Annexure B.

GLOBAL TEMPERATURES AND SEA LEVELS

Question 2

*Please explain the relationship between the temperature of the Earth's surface (**global temperatures**) and sea levels.*

In your answer, please address:

- *a) the relevance of:*
  - *a. sea and atmospheric temperatures;*
  - *b. ice and water on land; and*
- *b) whether there is any variation geographically.*

Introduction

6. **Ocean sea levels vary on a wide range of time and space scales.** Local winds cause ripples and waves with time scales of seconds, amplitudes from millimetres to metres, and wavelengths of up to hundreds of metres for ocean swell that can travel many tens of thousands of kilometres. Local and remote winds also cause changes in local and regional sea level by ocean currents and storm surges. Twice-daily and daily tides, generated by the gravitational attraction of the moon and sun, cause changes in sea level of centimetres to metres on time scales of hours to days. Other atmospheric (winds, changes in atmospheric pressure, and air-sea-ice fluxes of heat and freshwater) and oceanic phenomena (ocean eddies, seasonal variation and climate variability) result in changes in sea level of tens of centimetres that can propagate along coasts and across ocean basins. Additionally, earthquakes can cause tsunamis that can have devastating impacts on coastal regions.

7. **All of these oscillations change local *relative* sea level (i.e. local sea level relative to the ocean bottom) but (mostly) do not change the volume of water in the ocean or global mean sea level (i.e. the average height of sea level over the global ocean, GMSL).** The surface of the ocean does not follow an equipotential surface (what we might normally think of as a flat surface) because of ocean currents (and the associated variations in density, temperature and salinity of the ocean). A simple analogue to this is isobars on a weather map. If ocean currents change then ocean water is redistributed but the total volume of the ocean water does not necessarily change.

8. **Changes in global mean sea level are a direct result of changes in the volume of water in the oceans.** (See Figure 1 for a schematic representation of sea level change.) This volume is determined by the mass and density of the ocean. The mass changes when water is exchanged between the ocean and the land and to a lesser extent the atmosphere (e.g. sea level will increase if glaciers or ice sheets lose mass which enters the ocean). Land water storage occurs in glaciers, ice sheets and other land water storage. There are more than 100,000 glaciers in the world and they currently contain less than about 0.4 m of equivalent sea level (Church et al. 2013; Fox-Kemper et al. 2021). The ice sheets of Greenland and Antarctica contain much greater volumes of equivalent sea level (about 7.4

m for Greenland and 58 m for Antarctica). A smaller mass of water is also stored on land in lakes and reservoirs, aquifers, the soil and the biosphere, and with some deeper water storage that is essentially inaccessible.

9. **The volume of ocean water also increases as the ocean warms, even if the ocean mass does not change.** A simple analogue to this is the change in the height of liquid in a thermometer as the temperature changes. Averaged over the globe this is called 'ocean thermal expansion' – warmer ocean temperatures mean higher sea levels.

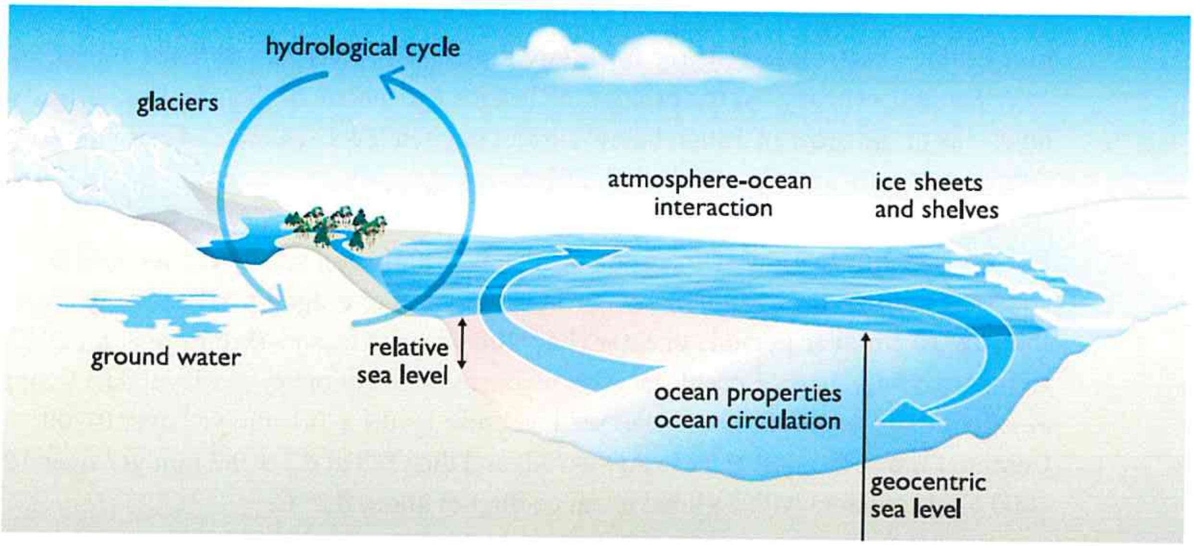

Figure 1. Climate-sensitive processes and components that can influence global and regional sea level. Changes in any of the components or processes shown will result in sea-level change. The term 'ocean properties' refers to ocean temperatures, salinity and density, which influence and are dependent on Ocean Circulation and its interaction with the atmosphere and cryosphere. Both relative and geocentric (i.e. relative to the centre of mass of the Earth) sea level vary with position. Note the Geocentre is not shown. (From Church et al. 2013; IPCC AR5)

Preindustrial Sea level Change

10. **Sea level has risen and fallen by over 100 metres during ice-age cycles of the last one million years** (Rohling et al. 2009). During ice ages, large ice sheets formed over North America, northern Europe and north Asia and the Antarctic and Greenland Ice Sheets were also larger. As a result of this large transfer of mass from the oceans to the land, during ice ages sea level was more than one hundred metres below current day sea level.

11. **Sea level was higher during past warm periods.** During the Mid Pliocene Warm Period (3.3 million years ago) sea level is estimated to have been between 5 and 25 m (or more) above present day levels, at carbon dioxide concentrations similar to today's and temperatures 2.5-4° C warmer than during 1850-1900 (Oppenheimer et al. 2019, Dutton et al. 2015).

12. **During the Last Inter-Glacial period (129,000-116,000 years ago), sea level is estimated to have been 5-10 m above present levels at global average temperatures 0.5-1.5° C warmer than 1850-1900 (Gulev et al. 2021; Masson-Delmotte et al. 2013; Church et al. 2013; Fox-Kemper et al. 2021).** These paleo data are clear indications that sea level was higher during warm periods and they are important in evaluating models of ice sheet evolution. However, because of different climate forcings and rates of change, they are not a direct analogue for future sea levels and there is recent work suggesting these sea level estimates may be too high (Dyer et al. 2021).

13. **As the Earth warmed coming out of the ice age, global sea level rose at a rate of more than a metre per century for many thousands of years, and with a peak rate of over 4 m per century.** At the peak of the last ice age, about 20 thousand years ago, sea level was of the order of 130 m below current day sea level. The rate of rise slowed after 8 thousand years ago (Lambeck et al. 2014).

14. **For the last 2 millennia prior to the industrial revolution sea level was almost constant with no indication of oscillations of global averaged oscillations greater than 15-20 cm over periods greater than 200 years (Masson-Delmotte et al. 2013; Lambeck et al. 2014).** Recent sea level reconstructions of proxy sea-level data (Kopp et al. 2016) indicates that global mean sea level rose by 0.1 ± 0.1 mm yr^{-1} over 0-700 Common Era (CE, equivalent to AD 0-700) and then fell at 0.2 ± 0.2 mm yr^{-1} over 1000-1400 CE associated with a global mean cooling of about 0.2° C.

15. **Because of different climate forcing and rates of change, none of these prehistorical periods are perfect analogues for future sea-level change.** These prehistorical sea levels and the rates of change are indications of what has happened in the past, including rapid rates of sea-level rise, and thus are indications of what could happen in the future. They are also important in developing and evaluating models of sea-level change.

<u>Relationship of changes in temperatures and sea level</u>

16. **The volume of ocean water increases as the ocean warms, even if the ocean mass does not change.** As mentioned above, a simple analogue to this is the change in the height of liquid in a thermometer as the temperature changes. Averaged over the globe this is called 'ocean thermal expansion'; i.e. warmer ocean temperatures means higher sea levels. The rate of ocean heat uptake (i.e. the rate of ocean warming) is approximately proportional to the increase in surface temperature above preindustrial (Kuhlbrodt and Gregory 2012; Church et al. 2013; Fox-Kemper et al. 2021). This means as the surface temperature increases the rate of thermal expansion increases. The heat is carried into the ocean from the surface by ocean currents and mixing. The climate models used in the AR6, and modern and paleo observations indicate the additional ocean heat content results in a thermal expansion at the rate of 0.113 ± 0.013 m YJ^{-1} (1 Yota Joule is 10^{24}J).

17. **The vast majority of the heat accumulating in the climate system is in the ocean.** About 90% of the heat that is accumulating in the climate system as a result of increasing

greenhouse gas concentrations is stored in the ocean and only about 1% in the atmosphere (Figure 1A; von Schuckmann et al. 2023). Over 1970 to 2018, surface temperatures increased from about 0.25 °C to 1.2 °C above preindustrial as ocean heat content increased by about 350 ZJ (Figure 1A; 1 ZJ = 10^{21} J), with the greatest amounts in the upper ocean. This ocean warming over 1970 to 2018 is equivalent to about 0.04 m of thermal expansion. Note however, because of the huge heat capacity of the oceans, they are out of balance with surface temperatures and will continue to warm for decades to centuries after surface temperatures are stabilised.

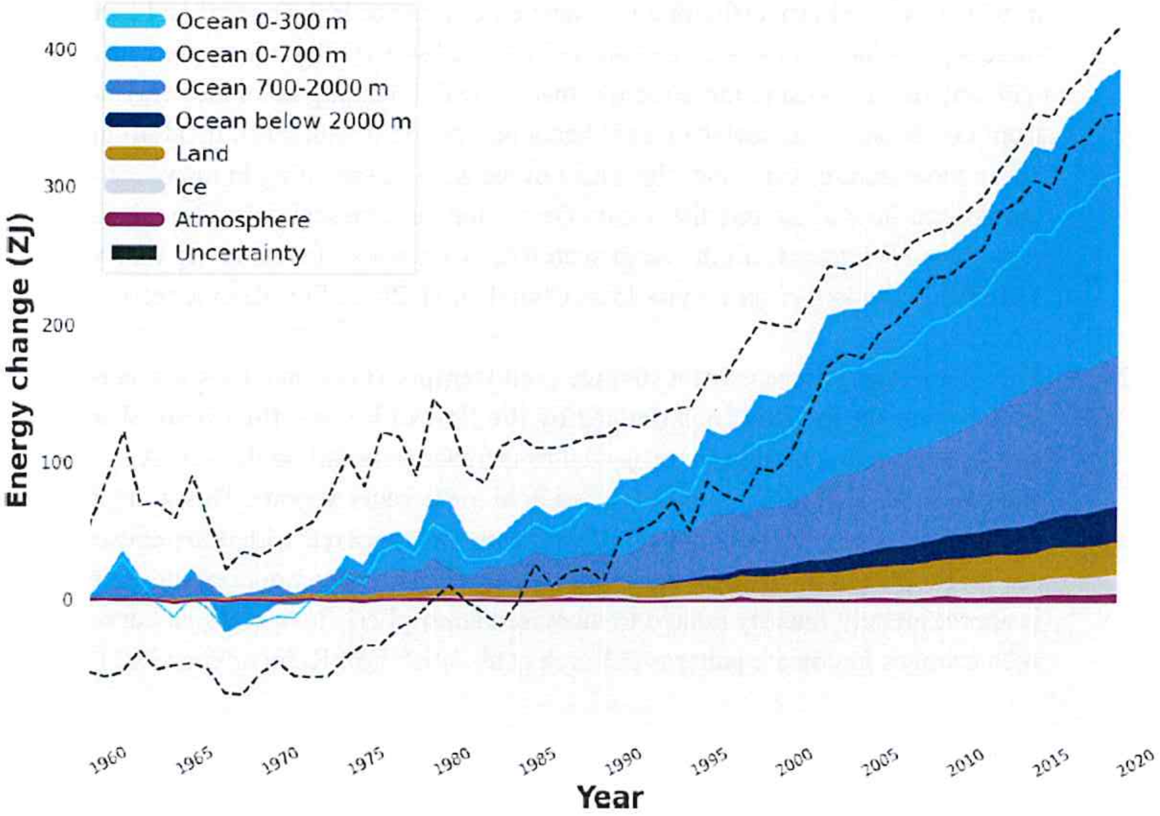

Figure 1A. Gain in observed heat content of the climate system over 1960 to 2020 in Zeta Joules (1ZJ = 10^{21}). (von Schuckmann et al. 2023)

18. **The rate of increased mass loss from the glaciers is approximately proportional to local surface temperature changes (greater ablation* with higher temperatures) and accumulation changes, but with the proportionality constant varying with location (e.g. Marzeion et al. 2012).** Glaciers receive snowfall at higher altitudes, with the resulting ice flowing downhill to ablate at lower altitudes or to flow directly into the ocean, as seen for example in Alaska. If surface temperatures warm, glaciers tend to ablate more rapidly and at higher altitudes, with much of this water eventually flowing into the ocean (although some may be retained (temporarily) in lakes or reservoirs) contributing to sea-level rise. Changes in snowfall may also change the mass of glaciers. [*The loss of mass by melting or evaporation.]

19. **The mass balance of the ice sheets of Greenland and Antarctica are more complex than for glaciers and they have a much larger potential contribution to sea-level change on the longer term.**

20. **For Greenland, recent changes in the surface mass balance (SMB; snowfall minus ablation) and faster flow of ice into the ocean have contributed to sea-level rise** (Fox-Kemper et al. 2021). Greenland currently loses more than half of the snowfall as surface ablation, most of which flows into the ocean (some of it below the ice-sheet surface), and the remainder as the direct flow of ice into the ocean. This flow of ice can be partially impeded by ice shelves (floating ice-sheet extensions over the ocean) and icebergs. Increased surface temperatures result in increased snowfall and increased surface ablation, with ablation increasing more rapidly than snowfall, leading to an increased loss of mass from Greenland. This surface loss is becoming the dominant term. In addition, warming ocean temperatures can cause the decay of ice shelves (resulting in many icebergs) and a more rapid flow of ice into the ocean. On the longer time scale, the Greenland Ice Sheet may (mostly) retreat from the coast such that increased surface melting will be the prime contribution to longer term mass loss (Church et al. 2013; Fox-Kemper et al. 2021).

21. **For Antarctica, there is little surface melt (temperatures are mostly too cold) and snowfall on the ice sheet is balanced by the flow of ice into the ocean.** Warming atmospheric temperatures are projected to increase snowfall on the vast Antarctic ice sheet because a warmer atmosphere can hold more water vapour. This will partially offset (a relatively small but not an insignificant amount compared with other causes of global sea level change) other contributions to sea-level rise. The amount of increased snowfall is approximately linearly related to increased atmospheric temperatures but may also vary with changes in climate patterns (Church et al. 2013; Fox-Kemper et al. 2021).

22. **The flow of ice from Antarctica into the ocean occurs via outlet glaciers but the factors controlling this flow are not well understood and there is concern that changes in the flow may lead to a more rapid rise in sea level than current projections.** The ice shelves exert a backstress on the glaciers. If the ice shelves collapse, the glacier may flow more rapidly into the ocean. This has been observed on the Antarctic Peninsular when warmer surface air temperatures and ocean temperatures resulted in a rapid (a few months) collapse of the Larsen B ice shelf followed by an increase flow of glaciers into the ocean (Scambos et al. 2004). Also, warm ocean waters can penetrate below the ice shelves, melting the ice near the grounding line (where the ice first begins to float after resting on the bedrock as it flows towards the ocean), allowing the outlet glacier to flow more rapidly into the ocean. If the bedrock slopes downward away from the ocean, any initial perturbation may be unstable (Figure 2). That is, an initial retreat of the grounding line may result in a more rapid flow of ice into the ocean and further retreat of the grounding line (called the Marine Ice Sheet Instability; MISI). These processes are incompletely observed, but recent observations and modelling studies suggest this process may be underway in parts of the West Antarctic Ice Sheet (Joughin et al. 2014). Other recent studies (DeConto and Pollard 2016; de Conto et al. 2021) have hypothesized that if the height of the face of the ice sheet exceeds a critical value, it may be unstable leading

to a more rapid retreat of the face of the ice sheet (the Marine Ice Cliff Instability; MICI) and more rapid rise in sea level. While DeConto and Pollard (2016) argued this process is necessary to simulate paleo sea levels, it's importance is disputed and others argue it is not essential to simulate paleo sea levels or makes smaller contributions (Edwards et al. 2019; Clerc et al. 2019; Fox-Kemper et al. 2021; van de Wal 2022). [redacted]

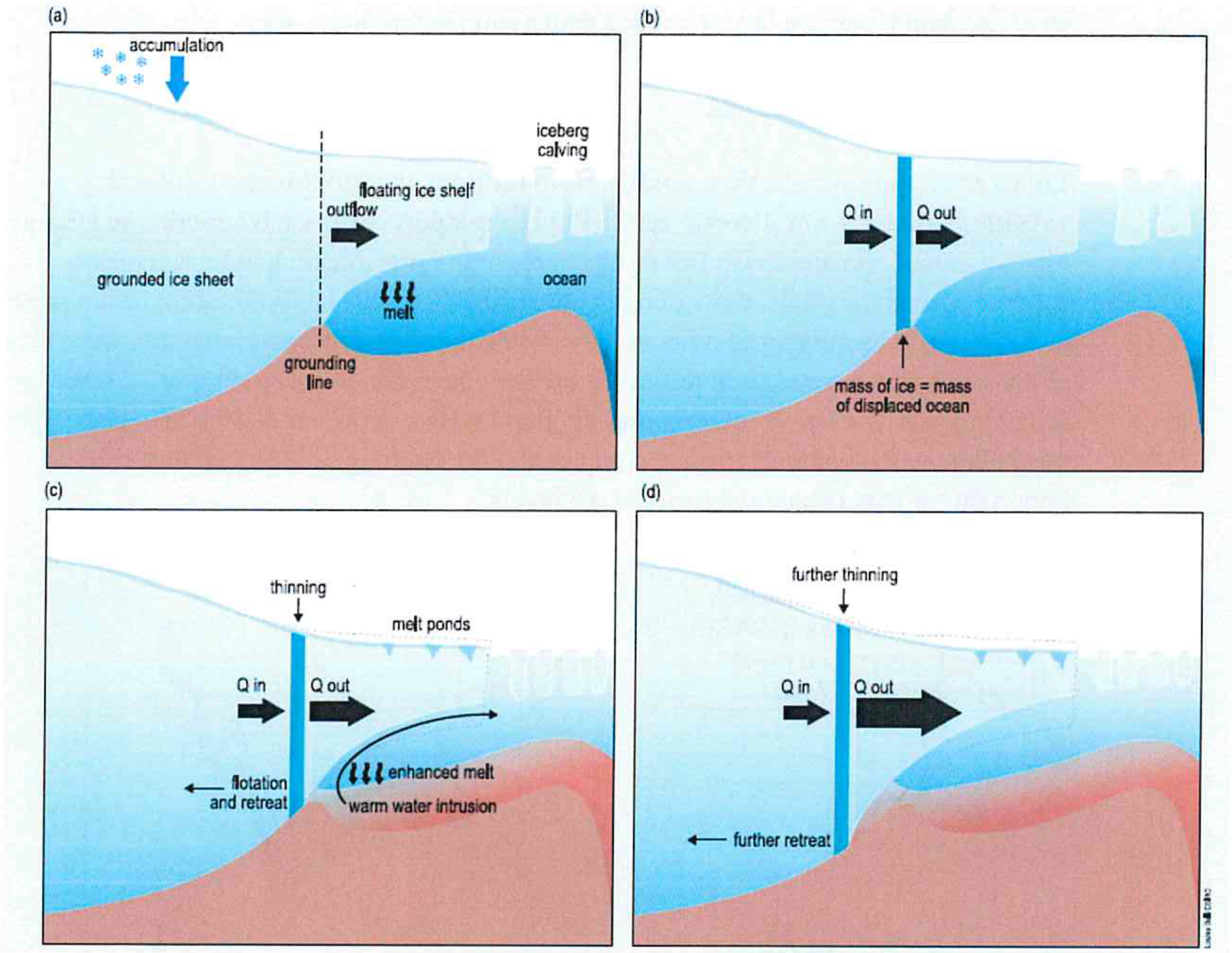

Figure 2. *Schematic of the processes leading to the potential unstable retreat of a grounding line showing (a) geometry and fluxes of a marine ice sheet, (b) the grounding line in Steady state, (c) climate change triggering outflow from the ice sheet and the start of grounding line retreat, and (d) self-sustained retreat of the grounding line (from Box 13.2, Figure 1; Church et al. 2013).*

23. **In summary, the *rate* of rise of global mean sea level from ocean thermal expansion, glacier and Greenland surface mass loss and increased Antarctic accumulation is approximately proportional to the temperature rise since preindustrial periods.** Mass loss from the outflow of glaciers in Greenland and Antarctica depends (not necessarily linearly) on both subsurface ocean temperatures and surface atmospheric temperatures. While this outflow is more uncertain, it could potentially lead to rapid rates

of sea-level rise (Church et al. 2013; Fox-Kemper et al. 2021). The *amount* of rise is the time integral of the rate of rise.

24. **Sea-level will continue to change for centuries even if surface temperatures are stabilised.** The oceans, glaciers and ice sheets all have long response times of decades to centuries and even millennia. As a result, they are out of balance with our rapidly changing climate and even with no further climate forcing, further change is unavoidable. This imbalance is larger for higher temperatures, implying larger rates and amounts of sea level rise, and lower sea level rise for smaller temperature increases.

Other contributions to sea-level change

25. **There are a number of other smaller contributions to global-mean sea-level variations that are not directly related to the temperature rise from climate change.** Firstly, natural climate variability results in changing precipitation and evaporation patterns around the globe. For example, during the 2010-2011 la Niña event heavy rainfall in Australia and a number of other regions resulted in flooding and global fall in the mass of the ocean and a consequent fall in sea level by the order of 5 mm (Figure 3). Over the following year, sea levels recovered as the flood waters flowed back into the ocean. While this interannual variability is small compared to the ongoing sea-level change, it is important for understanding historical sea levels.

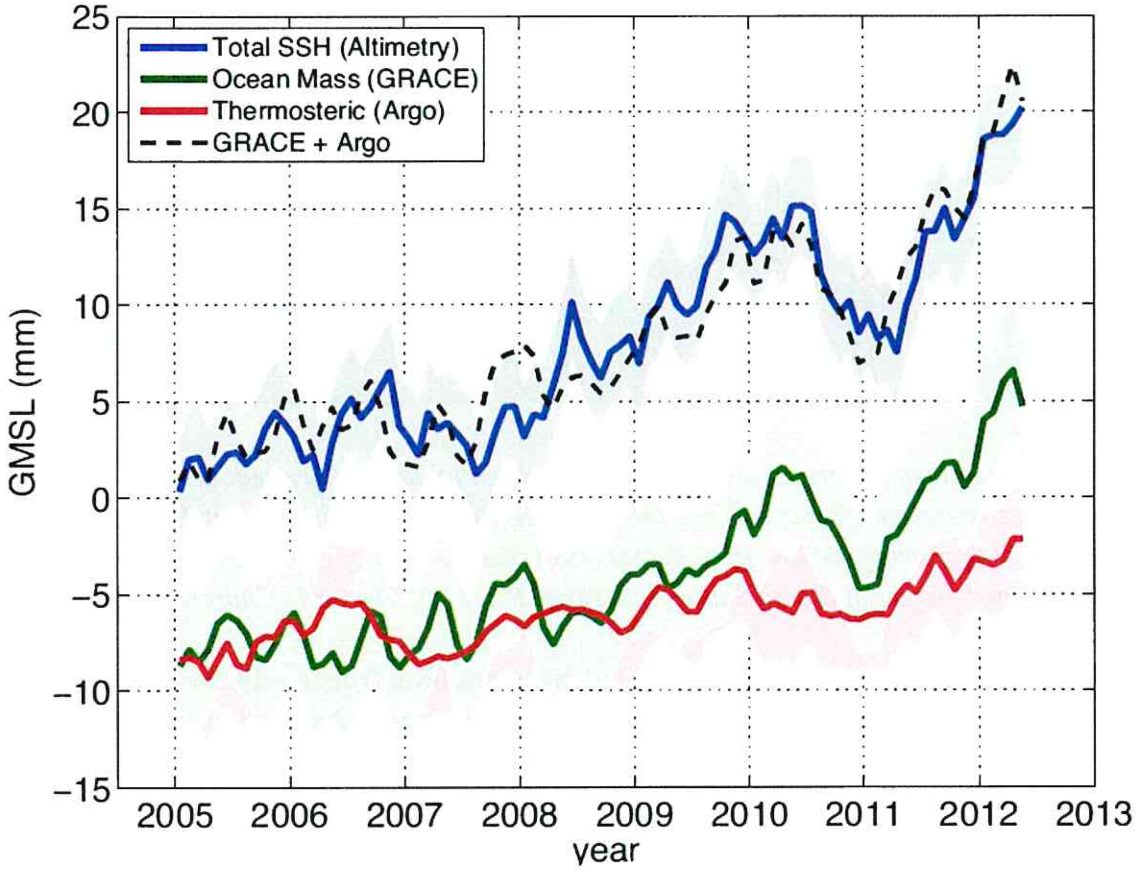

Figure 3. *Global mean sea level from altimetry* from 2005 to 2012 (blue line). Ocean mass changes are shown in green (as measured by Gravity Recovery and Climate Experiment (GRACE)) and thermosteric sea level changes (as measured by the Argo Project) are shown in red. The black line shows the sum of the ocean mass and thermosteric contributions (updated from Boening et al. 2012; from Figure 13.6, Church et al. 2013). [*Satellite altimeters measure the sea surface height (SSH) relative to the centre of mass of the Earth.]*

26. **There is also direct human intervention in the hydrological cycle.** Firstly, the building of terrestrial reservoirs has led to a reduction in ocean mass and sea level by the order of 20 mm since 1950. Secondly, much of the water extracted from aquifers eventually makes its way to the ocean and is now of a similar magnitude to the reservoir storage and is increasing. Again, while these contributions are small compared the ongoing sea-level change, they are important for understanding historical sea levels.

The spatial distribution of sea level rise

27. **Each of the contributions to sea-level change has a spatial distribution.**

28. **Changing winds, air-sea-ice fluxes of heat and freshwater change ocean currents (and the associated ocean temperature and salinity distribution) change sea level regionally.** Although there is significant variability between models, estimates of the projected regional sea-level change have some common features: a maximum in sea-level change at mid-latitudes in both hemispheres and in the Arctic Ocean, a minimum in sea level change close to Antarctica and a more complex structure in the North Atlantic. The sea-level rise along eastern and northern Australia are slightly above the global average rise in the suite of models used in the AR5 projections for the 21st century (Zhang et al. 2017).

29. **The large transfer of mass from the land to the ocean as glaciers and ice sheets lose mass results in changes of the surface loading (the weight of either liquid water or ice on the surface) of the Earth and changes in the gravitational and rotational fields of the Earth.** The net effect of these changes (called Gravitational, Rotational and Deformation (GRD) changes) is to have a greater than global average contribution (by up to about 25%) to sea-level rise in regions distant to the location of mass loss and a contribution to sea-level fall immediately adjacent to these regional of mass loss (Mitrovica et al. 2011). For both the 20th and 21st century changes Australia, particularly northern Australia, is in the region of greater than average sea-level rise from these processes.

30. **Changes in atmospheric pressure also changes the regional distribution of sea level.** High atmospheric pressures push the ocean surface down with the water moving to regions of lower atmospheric pressure.

Ongoing vertical land motion

31. **Relative sea-level change (that is the change in sea level relative to the land) is what is important for assessing the impacts of sea-level change.** Relative sea level is what coastal tide gauges measure (Figure 1).

32. **In response to the decay of ice sheets following the last glacial maximum and immediately prior to the recent anthropogenic sea-level changes, relative sea level (sea level relative to the land) was falling at the locations of the former ice sheets (e.g. Hudson Bay, Norway/Sweden), rising in the immediate surrounding area (for example the coasts of the USA), and falling slightly in the far field (such as the coast of Australia).** As indicated above, during ice ages there was a much greater mass of ice over the land (particularly far northern America and Europe/Asia), depressing the Earth's lithosphere. Following the flow of these ice sheets into the ocean after the last glacial maximum and the resultant redistribution of sea water, the Earth rebounded through a viscous process that is continuing today. For estimating future relative sea levels and understanding recent observations, this contribution, termed Glacial Isostatic Adjustment (GIA), needs to be included. For the Australian coastline this ongoing GIA adjustment is typically a few tenths of a mm yr^{-1} of relative sea-level fall.

33. **Recent/ongoing mass changes result in both a global mean sea-level change and also a regional sea level change as a result of the changing the Earth's Gravitational and Rotational fields and the Deformation (GRD) of the Earth.** These changes include both a plastic (essentially instantaneous) and an ongoing viscous response.

34. **Satellite altimeters measure geocentric sea level (sea level relative to the centre of mass of the Earth).** These measurements need to be adjusted for the ongoing subsidence of the ocean floor to estimate the change in volume of the ocean and for local land motion to estimate relative sea level change.

35. **In addition to the global scale GIA, local tectonic motions of the land change relative sea level.** These tectonic motions include subsidence from compaction of sediments (accentuated by the withdrawal of water or petroleum products), earthquakes and other solid Earth motions.

36. **The impacts of sea-level rise include coastal flooding and inundation, erosion, higher waves at the coast and saltwater intrusion into estuaries, coastal wetlands and aquifers.**

GLOBAL TEMPERATURES AND EXTREME SEA LEVEL EVENTS

Question 3

What is meant by the term 'extreme sea level events'?

37. **Extreme high (or low) sea level events occur when different phenomena combine to result in relatively rare and temporary (usually a few days or less) increase (or decreases) in sea level heights above (or below) what is normally expected.** Examples include large storm surges driven by strong winds and decreases in atmospheric pressure and the combination of a high tide with a storm surge. Different tidal components may also combine to result in high than normal sea levels. Both extreme low and high sea levels can have negative impacts, but generally it is high sea levels that are of more concern.

38. **At the regional and estuary scale, changing sea levels are felt most acutely through the impacts of extreme events.** The height of these extreme events is impacted by phenomena over a wide range of space scales from global (tides, large-scale climate change and variability) to local features (regional and local storm surges) and on time scales from days and hours (tides, storm surges and waves) to decades and centuries (climate change and variability). Rising sea levels result in more frequent coastal flooding (e.g. flooding as roads are intermittently closed; Sweet and Park 2014; Moftakhari et al. 2015) or exacerbate catastrophic events (such as Hurricane Katrina in New Orleans and Hurricane Sandy in New York and New Jersey (Strauss et al. 2021)).

Question 4

Please explain the relationships between global temperatures, sea levels, and extreme sea level events. In your answer, please address:

a) whether the relationships are linear or non-linear; and

b) whether there is any variation geographically.

39. **The severity and frequency of extreme sea level events can change if the mean sea level changes or the variability (from tides, storm surges etc) of sea level about its mean level changes.** The impact of temperature on mean sea level has been discussed above. Now I will consider the impact of changes in mean sea level on the frequency and height of extreme sea-level events.

40. **The frequency of extreme sea-level events (such as a 1 in 100 year event) can increase rapidly with a rise in mean sea-level.** The frequency of exceedance of a particular level is described by stochastic extreme event theory. The frequency increases exponentially with a rise in mean sea level and is also dependent on the local variability in sea level. Church et al. (2008) found that for a number of locations around Australia, a 0.1

m rise in sea level resulted in an increase in frequency of extreme events by a range of 1.8 to 5.8 (with an average of 3.1), broadly consistent with the 20th century observations for Fremantle and Fort Denison, Sydney (Church et al. 2006). This increase in frequency varies across the globe and is dependent on the local mean sea level change and the sea-level variability (Woodworth et al. 2021). [Note: In the example above, a sea level rise of 0.2 m would imply an average increase in frequency of 3.1^2 or 9.6, etc.]

41. **As mean sea level rises, high tides alone (i.e. without any additional storm surge) can result in what are often termed "nuisance" flooding (for example flooding of coastal roads etc.).** Increases in "nuisance" flooding have been observed in a number of locations over recent decades; for example in the USA (Moftakhari et al. 2015) and at a number of locations in northern Australia (Hague et al. 2019). This type of flooding is predictable with standard tidal theory once the mean sea level rise is known.

42. **A warming climate results in more energy in the atmosphere, an increase in the intensity of climate variability, changes in climate patterns and the potential for a change in wind speed and or direction and thus changes in sea-level extremes.** Any change in winds will alter the intensity and frequency of sea-level variability about the (time varying) changes in mean sea level.

43. **Tropical cyclones result in extreme sea level events.** For tropical cyclones, the global projection is for an increase in intensity (rainfall and winds) of the most severe cyclones but a decrease in the overall number of cyclones (Knutson et al. 2019). However, there is only low confidence that anthropogenic changes in tropical cyclones or their impacts on sea level (see below) have been detected and attributed during the historical record (Knutson et al. 2019). Climate Change impact on tropical cyclones over 1980 to 2018 was found to be more evident in the spatial pattern of tropical cyclone occurrence, rather than the number of tropical cyclones (Murakami et al. 2020).

44. **The height of extreme sea level events will increase with the amount of sea-level rise.** While this is the dominant impact, additional changes could occur with changes in the intensity of storms, changes in the bathymetry allowing a greater/lesser amplification of tides or storm surges or the propagation of surface waves closer to the coast. Determining these potential changes requires consideration of local factors and detailed modelling studies. The impact of extreme sea-level events may rise rapidly if particular thresholds, such as overtopping a levee, are crossed.

HISTORICAL CHANGES IN SEA LEVELS AND EXTREME SEA LEVEL EVENTS

For questions 5-8, consider the position globally, in Australia, and in the Torres Strait Islands.

Question 5

*Please describe any changes in sea levels since the 1850-1900 average (the **Baseline**). In your answer, please describe both the amount and the rate of any changes.*

45. Changes in sea level in preindustrial times are discussed in the response to question 2 above.

Sea-level rise has been accelerating since the 19th century

46. **The rate of global averaged sea-level rise has accelerated since the 19th century.** The first continuous direct measurements of coastal sea level began with the installation of tide gauges in some European ports in the 18th century, with the number of gauges increasing during the 19th and 20th centuries. Analysis of this coastal sea-level data indicate the rate of global mean sea-level rise began accelerating in the 19th century (Church and White 2006, 2011; Kopp et al. 2016).

47. **Sea level during the 20th century rose faster than over previous millennia.** For 1900 to 2018, the most recent assessment (Gulev et al. 2021; Fox-Kemper et al. 2021) is that global mean sea level rose at an estimated rate of 1.73 mm yr^{-1} (with a *very likely* (5-95%) range of 1.28 to 2.17 mm yr^{-1}) and an acceleration over 1900 to 2010 of 0.0053 mm yr^{-2} (with a *very likely* (17-83% probability) range of 0.0042 to 0.0073 mm yr^{-2}). For 1970 to near present, this acceleration has increased to 0.06 mm yr^{-2} (Dangendorf et al. 2019; Wang et al. 2021a). The 20th century sea-level rise is *extremely likely* (probability > 0.95) faster than during any century of the last three millennia common era (Kopp et al. 2016).

48. **Global averaged rate of sea-level rise has increased to 3.25 mm yr^{-1} since 1993 and is continuing to accelerate.** Direct observations of near global (rather than just coastal) sea-level data as measured by satellite altimeters are available since 1993. The *very likely* range of the rate of global mean sea-level rise is 2.88 to 3.61 mm yr^{-1} over 1993 to 2018 with an acceleration of 0.094 mm yr^{-2} (with a *very likely* range of 0.082 to 0.115 mm yr^{-2}) (Gulev et al. 2021; Fox-Kemper et al. 2021; Wang et al. 2021a). An update of the altimeter record (Figure 4) indicates a rate of rise of 3.3 ± 0.3 mm yr^{-1} and an acceleration of 0.12 ± 0.05 mm yr^{-2}. The rate of global mean sea-level rise is now larger than 4 mm yr^{-1} over the last decade (WCRP Global Sea Level Budget Group 2018; Wang et al. 2021a). Analysis of coastal tide gauges also show a similar increase in the rate over the period of the satellite altimeter observations since 1993.

49. **The change in GMSL (Global Mean Sea Level) for 1900 to 2020 is about 0.21 m (0.16-0.26 m).** This estimate is based on tide gauge data prior to 1993 and then satellite altimeter data from 1993 to 2020. Compared to 1900, the rise by 1993 is 0.13 m (0.08 -

0.18 m). From 1900 to the reference period (1995-2014) for the Intergovernmental Panel on Climate Change 6th Assessment Report (IPCC AR6) projections, the historical sea level rise is estimated as 0.16 m. (Fox-Kemper et al. 2021; WCRP Global Sea Level Budget Group 2018).

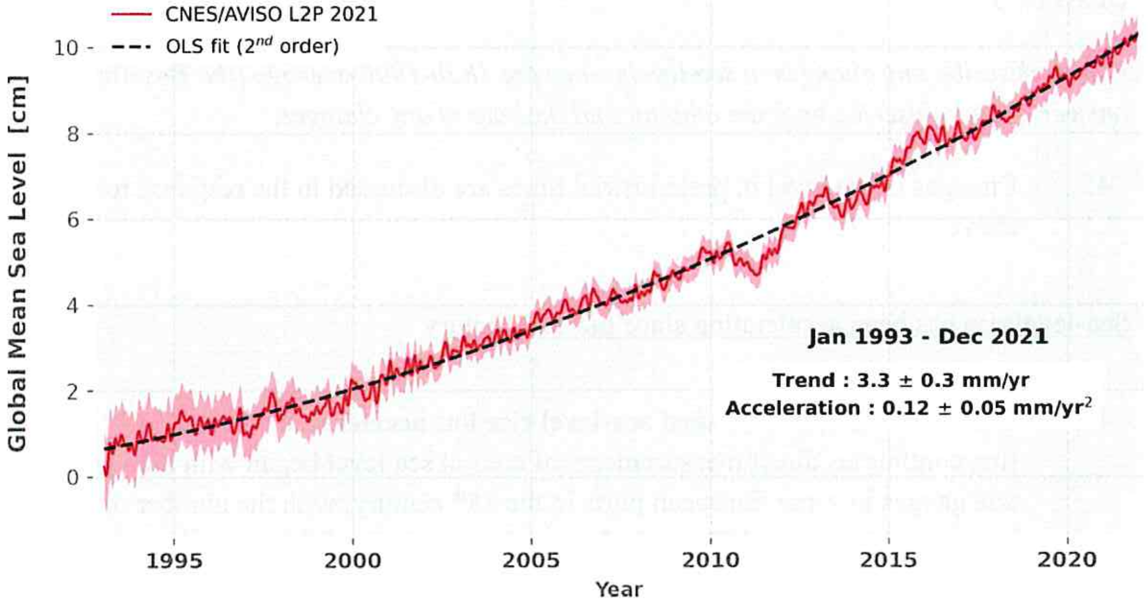

Figure 4. *CNES/AVISO Global mean sea level record and its associated uncertainties. The record has been corrected for TP-A drift as well as for the GIA. Seasonal signals are removed, and the time series is 2-month-filtered. The uncertainty envelope (shaded red area) is given at the 90% C.L., as are the trend and acceleration uncertainties indicated in the white box. (From Guerou et al 2023.)*

50. **Sea level does not rise uniformly around the globe.** On multi-century time scales, there are clear differences in the rate of relative sea-level change (ocean surface relative to the land). In some regions of former ice sheets (during the last glacial maximum, e.g. Sweden) prior to the 20th century, relative sea level has been falling (Peltier 1998), whereas in the immediately adjacent regions to ice sheets (such as the north-east coast of the USA) relative sea level has been rising. These multi-century trends are associated with ongoing vertical land motion (Glacial Isostatic Adjustment, GIA, as discussed above) as a result of the changing surface load on the Earth as large ice sheets melted after the last glacial maximum (Peltier 1998). These GIA trends directly impact present and future sea-level change with some parts of the north-east coast of the USA having experienced a 20th century rise about double the global average rise.

51. **Changes in ocean circulation results in regional differences in the rate of sea-level change.** The satellite altimeter data has revealed large scale patterns of interannual to decadal variability in sea level since 1993, particularly in the low latitude Pacific Ocean (e.g. Zhang and Church 2012) primarily related to variations in the zonal winds (Merrifield et al. 2012). From 1993 to 2018, sea levels rose faster in the western Pacific than the eastern Pacific (Fox- Kemper et al. 2021).

52. **Changes of the mass of water stored on land results in changes the Earth's Gravitational and Rotational Fields and Deformation of the Earth's surface (GRD) and hence changes in regional sea levels. (Gregory et al. 2019)**

Australian and Torres Strait Sea levels are rising

53. **As a result of the acceleration in global sea-level rise, sea level is now rising along all parts of the Australian coastline at an average rate roughly consistent with global mean trends, with an increase in the rate of rise in the early 1990s.** Ongoing Glacial Isostatic Adjustment (GIA; the ongoing movement of the Earth and its gravitational field as a result of loading/unloading of the surface of the Earth by the formation/decay of ice sheets on the land and the decreased/increased mass of the ocean) means sea level around the Australian coast had been falling relative to the land by several tenths of mm yr^{-1} over recent millennia prior to the recent acceleration in sea levels. The latest comprehensive assessment of sea level around Australia (White et al. 2014) reports that for the periods 1966 to 2009 and 1993 to 2009, the average trends of sea level relative to the land around the Australian coastline are 1.4 ± 0.3 mm yr^{-1} and 4.5 ± 1.3 mm yr^{-1}. To isolate the sea-level change associated with changes in ocean volume, it is necessary to remove the effects associated with natural climate variability (including those associated with the El Nino-Southern Oscillation (ENSO) that strongly impacts Australian climate and sea levels), changes in atmospheric pressure and GIA. After this, the corresponding trends are 2.1 ± 0.2 mm yr^{-1} from 1966 to 2009 with an acceleration to 3.1 ± 0.6 mm yr^{-1} for 1993 to 2009, consistent with the global-average rise over the same periods of 2.0 ± 0.3 mm yr^{-1} (estimated from tide gauge data) and 3.4 ± 0.4 mm yr^{-1} (measured with satellite altimeters) (White et al. 2014). The two longest tide-gauge records in Australia at Fort Denison, Sydney and at Fremantle indicate sea level rising relative to the land at average rates of 0.7 mm yr^{-1} (1886 – 2010) and 1.6 mm yr^{-1} (1897 – 2010) respectively, with larger rates over recent decades (White et al. 2014).

54. **Over the last three decades, sea-level rise along northern Australia has been larger than southern Australia and the global average.** The 2020 update using the Australian Baseline Sea Level Monitoring Project of coastal tide gauges (installed in the early 1990s to monitor climate change impact on Australian coastal sea levels) indicates the rate of relative sea-level rise in northern Australia from the early 1990s to 2020 is above the global average at about 4-6 mm yr^{-1} (similar to the local altimeter rate and larger than the global average) but similar to the global average at about 2-4 mm yr^{-1} along the south east coast (Church and Zhang 2022). Part of this larger than global average rise along the northern coastline may be a result of climate variability (Zhang and Church 2012; White et al. 2014). Data suitable for estimating trends is available from the Permanent Service for Mean Sea Level (Holgate et al. 2013). The short (annual) records available indicate rates of relative sea-level rise at Goods and Booby Islands in the Torres Strait of 3.7 ± 3.8 (1990-2018) and 4.2 ± 4.1 (1988-2022) mm yr^{-1}, respectively. The average of these would indicate a sea level rise for a total of about 120 mm (0.12 m) from 1993 to 2023. However, because of to the short time period and significant natural variability, there is significant uncertainty in these rates as an indication of the long term trend. There is a

recent addition (in April 2015) to the Australian Baseline Sea Level Monitoring Project with a coastal tide gauge at Thursday Island (Torres Strait), but this record (since April 2015) is still too short a period to be meaningful.

55. **Recent analysis suggest Australian sea-level rise is continuing to accelerate.** After allowance for the effects of changing ocean volume caused by GIA (Peltier 2004), Rezvani et al. (2022) estimated average rates of sea-level rise around Australia are 3.80 ± 0.34 mm yr^{-1} and 3.87 ± 0.23 mm/year for tide gauge and satellite altimeter records, respectively. These are approaching 1.0 mm yr^{-1} higher than that from White et al. (2014) who used data up to the end of 2010, suggesting an acceleration in sea-level around Australia, consistent with findings across the Oceania region from Wang et al. (2021a).

Question 6

Please explain the causes of any changes in sea levels described in your answer to question 5.

56. **We now have a reasonably good understanding of sea-level change (the sea-level budget) over the 20th century and particularly recent decades.** Understanding the reasons for the sea-level change observed over the 20th century has developed considerably since 1993 (when the satellite altimeter record commenced) and 2006 when satellite measurement of changes in the mass of the ocean and high quality near global measurements of ocean warming became available. Particular progress was made in the studies focussing on the rise in global mean sea-level rise since the 1960s (Church et al. 2011; Moore et al. 2011), for the complete 20th century (Gregory et al. 2013; Frederikse et al. 2020), for the satellite altimeter period (1993 to present; Chen et al. 2017; WCRP Budget Group 2018), for regional sea-level change since the 1950s (Frederikse et al. 2020) and local sea-level change since the 1950s (Wang et al. 2021b).

57. **The two largest contributions to sea-level rise since 1900 are ocean thermal expansion (ocean water expands as it warms and as a result sea level rises) and the loss of mass from glaciers, including the peripheral glaciers on Greenland (See Fox-Kemper et al. 2021 and Wang et al. 2021b for the latest sea-level budget; Figure 5).** There were also smaller contributions from the ice sheets of Greenland and Antarctica but these have been accelerating significantly over the last three decades (Chen et al. 2017; Fox-Kemper et al. 2021).

58. **There are also other small sea level changes as a result of changes in water stored on land.** The mass of water stored on land changes as a result of natural climate variability and also human interference in the water cycle through the extraction of water from aquifers (much of which makes its way to the ocean) and the storage of water in terrestrial reservoirs (TWS). These aquifer and reservoir storages are important in understanding the reasons for 20th century change but are likely less important in projections for the 21st century (Church et al. 2013; Fox-Kemper et al. 2021).

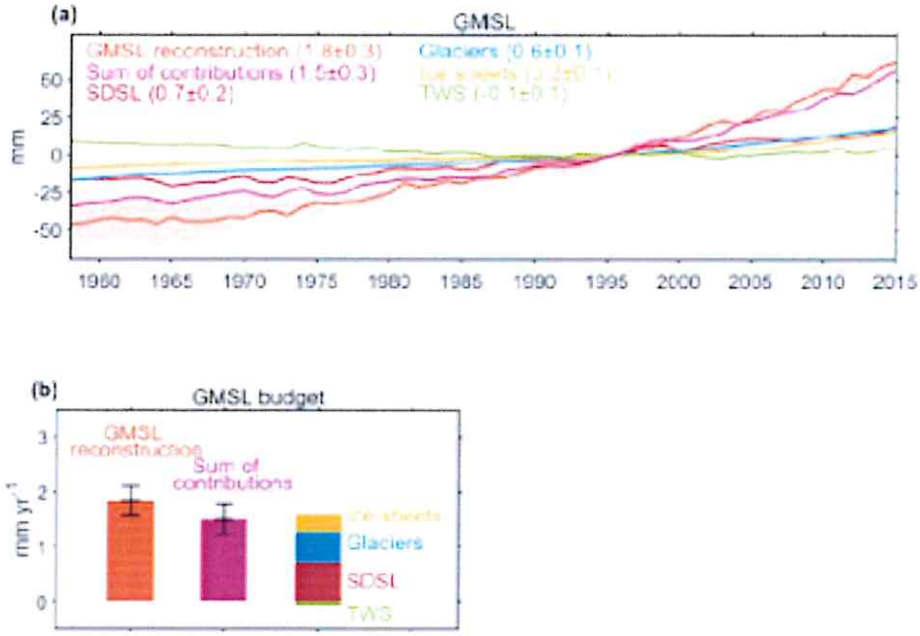

Figure 5. The global sea level budget. (a) GMSL time series (mm) from the ensemble mean of different reconstructions (orange; shading area indicating 90% confidence limit (CL)), the sum of all contributions (purple), ocean thermal expansion (indicated by stereo dynamic sea level (SDSL) (red) in Figure 5), glaciers (blue), ice sheets (yellow), and TWS (green). (b) The trend (mm yr^{-1}) of GMSL and individual contributions over 1958-2015, with the same colour defined in (a). The Error bars indicate 90% CL. (from Wang et al. 2021b.)

59. **Analyses clearly indicate that sea-level change is a result of increases in global temperatures.** Warming of the oceans and the related ocean thermal expansion, the loss of mass from glaciers and the negative surface mass balance (increased ablation is larger than increased snowfall) of the Greenland ice sheet are all a result of an increase in surface temperatures (Church et al. 2013; Fox-Kemper et al. 2021). For Antarctica, analysis of data since the early 1990s (Shepherd et al., 2018, 2019) indicates that accelerated ice discharge (resulting from warming of ocean waters near ice shelves; mainly in west Antarctica) is larger than the increased snowfall (also related to increased atmospheric temperatures), resulting in a net positive contribution to sea-level rise. Parts of the West Antarctic Ice Sheet are in dynamical imbalance and as a result ice is flowing more rapidly into the ocean (Shepherd et al. 2019).

60. **There is now a clear indication that anthropogenic climate change is causing warming global temperatures and thus sea-level rise.** While natural variability in sea level tends to obscure the long-term trends at individual tide-gauges, models of the various contributions forced by anthropogenic factors, together with observational estimates of ice sheet and land water contributions can now reasonably represent global mean sea-level change over the 20th century (Church et al. 2013; Slangen et al. 2017) and its regional distribution (Meyssignac et al. 2017). Different forcing factors (greenhouse gases, aerosols, ozone changes and natural variability) result in different temporal and spatial fingerprints of ocean change (Slangen et al. 2015; Bilbao et al. 2015; Fasullo et al. 2020). These patterns have been used to detect the anthropogenic influence in ocean

temperatures (Marcos and Amores 2014; Slangen et al. 2014) and in zonal means of sea-level change over 1993-2015 (Richter et al. 2020). The anthropogenic signal has also been detected in the glacier contribution to sea-level change for the latter 20th century (Marzeion et al. 2014) with a more recent analysis indicating the anthropogenic signal is present throughout the 20th century (Roe et al. 2021). Since 1970, anthropogenic climate change has been the largest cause of sea level rise (69 ± 31% after 1970, reaching 72 ± 39% in 2000) (Slangen et al. 2016).

61. **The ability to model past changes has improved over the last decade.** When models of ocean warming, glacier response and Greenland surface mass balance and estimates of vertical land motion from GIA are combined with observations of ice sheets they approximately explain the post 1900 observed global mean (Church et al. 2013; Slangen et al. 2017) and local (Meyssignac et al. 2017) sea-level change. Models of ice sheet behaviour have and are progressing rapidly but a number of uncertainties remain.

Question 7

Please describe any changes in extreme sea level events since the Baseline. In your answer, please describe both the amount and the rate of any changes.

Question 8

Please explain the causes of any changes in extreme sea level events described in your answer to question 7.

62. **The frequency and severity of extreme sea-level events have increased over recent decades**. This has occurred both regionally (e.g., Church et al. 2006; Marcos et al. 2019; Grinsted et al. 2012; Sweet and Park 2014; Moftakhari et al. 2015; Haigh et al. 2014) and globally (e.g., Woodworth and Blackman 2004; Menéndez and Woodworth 2010; Marcos et al. 2019).

63. **The dominant driver of the observed increase in flooding from extreme sea level events has been the rise in (local) mean sea level**. The dominant cause is the long term rise in mean sea level in response to global warming. There is also variability in coastal flooding events as a result of the seasonal cycle, climate variability and ocean eddy variability (Woodworth and Blackman 2004; Menéndez and Woodworth 2010, Woodworth and Menéndez 2015; Barnard et al. 2015). For the USA, relative sea-level rise has driven large increases in the annual duration and frequency above minor (nuisance level) coastal flooding elevations over the last 50 years (Moftakhari et al. 2015).

64. **At a small number of locations there is a difference between long-term relative mean sea-level trends and extreme sea water level trends** (e.g. Rashid and Wahl, 2020; Feng et al. 2019; Fox-Kemper et al. 2021). These differences in trends can result from changes in the surge, tidal components or waves (including wave setup and wave runup), including both wave set-up and run-up, and can include non-linear interactions between tide, surge, waves and relative sea-level change (Arns et al., 2017, 2020; Schindelegger et al., 2018). From the limited studies to date, there is some evidence that changes in storminess have

caused changes in extreme sea levels (e.g., at locations along the western North Pacific, Oey and Chou, 2016; along the USA east coast, Grinsted et al., 2012; along the China coast, Feng et al. 2019). Further studies are required to identify any broader scale impact of changes in storminess on extreme sea levels.

65. **Flooding from the combination of extreme events and sea level rise is not restricted to the coastline** but also occurs far from the ocean along estuaries and tidal lakes (e.g., Hanslow et al. 2018; Lopes et al. 2022).

66. **In Torres Strait, near annual exceedance of impact thresholds (for example flooding of coastal roads etc.) has increased.** For Booby Island, Torres Strait, there were at least 21.4 hours of flooding per year over the period 1987 to 2017, with a 50% increase (11.2 hours/year) each decade (Hague et al. 2019).

67. **Extreme sea level events are already causing flooding in communities in Torres Strait.** By 2010, five communities were experiencing coastal flooding. Modelling from Systems Engineering Australia (2011) suggests an annual likelihood of encroachment into some habitation areas in Saibai of up to 0.5 m in depth. For a 1000 yr return period (a 0.1% chance in any single year or a 5% chance over any 50 y period), the flooding could reach a depth of 1 m. The next most vulnerable islands are Boigu, Masig, Warraber and Iama. The study also indicates finds that the height of extreme events increases with local mean sea level rise (Systems Engineering Australia Pty. Ltd. 2011), implying that the average depth of flooding would have increased 0.12 m from 1993 to 2023. In the absence of local information, the global average rise in mean sea level is likely the best estimate of mean sea level rise in Torres Strait prior to 1993. This would imply that the average depth of flooding would have increased by about 0.25 m from 1900 to 2023.

68. **The historical increase in mean sea level in Torres Strait implies there has been an increase in the frequency of extreme events of a given height.** The Systems Engineering Australia (2011) study implies an average increase across locations considered in Torres Strait by a multiplication factor of 5.2 (range of 2.2 to 11.5 across the islands considered) for a 0.1 m of sea level rise. In a global study, Woodworth et al. (2021) estimated multiplication factors for 6 sites in Torres Strait. These have an average multiplication factor of 2.1 (range of 1.5 to 3 across the sites) for 0.1 m of sea level rise. The reason for this difference between these two estimates is not clear but it may relate to inadequate inclusion of the interannual variability in the Systems Engineering Australia study, improved meteorological forcing in the Woodworth et al. study, or the inability of the global study to adequately represent some local features. The average of the Woodworth et al. factors imply a more than doubling in the frequency of extreme sea level events of a given height over 1993 to 2023 (mean multiplication of 2.4 with a range of 1.6 to 3.7, for a 0.12 m of sea level rise), and an increase by a multiple of 6.4 (range of 2.7 to 15.6) for 1900 to 2023. The equivalent multiplication factor implied by the Systems Engineering Australia study are much larger at 7 (range of 3 to 19) for 1993 to 2023 and more than 61 (7 to 448) for 1900 to 2023.

69. **As well as flooding and inundation, rising sea levels are associated with salt-water intrusion, an increase in erosion (a substantial proportion of the world's sandy beaches already eroding (Vousdoukas et al. 2020) and other impacts on estuarine and coastal ecosystems.**

PROJECTED CHANGES IN SEA LEVELS AND EXTREME SEA LEVEL EVENTS

For questions 9-10, consider the position globally, in Australia, and in the Torres Strait Islands.

Question 9

*Please describe the projected change to sea levels between now and the conclusion of the 21st Century consistent with each of the Representative Concentration Pathways **(RCPs)** and Shared Socioeconomic Pathways **(SSPs)** as used by the Intergovernmental Panel on Climate Change (IPCC).*

Question 10

Please describe the projected nature, frequency, and intensity of extreme sea level events between now and the conclusion of the 21st century consistent with each of the RCPs and SSPs.

70. In this section, the sea level projections relative to the reference periods in the primary assessments are presented first. The AR6 projections relative to 1900 are also presented. These are obtained by adding the global mean sea level in the reference period relative to 1900 to the projections from the reference period.

71. **There are many components to bring together to make global-mean and regional sea-level projections for the 21st century and beyond (Church et al. 2013; Fox-Kemper et al. 2021) resulting from greenhouse gas concentrations.** Climate models (coupled atmosphere-ocean-cryosphere-land surface models) are used to evaluate sea-level changes resulting from warming of the oceans. Sea-level changes have a global mean component from ocean thermal expansion and a regional distribution as sea-level change that is not uniform around the globe. These regional changes are associated with a changing ocean circulation resulting from changing interactions with the atmosphere (changing surface winds and air-sea-ocean fluxes of heat and freshwater). Additional models are used to evaluate changes in the mass of glaciers, ice sheets and land water changes and thus the mass of the ocean. These mass changes result in an additional global mean sea-level change and also a regional distribution as a result of the changing of Earth's Gravitational and Rotational fields and the Deformation (GRD) in response to these large mass transfers. There are also large-scale ongoing changes to the Earth following the loss of ice sheets at the end of the last glacial maximum (GIA) and regional/local tectonic changes from earthquakes, compaction of sediments etc. Many uncertainties remain about the future of the Antarctic ice sheet contributions to sea-level change. These uncertainties are not symmetric and could result in a substantially larger rise but not a significantly smaller rise.

Global Projections to 2100

72. **Global Climate Projections have been evaluated for a range of possible future greenhouse gas emission scenarios.** The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5; IPCC 2013) and the IPCC Special Report on the Oceans, Cryosphere and Climate (SROCC; IPCC 2019) used four different scenarios,

called Representative Concentration Pathways (RCPs) in an attempt to span potential future scenarios. The lowest used in the AR5 (RCP2.6) requires strong mitigation of greenhouse gas emissions and negative emissions after about 2070, whereas the highest (RCP8.5) represents continued growth of emissions beyond 2100. Two intermediate scenarios are RCP4.6 and RCP6.0. The IPCC 6th Assessment Report (IPCC 2021) used 5 Shared Socio-economic Pathways, ranging from SSP1-1.9 (designed to be consistent with the Paris Target of 1.5° C of global warming), SSP1-2.6 (similar to RCP2.6), SSP2-4.5 (similar to RCP4.5), SSP3-7, and SSP5-8.5 (similar to RCP8.5).

73. **After 2050, projected sea-level rise is strongly dependent on future emission scenarios and continues to accelerate for high emissions.** Before 2050, projected sea-level rise depends on past emissions and is only weakly dependent on future emission scenarios. For strong mitigation of greenhouse gas emissions (RCP2.6) consistent with warming relative to pre-industrial levels of just under 2°C, the central projection for 2100 of IPCC AR5 is a 0.44 m rise with a projected range of 0.28 to 0.61 m relative to 1986-2005 (AR5; Church et al. 2013, Table 1). For this scenario, the rate of rise over 2081-2100 is about 4.4 mm yr^{-1}, having stabilised and decreasing slowly. For continuing emission with RCP6.0 and RCP8.5, the projected sea-level rise in 2100 is larger at 0.55 (0.38-0.73) m and 0.74 (0.52-0.98) m. Importantly, for these scenarios, the rate of rise is large at 7.4 (4.7-10.3) mm yr^{-1} and 11.2 (7.5-14.7) mm yr^{-1}, particularly for RCP8.5, and is continuing to increase, implying rapidly rising sea levels over subsequent decades and centuries. These latter values are equivalent to the rate of rise during the last major deglaciation of the Earth when sea level rose at over a metre per century for many thousands of years.

74. **The IPCC Special Report on the Oceans, Cryosphere and Climate projected larger sea level rise than the AR5 for high emission scenarios.** The **SROCC** projections (Oppenheimer et al. 2019) were based on the **AR5** projections but with a slightly larger contribution for the Antarctic ice sheet under high emission scenarios.

75. **The IPCC AR5 and SROCC projections of sea level change are consistent with observations both globally (Figure 6) and regionally for the available short period of overlap**. The observed trends from GMSL and the regional weighted mean at tide-gauge stations confirm the projections within 90% confidence level during 2007–2018. However, the central values of the observed GMSL acceleration over 1993-2021 (0.12 ± 0.05 mm yr^{-2}, Figure 4) is larger than the central values of the projected accelerations (Wang et al. 2021a) for 2007-2032 for the AR5 RCP2.6 (0.035 ± 0.052 mm yr^{-2}), RCP4.5 (0.048 ± 0.048 mm yr^{-2}), and even RCP8.5 (0.067 ± 0.049 mm yr^{-2}).

	RCP2.6	**RCP4.5**	**RCP6.0**	**RCP8.5**
Global Mean rise (m)	0.44 (0.28 to 0.61)	0.53 (0.36 to 0.71)	0.55 (0.38-0.73)	0.74 (0.52 to 0.98)
Rate of rise (mm/yr)	4.4 (2.0 to 6.8)	6.1 (3.5 to 8.8)	7.4 (4.7-10.3)	11.2 (7.5 to 15.7)
Torres Strait rise (m)	0.42 (0.23-0.60)	0.52 (0.31-0.73)	0.54 (0.34-0.65)	0.74 (0.50-1.00)
Rate of rise (mm/yr)	4.0 (1.3-6.6)	5.9 (3.0-8.8)	7.4 (4.4-10.6)	11.3 (7.2-16.2)

Table 1: *IPCC* ***AR5*** *projections of global mean sea level (Church et al. 2013), and sea level near Torres Strait (McInnes et al. 2015) in 2100 compared to 1986-2005. The numbers in each box are the central estimate of sea-level rise, with the likely range (17-83%) given in brackets and the estimated rate of rise over 2081 to 2100 is on the second line. The AR5 noted the potential of an additional several tenths of a metre sea level contribution from possible but uncertain instabilities of the Antarctic ice sheet, particularly for the high emission scenarios. The regional projections are available at the* CoastAdapt website *(https://coastadapt.com.au/tools/coastadapt-datasets#future-datasets) and were prepared by CSIRO based on the IPCC AR5 projections. (Note, for comparison to the AR6 GMSL projections, about 0.03 m needs to be subtracted from the AR5 projected rise in 2100 because the AR6 projections are relative to a later base period of 1995 to 2014.)*

	SSP1-1.9	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**	**SSP5-8.5**	**SSP5-8.5 Low confidence**
Global Mean rise (m)	0.38 (0.28-0.55)	0.44 (0.32-0.62)	0.56 (0.44-0.76)	0.68 (0.55-0.90)	0.77 (0.63-1.01)	0.88 (0.63-1.60)
Rate of rise (mm/yr)	4.~~3~~2 (2.~~5~~4-6.6)	5.~~3~~2 (3.~~3~~2-8.~~1~~0)	7.7 (5.2-11.6)	10.4 (7.~~5~~4-14.~~9~~8)	12.~~2~~1 (8.~~8~~6-17.~~7~~6)	15.~~9~~8 (8.~~8~~6-30.~~2~~1)

Table 2: *IPCC* ***AR6*** *projections of global mean sea level (Fox-Kemper et al. 2021) in 2100 compared to 1995-2014. The numbers in each box are the central estimate of sea-level rise, with the likely range (17-83%) given in brackets, and the estimated rate of rise over 2080 to 2100 is on the second line. The AR6 noted the potential of an additional low confidence contribution from possible but uncertain instabilities of the Antarctic ice sheet for the high emission scenarios.*

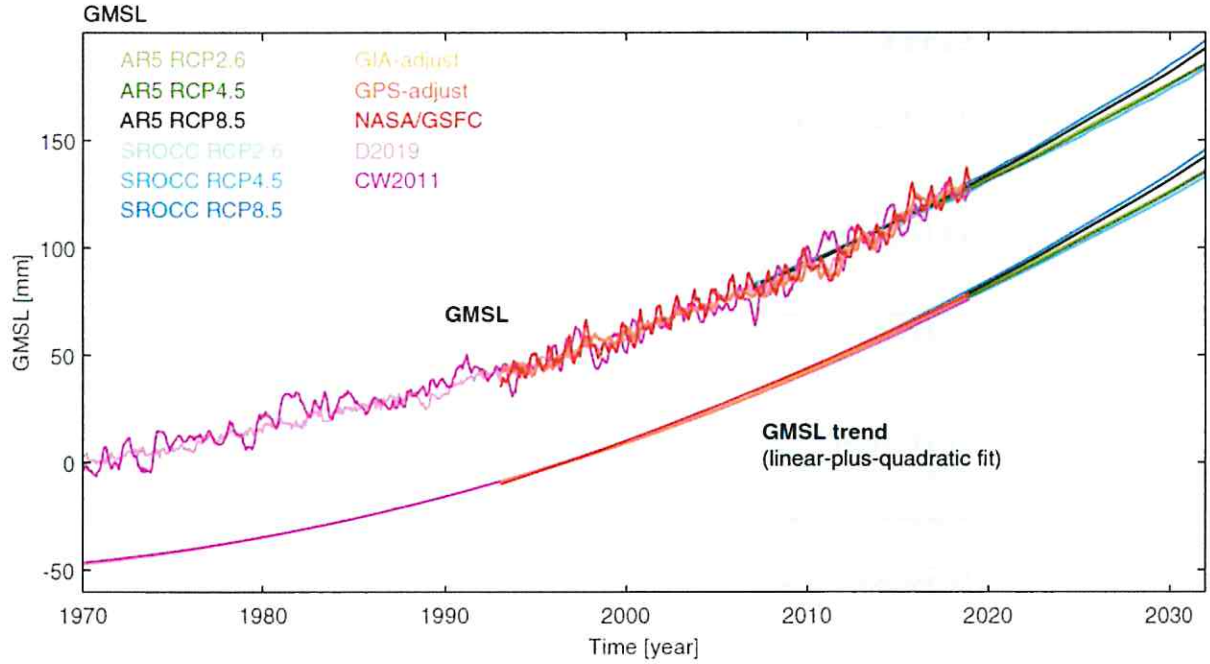

Figure 6. *GMSL from observations compared with projections. Monthly GMSL from satellite altimeter (1993-2018) and reconstructions (1970-2018) smoothed with a 5-month running mean filter, and annual multi-model averaged GMSL from the AR5 and SROCC projections (2007-2032) under three RCPs. GMSL trends including both linear and quadratic terms are also shown offset by -50 mm. The blue shaded area indicates the overlapping period between observations and projections (2007-2018). (from Wang et al. 2021a).*

76. **The IPCC AR6 global sea-level projections (Figure 7, Table 2) are relative to 1995-2014.** The 2021 AR6 assessment included a lower emission greenhouse gas scenario (SSP1-1.9) consistent with a global mean surface warming by 2081-2100 of 1.4° C (1.0-1.8° C; consistent with the Paris target of 1.5° C). These projections benefited from an improved constraints on the knowledge of the climate sensitivity to greenhouse gases and the first internationally coordinated ice sheet and glacier model intercomparison projects. Most importantly, this resulted in a slightly larger and more robust estimate for the projected Antarctic contribution, although significant uncertainties remain. For SSP1-1.9, the *likely* projected global-mean sea-level rise by 2100 relative to 1995-2014 is 0.38 m (0.28-0.55) whereas for SSP5-8.5 the rise is essentially double this at 0.77 m (0.63-1.02 m) (Table 2, Figure 7). The AR6 did not complete projections equivalent to RCP6.0 but included SSP3-7.0 (equivalent to a warming of about 3.6° C (2.8-4.6° C) (Fox-Kemper et al. 2021).

77. **The AR6 also included a low-likelihood, high-impact story line which implies a higher amount and rate of sea level rise.** This projection allows for potential instability of the ice sheets but there is low confidence in the projected range of 0.88 (0.63-1.61) m, with a rate of rise over 2080-2100 of 1.5~~9~~8 (0.8~~8~~6-3.0~~2~~1) m century^{-1} (Fox-Kemper et al. 2021).

	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP5-8.5 Low confidence
Global mean rise - 2050 relative to 1900 (m)	0.34 (0.31-0.39)	0.35 (0.32-0.41)	0.36 (0.33-0.42)	0.38 (0.34-0.43)	0.39 (0.36-0.45)	0.40 (0.36-0.56)
Global mean rise - 2100 relative to 1900 (m)	0.54 (0.44-0.71)	0.60 (0.48-0.78)	0.72 (0.60-0.92)	0.84 (0.71-1.06)	0.93 (0.79-1.17)	1.04 (0.79-1.76)

***Table 3:** IPCC **AR6** projections of global mean sea level (Fox-Kemper et al. 2021) in 2050 and 2100 compared to 1900. The numbers in each box are the central estimate of sea-level rise, with the likely range (17-83%) given in brackets. The AR6 noted the potential of an additional low confidence contribution from possible but uncertain instabilities of the Antarctic ice sheet for the high emission scenarios. Changes relative to 1900 are estimated by adding the observed global mean rise of 0.16 m to the projections (Table 2) relative to 1995-2014.*

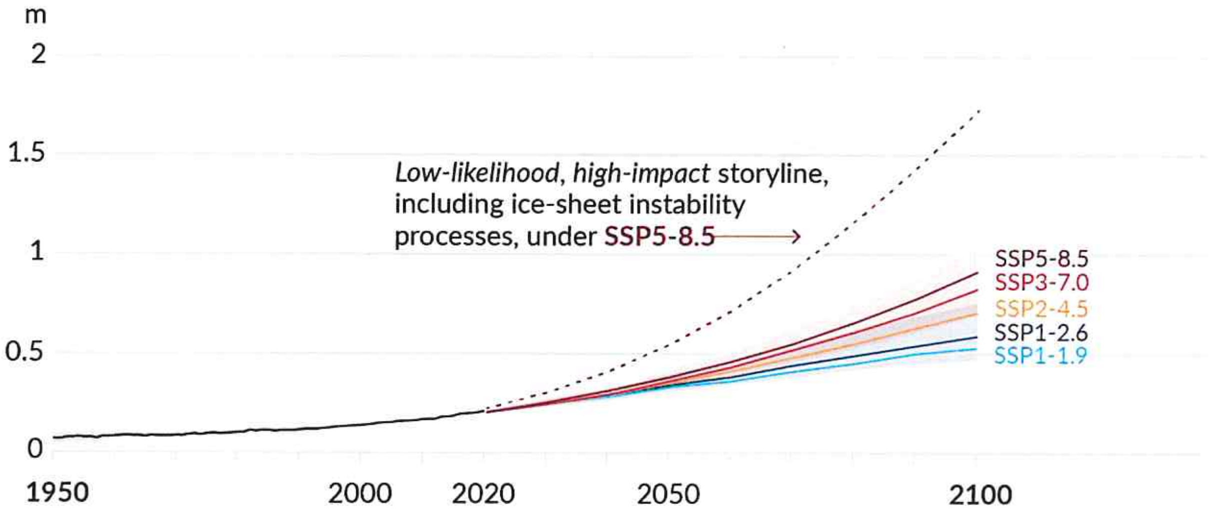

***Figure 7.** Global mean sea level change in meters, relative to 1900. The historical changes are observed (from tide gauges before 1992 and altimeters afterwards), and the future changes are assessed consistently with observational constraints based on emulation of Coupled Modelling Intercomparison Project Phase 6 (CMIP6), ice-sheet, and glacier models. Likely ranges are shown for SSP1-2.6 and SSP3-7. Only likely ranges are assessed for sea level changes due to difficulties in estimating the distribution of deeply uncertain processes. The dashed curve indicates the potential impact of these deeply uncertain processes. It shows the 83rd percentile of SSP5-8.5 projections that include low likelihood, high-impact ice sheet processes that cannot be ruled out because of low confidence in projections of these processes. This curve does not constitute part of a likely range. Changes relative to 1900 are calculated by adding 0.158 m (observed global mean sea level rise from 1900 to 1995-2014) to simulated and observed changes relative to 1995-2014. (From IPCC 2021, AR6 Summary for Policy Makers).*

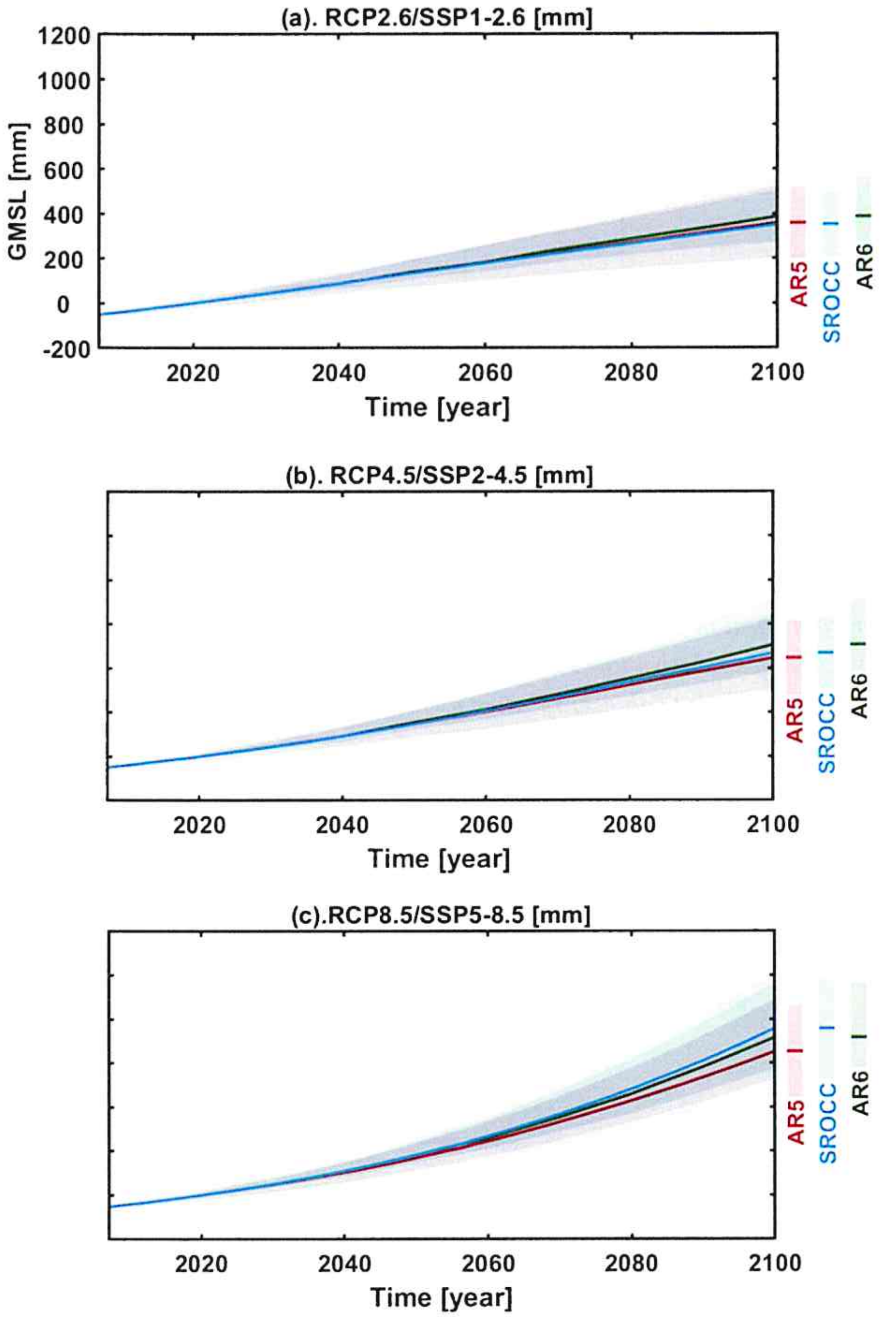

Figure 8. *Comparison of the RCP 2.6, 4.5 and 8.5 Scenario projections from the AR5, the SROCC and the AR6, all relative to 2020.*

78. **The AR5, SROCC and AR6 GMSL projections (and their likely ranges) are very similar when adjusted to be compared to the same time base (Figure 8).** The AR6 projections are about 0.03 m higher for SSP1-2.6 than the AR5 equivalent projections, and about 0.06 m higher for SSP5-8.5. The SROCC has the highest projections for RCP8.5, at about 0.04 m higher than the AR6 and 0.10 m than the AR5. (Figure 8, Tables 1 and 2; Fox-Kemper et al. 2021)

79. **Note that the uncertainties in the amount and rate of sea-level rise from the ice sheets are not symmetric, with the possibility of substantially larger rates and amounts for high emission scenarios.** This asymmetry is a result of the potential instabilities of the Antarctic Ice Sheet discussed above and thus the potential for a faster flow of ice into the ocean.

80. **The uncertainties associated with the Antarctic Ice Sheet could result in a substantially larger rise but not a significantly smaller rise.** The AR5 recognised the potential for marine ice sheet instabilities in Antarctica to lead to a substantially larger rise, particularly for high emission scenarios, but was unable to make precise projections. Based on limited evidence, it suggested this "additional contribution would not exceed several tenths of a metre of sea level rise during the 21st century".

81. **The AR6 concluded higher amounts of GMSL rise before 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt and widespread onset of marine ice sheet instability, potential marine ice cliff instability around Antarctica, and faster-than-projected changes in the surface mass balance and discharge from Greenland.** There is low confidence in these projections of a rise of 0.88 m (0.63 to 1.61 m) in 2100, with sea level rising rapidly at that time (Figure 7). The processes are characterized by deep uncertainty arising from limited process understanding, limited availability of evaluation data, uncertainties in their external forcing and high sensitivity to uncertain boundary conditions and parameters. In a low-likelihood, high-impact storyline, under high emissions such processes could, in combination, contribute more than one additional metre of sea level rise by 2100. (Fox-Kemper et al. 2021)

82. **Beyond 2100, the AR5, SROCC and the AR6 projected GMSL will continue to rise for centuries due to continuing deep-ocean heat uptake and mass loss from the Greenland and Antarctic ice sheets.** Considering only processes for which projections can be made with at least medium confidence, and assuming no increase in ice-mass flux after 2100, relative to the period 1995–2014, by 2150, the AR6 projected GMSL will rise between 0.6 [0.4 to 0.9, likely range] m (SSP1-1.9) and 1.4 [1.0 to 1.9, likely range] m (SSP5-8.5). By 2300, GMSL will rise between 0.3 m and 3.1 m under SSP1-2.6, between 1.7 m and 6.8 m under SSP5-8.5 in the absence of marine ice cliff instability, and for low confidence projections that include the uncertain marine ice cliff instability, up to 16 m under SSP5-8.5 (Fox-Kemper et al. 2021).

Global implications from the AR5 and AR6 Projections

83. **The projections for the 21st century are larger than the observed sea-level rise over the 20th century (Church et al. 2013; Fox-Kemper et al. 2021) for all scenarios.** These projections include growing contributions from ocean thermal expansion and loss of mass from glaciers and ice sheets.

84. **The world will have to adapt to that part of sea-level rise we can no longer prevent.** All projections indicate past greenhouse gas emissions have not only resulted in sea-level rise during the 20th century but also guarantees ongoing sea-level rise as a result of the long time scales explained above. Projections of the amount of sea-level rise before 2050 are partly a result of past greenhouse gas emissions and are only weakly dependent on greenhouse gas emissions between now and 2050 (Church et al. 2013; Fox-Kemper et al. 2021; Wang et al. 2021a).

85. **Larger greenhouse gas emissions result in higher sea levels by 2100 and beyond.** Greenhouse gas emissions determine the rate of acceleration of sea-level rise and are thus a strong control on the amount of sea-level rise after 2050, by 2100 and beyond (see below) (Church et al. 2013; Fox-Kemper et al. 2021; Wang et al. 2021a).

86. **Earlier mitigation of greenhouse gas emissions result in a greater reduction in sea-level rise then delayed reduction in emissions.** Global surface temperatures are directly related to the sum of greenhouse gas emissions. For sea-level rise by any given time-frame, early greenhouse gas emissions result in a larger sea-level rise than later emissions of the same total amount (Bouttes et al. 2013; Church et al. 2013; Fox-Kemper et al. 2021). Thus, delayed mitigation leads to a larger sea-level rise.

Regional Projections for the 21st century

87. **The regional differences in the projections of sea-level change are within about 20% of the global mean projections for the majority (nonpolar regions and far from regions of former ice sheets) of the world's coastline.** The regional projections of sea-level change flow directly from the global projections. The regional pattern associated with ocean thermal expansion component comes from climate models directly. The regional pattern associated with mass changes comes from evaluation of changes in the Earth's gravitation and rotational fields and changes in vertical land motion (Church et al. 2013; Fox-Kemper et al. 2021).

88. **Relative sea-level rise projections are also dependent on estimates of vertical land motion.** The AR5 only included vertical land motion from global scale phenomena GIA and GRD and deliberately left it to local groups to estimate local vertical land motion from other processes such as local subsidence from sediment compaction and extraction of ground water and petroleum products (Church et al. 2013). The AR6 included estimates of all vertical land motion. However, they caution that there is only "*low* to *medium confidence* in the GIA and VLM projections employed in this report. In many regions, higher fidelity projections would require more detailed regional analysis." (Fox-Kemper et al. 2021).

Projections for Australia based on the AR5 and AR6

89. **AR5 Projections of sea-level rise for the Australian coast line to 2100 are similar to the global mean sea-level projections** and are almost independent of the Representative Concentration Pathways (RCPs) for the first decades of the 21st century, but they begin to diverge significantly from about 2050. For the business-as-usual scenario (RCP8.5), the rates increase through the 21st century reach almost 12 mm yr^{-1} by 2100 at all locations (McInnes et al. 2015; Zhang et al. 2017). The projections for all Australian Coastal Councils are given on the CoastAdapt website (https://www.coastadapt.com.au/tools/coastadapt-datasets#future-datasets).

90. **The AR5 projections for 2100 for Torres Strait are almost equal to the AR5 GMSL projections (Table 1).** There is very little difference in the projected sea levels within the Torres Strait region (Zhang et al. 2017).

91. **The AR6 estimates of sea level rise in Torres Strait are smaller than the AR5 because the AR6 estimated 24 cm of rising vertical land motion by 2100. However, this is not consistent with independent estimates which indicate slightly falling land motions.** Direct Global Positioning System observations (Riddell et al. 2020) and the combination of satellite and in situ measurement of sea level (Rezvani et al. 2022) indicate small rates of land subsidence. Hence, consistent with the AR6 caution mentioned above, there is "low confidence" in the AR6 vertical land motion estimates and they are not used in revised projections for Torres Strait (Table 4 and 5). This "low confidence" is consistent with the AR6 caution assigning "*low* to *medium confidence* in the GIA and VLM projections employed in this report. In many regions, higher fidelity projections would require more detailed regional analysis." (Fox-Kemper et al. 2021).

92. **The revised projections for Torres Strait (Table 4 and 5) replace the IPCC AR6 land motion estimates with the same GIA correction as used in the AR5.** After allowing for the different time-base, these revised AR6 projections are 0.07 (RCP2.6) and 0.09 m higher than the AR5 regional projections. The majority of this difference is the difference in the global mean projections with small additional differences from the regional distribution. These projections are slightly higher than the global mean projections and as was the case for the AR5, the projections have little spatial variation within Torres Strait. Changes relative to 1900 are estimated by adding the observed global mean rise (in the absence of estimate of regional changes from 1900 to the reference period) by 0.16 m to the projections relative to 1995-2014 (Table 4).

	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
2050 relative to 1995-2014	0.18 (0.14-0.25)	0.20 (0.15-0.27)	0.21 (0.16-0.29)	0.22 (0.18-0.29)	0.24 (0.18-0.32)
Woodworth Multiplication factors	4 (2-7)	4 (2-9)	5 (2-10)	5 (2-11)	6 (3-14)
SSA Multiplication factors	19 (4-81)	27 (5-132)	32 (5-169)	38 (6-203)	52 (7-330)
2100 relative to 1995-2014	0.40 (0.26-0.60)	0.46 (0.30-0.67)	0.58 (0.41-0.83)	0.71 (0.53-0.98)	0.80 (0.60-1.11)
Woodworth Multiplication factors	19 (5-81)	30 (6-156)	74 (10-585)	193 (18-2,441)	378 (26-6,561)
SSA Multiplication factors	731 (23-17,500)	1,970 (38-75,700)	14,200 (97->100,000)	>100,000 (270->100,000)	>100,000 (549->100,000)

Table 4: *Projections of mean sea level for Torres Strait relative to 1995-2014 based on the AR6 results but with the estimate of local vertical land motion using the same GIA estimates as used in the AR5. The numbers in each box are the central estimate of sea-level rise, with the likely range (17-83%) given in brackets. The AR6 noted the potential of an additional low confidence contribution from possible but uncertain instabilities of the Antarctic ice sheet for the high emission scenarios but the regional projections for this low confidence estimates are not given here. The multiplication factor is the factor by which the return period of extreme sea level events at a given height is divided by for a given sea level rise. For example, if the factor is 4, a return period of 100 years becomes 25 years. The factor is calculated here for the mean sea level rise for each scenario and the range of multiplication factors across the islands in the studies of Woodworth et al. (2021) and Systems Engineering Australia (SSA, 2011).*

	SSP1-1.9	**SSP1-2.6**	**SSP2-4.5**	**SSP3-7.0**	**SSP5_8.5**
2050 relative 1900	0.34 (0.30-0.41)	0.36 (0.31-0.43)	0.37 (0.32-0.45)	0.38 (0.34-0.45)	0.40 (0.34-0.48)
Woodworth Multiplication factors	12 (4-42)	14 (4-52)	16 (4-58)	17 (5-65)	19 (5-81)
SSA Multiplication factors	272 (15-4,040)	378 (17-6580)	446 (18-8410)	526 (20->10,000)	731 (23->10,000)
2100 relative to 1900	0.56 (0.42-0.76)	0.62 (0.46-0.83)	0.74 (0.57-0.99)	0.87 (0.69-1.14)	0.96 (0.76-1.27)
Woodworth Multiplication factors	64 (10-470)	99 (12-908)	242 (20-3,390)	636 (34-14,200)	1,240 (49->10,000)
SSA Multiplication factors	>10,000 (83->10,000)	>10,000 (133->10,000)	>10,000 (342->10,000)	>10,000 (953->10,000)	>10,000 (1,940->10,000)

Table 5: *Projections of mean sea level for Torres Strait relative to 1900 based on the AR6 results but with the estimate of local vertical land motion using the same GIA estimates as used in the AR5. The numbers in each box are the central estimate of sea-level rise, with the likely range (17-83%) given in brackets. Changes relative to 1900 are estimated by adding the observed global mean rise (in the absence of estimate of regional changes) from 1900 to the reference period by 0.16 m to the projections relative to 1995-2014 (Table 4). The multiplication factor is the factor by which the return period of extreme sea level events at a given height is divided by for a given sea level rise. For example, if the factor is 4, a return period of 100 years becomes 25 years. The factor is calculated here for the mean sea level rise for each scenario and the range of multiplication factors across the islands used in the studies of Woodworth et al. (2021) and Systems Engineering Australia (SSA, 2011).*

Projected changes in Extreme Events

93. **Regional sea level change has been the main cause of changes in extreme sea level events during the 20th century and will be the main cause of a substantial increase in the frequency of extreme sea level events during the 21st century.**

94. **There will be a rapid increase in the number of coastal locations that will experience the present-day 100-yr extreme-sea-level events at least once a year.** The IPCC AR6 found that for stationary tides, storm-surge, and wave climate, "extreme sea level events that currently occur once per century will occur annually or more frequently at about 19–31% of tide gauges by 2050 and at about 60% (SSP1-2.6) to 82% (SSP5-8.5) of tide

gauges by 2100 (*medium confidence*). In total, such extreme sea levels will occur about 20 to 30 times more frequently by 2050 and 160 to 530 times more frequently by 2100 compared to the recent past, as inferred from the median amplification factors for SSP1-2.6, SSP2-4.5, and SSP5-8.5 (*medium confidence*)." (Fox-Kemper 2021) The tropics appear more sensitive than the Northern high latitudes. (Tebaldi et al. 2021). Any changes in tides, storm surges or waves, would further change these return frequencies.

95. **Only a few studies have attempted to specifically quantify the role of anthropogenic climate change in the short term variability of sea level from local mean sea level** (e.g., Mori et al., 2014; Takayabu et al., 2015; Turki et al., 2019). Detection and attribution of the human influence on climatic changes in surges, and waves remains a challenge (Ceres et al., 2017). There is limited evidence to suggest that in some instances (for example, poleward migration of tropical cyclones in the Western North Pacific) changes in surges and waves can be attributed to anthropogenic climate change.

96. **The height of the 1 in 100 year extreme event will increase with rises in local mean sea level.** After including potential changes in winds and cyclone intensity as well as assumed rises in mean sea level, the Systems Engineering Australia Study (2011) found that the increase in height of extreme events was virtually identical to the increase in mean sea level, consistent with the observation above that changes in storminess have less impact than the rise is mean sea level on changes in the return frequency of extreme sea level event of a given value. They found (at pg. xi-xii) that:

> "...for the projected future climate of 2050, the existing five communities that are already principally affected will be further impacted by the possible 0.3 m sea level rise. Erub is also affected then at the 5 y return period, Hammond is increasingly vulnerable by the 25 y level and Poruma becomes at risk around 100 y. It is likely that by 2050, five communities (Saibai, Boigu, Warraber, Iama and Masig) would be experiencing significantly adverse impacts. Notwithstanding these chronic incursions by the sea there would be increased stress placed on emergency services in the event of a higher magnitude event (longer return period) occurring.
>
> By 2100, with a possible 0.8 m sea level rise and with increased tropical cyclone intensities, a total of 13 sites are affected beyond the 5 y level and 11 of these sites are affected across the full return period range. It is likely that 8 communities (Saibai, Boigu, Warraber, Masig, Iama, Erub, Poruma and Hammond) would be experiencing significantly adverse impacts. Where retreat is likely not to be possible, such as at the low lying islands of Saibai, Boigu, Masig, Warraber and Poruma, communities may have to consider the viability of maintaining permanent habitation on these islands. Again, emergency services will come under increasing stress across the remaining communities."

(Note that 5 y (and other periods) refers to the 1 in 5 year (and other periods) return period extreme sea level events).

97. **There will be a rapid increase in the frequency during the 21st century (and beyond) of extreme sea levels of a given height as mean sea level in Torres Strait rises.** The average of the Woodworth et al. (2021) multiplication factors discussed above (see Tables 4 and 5) increase rapidly with time and larger emission scenarios and with significant differences between the locations considered in the study. The older Systems Engineering Australia study (2011) has larger multiplication factors and also a wide range of factors across the different locations considered. The study also considered a greater number of locations.

TIPPING POINTS

Question 11

Please explain the relevance, if any, of 'tipping points' to sea levels and extreme sea level events.

Question 12

Please describe the respective risk of reaching tipping points and the corresponding consequences for sea levels and extreme sea level events consistent with the RCPs and SSPs.

98. **Evidence of past sea levels metres higher than present values and rapid rates of sea-level rise after the last glacial maximum (See Question 2) highlights the need to consider the possibility of longer term sea level rise.** These rises can be either ongoing from past emissions and/or evolution to new states, either evolving slowly over time or via a rapid transition. In some cases, the transitions may be essentially irreversible on timescales of hundreds to thousands of years.

99. **It is inevitable that there will be further sea-level rise for decades to centuries after 2100 as a result of ongoing ocean thermal expansion, the loss of mass from glaciers and changes in ice sheets.** Different elements of the climate system respond to changes in greenhouse gas concentrations on a wide range of time scales. The ocean's huge heat capacity and the relatively slow rate of ocean heat uptake means that the climate system is out of balance. As a result, even if atmospheric greenhouse gas concentrations are stabilised, surface temperatures will continue to rise as the deep ocean warms, implying a commitment to long-term ongoing sea-level rise from ocean thermal expansion. Surface temperatures will only stabilise and fall slowly when anthropogenic emissions are reduced to zero, with a smaller but ongoing ocean warming and thermal expansion. This rise would be essentially irreversible on time scales of centuries to millennia. Glaciers have a limited mass, limiting their potential long term contribution (Church et al. 2013; Fox-Kemper et al. 2021).

100. **The Greenland Ice Sheet will likely contribute metres of sea-level rise for high emission scenarios.** The Greenland Ice Sheet gains mass from snowfall and loses mass from ablation and the flow of ice into the ocean. Because the ice sheet is (mostly) grounded above sea level, it can retreat from the coastline such that the balance is between snowfall and ablation. For surface warming, ablation increasing more rapidly than snowfall (as observed and modelled), there could be a warming threshold above which the ice sheet decays contributing up to 7.4 metres of sea-level rise over centuries to a millennia or more. This threshold is not well defined but the IPCC AR5 estimated it likely lies in the range of 1° C to 4° C, meaning that we could have already crossed or are rapidly approaching it. For higher emission scenarios, the threshold would very likely be exceeded before 2100, thus increasing the probability of metres of sea level rise and faster rates of rise. Gregory et al. (2020) argued that Greenland, with a potential sea-level equivalent of 7.4 m, does not have a bistable state (or threshold) but rather that there is a

loss of ice with increasing temperatures (about a third of the ice sheet for 1.5° C, a half for 2° C and two thirds for 2.5° C of warming). Again, for larger temperature rises, the rate of sea level rise is larger. If these events occur, they are essentially irreversible on time scales of millennia and would require temperatures to fall to pre-industrial values, or possibly below.

101. **For Antarctica, the flow of ice into the ocean occurs via outlet glaciers but the factors controlling this flow are not well understood and there is concern that it may lead to a more rapid rise in sea level than current projections.** The Antarctic Ice Sheet, with a sea level equivalent of 58 m, gains mass from snowfall in the interior and loses mass by the flow of this ice into the ocean. Antarctica is mostly too cold at present for there to be any significant surface melting. Ice-ocean-atmosphere interactions are critical to the outflow of ice. The ice shelves exert a backstress on the glaciers. If the ice shelves collapse, the glacier may flow more rapidly into the ocean. This has been observed on the Antarctic Peninsular when warmer surface air temperatures and ocean temperatures resulted in a rapid (a few months) collapse of the Larsen B ice shelf followed by an increase flow of glaciers into the ocean (e.g. Scambos et al. 2004). Also, warm ocean waters can penetrate below the ice shelves, melting the ice near the grounding line (where the ice first begins to float after resting on the bedrock as it flows towards the ocean), allowing the outlet glacier to flow more rapidly into the ocean. If the bedrock slopes downward away from the ocean, as is the case in much of west Antarctica and parts of east Antarctica, any initial perturbation may be unstable (Figure 2). That is, an initial retreat of the grounding line may result in a more rapid flow of ice into the ocean and further retreat of the grounding line (called the Marine Ice Sheet Instability; MISI). These processes are incompletely observed, but recent observations and modelling studies suggest this process may be underway in parts of the West Antarctic Ice Sheet (for example Joughin et al., 2014). Other recent studies (de Conto and Pollard 2016) have hypothesized that if the height of the face of the ice sheet exceeds a critical value, it may be unstable leading to a more rapid retreat of the face of the ice sheet (the Marine Ice Cliff Instability; MICI) and more rapid rise in sea level. While de Conto and Pollard (2016) argued this process is necessary to simulate paleo sea levels, it and its impacts are controversial (van de Waal et al. 2022; Clerc et al. 2019) and others disagree that it is essential to simulate paleo sea levels (Edwards et al. 2019).

102. **Some marine-based catchments of the East Antarctic Ice Sheet (EAIS) that lost mass during past warm periods are losing mass at present but increased accumulation across the EAIS over the twenty-first century may keep it broadly in balance.** Beyond 2100, substantial mass loss could be averted if the Paris Agreement to limit warming below 2° C is satisfied. However, the stability of portions of the EAIS may depend on the integrity of ice at the margins of parts of the marine ice-sheet, which could impart tipping behaviour leading to large-scale ice loss over centuries (Mengel and Levermann, 2014). Thus, high-emissions scenarios could potentially result in several metres of sea-level rise within a few centuries (Stokes et al. 2022). However, not enough is currently known to assign probabilities to these scenarios.

Sea Level Commitments beyond 2100

103. **Under all scenarios, sea level will continue to rise for centuries because of the long-time scales of ocean warming and ice sheet responses but the amount of rise is strongly dependent on future emissions.** Projections to 2300 in the IPCC AR6 under SSP1-2.6 are for a sea-level rise of 0.5 to 3 m, and under SSP5-8.5 a rise of 2 to 7 m. It was also noted in AR6 that rises higher than 15 m cannot be ruled out (IPCC 2021).

104. **Alternative sea level estimates for high emission scenarios also indicate large rises.** As potential high end sea-level rises are poorly defined by existing models, a recent community effort (combining scientists and practitioners and building on a framework of physical evidence) attempted to quantify high-end global SLR to complement the IPCC AR6. This assessment included a focus on the importance of the timing of ice shelf collapse around Antarctica. This is highly uncertain due to low understanding of the driving processes. For global warming of 2° C in 2100 (RCP2.6/SSP1-2.6), they estimated high-end global SLR estimates are up to 0.9 m in 2100 and 2.5 m in 2300. For RCP8.5/SSP5-8.5, they estimated up to 1.6 m in 2100 and up to 10.4 m in 2300 (van de Waal et al. 2022).

105. **The large and growing differences between the scenarios beyond 2100 emphasize the long-term benefits of mitigation.** Even 2° C warming may cause multi-meter SLR on centennial time scales with profound consequences for coastal areas.

106. **Sea-level rises under high emission scenarios are effectively irreversible on centennial and potentially millennial time scales and could be significantly determined by global warming occurring before 2100.**

107. **Future impacts expected under high emission scenarios are likely to be substantially larger than recently observed impacts.** Note that while the current rates of sea-level rise in Torres Strait may be slightly above the global average over the last few decades, they are substantially smaller than projected rates of sea-level rise under higher climate emission scenarios.

108. **The paleo data indicate that for high emission scenarios the question is not if there will be metres of sea-level rise but rather how quickly they will occur.**

Risk of Crossing Tipping Points

109. **Pre-October 2021 National Policies and Pledges (globally) are not consistent with the United Nations Framework Convention on Climate Change 2015 Paris targets of keeping warming well below 2° C, while pursuing efforts to limit it to 1.5° C.** Pre-October 2021 national policies from nations around the world imply warming above pre-industrial temperatures (approximated by 1850-1900 temperatures) of 2.9-3.2° C, with current pledges implying 2.4-2.9° C of warming. Recent promises of many nations to have net zero emissions (covering 72% of global emissions) imply 2.0-2.4° C of global

warming, potentially bringing the Paris Agreement goal of well below 2° C within reach, if they are fully and swiftly implemented (Höhne et al. 2021), and followed by further actions.

110. **As of 1 June 2023, The Climate Action Tracker global policies are not consistent with the 2015 Paris Targets.** The global policies and actions are consistent with warming of 2.7° C (2.1-3.5° C). Targets only are consistent with 2.4° C (1.9-2.9° C). Pledges and Targets are consistent with 2.0° C (1.6-2.6° C). Only an optimistic scenario of 1.8° C (1.5-2.3) is approaching the Paris target (https://climateactiontracker.org).

111. **As of 1 June 2023, according to The Climate Action Tracker, Australian policies are not consistent with the 2015 Paris Targets.** For Australia, the policies were assessed as being insufficient and consistent with more than 3° C of warming (although this assessment needs to be updated as new policies are implemented) and the 2030 target was assessed as almost sufficient and consistent with 2° C of warming. Australia ranks eighth highest in the world for its emissions per capita, and first for coal power emissions per capita. And policies for the net zero target of 2050 were rated as poor. (https://climateactiontracker.org) (See also Rogelj et al. 2023.)

112. **The latest estimates of the rate of acceleration of both global and local sea-level rise for 1993 to 2018 are most consistent with the higher emission scenarios** (Wang et al. 2021a; Guerou et al. 2023).

113. **The current Global and Australian Policies are consistent with a multi-metre contribution to sea-level rise from Greenland alone.** These policies imply about a 50% probability of crossing the Greenland threshold, or about 4-5 m of sea level equivalent if the Gregory et al. (2020) analysis is correct. This compares with perhaps a 10-20% chance and 2 m of sea level equivalent if the Paris Target is achieved.

Urgent Mitigation and Adaptation is required to avoid the worst impacts of sea level rise.

114. **We cannot stop all sea-level rise and we will need to adapt to the sea-level rise we can no longer prevent. However, after about 2050, the amount of adaption necessary is strongly related to future greenhouse gas emissions.** Higher emissions (particularly higher than SSP2-4.5) commit the world to more rapid rises and the likelihood of crossing thresholds during the 21st century leading to ongoing, and likely essentially irreversible, sea-level rise amounting to metres over coming centuries. There are already enough fossil fuels available for crossing these thresholds. Avoiding these scenarios requires significant, urgent and sustained reduction of present day greenhouse gas emissions.

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ANNEXURE A

PHI x FINNEY x MCDONALD

9 March 2023 **PRIVILEGED AND CONFIDENTIAL**

Professor John Church
Climate Change Research Centre,
School of Biological, Earth & Environmental Sciences,
University of New South Wales

By email: [redacted]

Dear Professor Church,

Pabai & Anor v Commonwealth of Australia (VID622/2021)

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1. Letter of Instruction

1.1. We refer to our letter of retainer dated 2 February 2023 (**Retainer Letter**) and confirm that you are retained by Uncle Pabai Pabai and Uncle Paul Kabai (**Applicants**) to act as an independent expert in the matter of *Pabai & Anor v Commonwealth of Australia*, VID622/2021 (**Proceeding**).

1.2. We confirm that the confidentiality obligations in respect of documents and information provided to you for the purpose of this engagement are governed by the terms of the Retainer Letter and the Deed of Confidentiality dated 5 March 2023.

1.3. We also remind you of the roles and duties of expert witnesses as set out in the Retainer Letter and ask that you refer to them as you prepare your expert report(s) in this proceeding. In particular, please take some time to reacquaint yourself with the following documents, which we provided to you along with the Retainer Letter:

(a) the Federal Court of Australia Expert Evidence Practice Note (**GPN-EXPT**), including the Harmonised Expert Witness Code of Conduct (the **Code**) at Annexure A of that Practice Note and the Concurrent Expert Evidence Guidelines (the **Guidelines**) at Annexure B (collectively, the **Practice Note**); and

(b) Rule 23.13 of the *Federal Court Rules 2011* (Cth).

1.4. The purpose of this letter is to request that you prepare a written report, providing your independent expert opinion, in response to the questions outlined at Annexure B to this letter.

2. Brief of Materials

2.1. Set out at Annexure A is an index of the documents provided to you, which form your brief. If you would prefer to receive a copy of some or all of the Annexure A documents in hard copy, please do not hesitate to contact us with such a request.

2.2. If you consider that you require any additional documents or materials in order to complete your work, please request such materials from us.

3. Your Opinion

3.1. Once you have reviewed the material in your brief, we request that you provide a written report addressing the questions set out in Annexure B to this letter.

3.2. In answering the questions set out in Annexure B, please provide detailed reasons for your opinions, including the facts or assumptions that affect your reasoning and conclusions.

4. Preparation of Your Report

4.1. We would be grateful if you would set out the answers to the questions at Annexure B in a written report, having regard to the requirements set out in the Practice Note.

4.2. After you have had the opportunity to consider the questions at Annexure B, as well as the materials listed in Annexure A, we would be grateful if you could advise of any material not currently in your brief which you require to respond to any of the questions set out in Annexure B.

If you have any questions, please do not hesitate to contact me on [redacted]

Yours faithfully,

Brett Spiegel
Principal Lawyer
Phi Finney McDonald

Encl.

ANNEXURE A

Index to Brief

Tab No.	Date	Description of document
A	**LETTERS OF INSTRUCTION**	
A1.	9 March 2023	Letter of instruction
B	**PLEADINGS**	
B1.	31 March 2022	Concise Statement
B2.	14 April 2022	Concise Statement in Response
B3.	7 October 2022	Amended Originating Application
B4.	3 February 2023	Further Amended Statement of Claim
B5.	3 March 2023	Defence to Further Amended Statement of Claim

ANNEXURE B

Basis of expertise

1. Please describe your academic qualifications, professional background, and experience in the field of climate science, and any other training, study, or experience that is relevant to this brief (you may wish to do so by reference to a current curriculum vitae).

Global temperatures and sea levels

2. Please explain the relationship between the temperature of the Earth's surface (**global temperatures**) and sea levels.

   In your answer, please address:

   a) the relevance of:

      a. sea and atmospheric temperatures;

      b. ice and water on land; and

   b) whether there is any variation geographically.

Global temperatures and extreme sea level events

3. What is meant by the term 'extreme sea level events'?

4. Please explain the relationships between global temperatures, sea levels, and extreme sea level events. In your answer, please address:

   a) whether the relationships are linear or non-linear; and

   b) whether there is any variation geographically.

Historical changes in sea levels and extreme sea level events

For questions 5-8, consider the position globally, in Australia, and in the Torres Strait Islands.

5. Please describe any changes in sea levels since the 1850-1900 average (the **Baseline**). In your answer, please describe both the amount and the rate of any changes.

6. Please explain the causes of any changes in sea levels described in your answer to question 5.

7. Please describe any changes in extreme sea level events since the Baseline. In your answer, please describe both the amount and the rate of any changes.

8. Please explain the causes of any changes in extreme sea level events described in your answer to question 7.

Projected changes in sea levels and extreme sea level events

For questions 9-10, consider the position globally, in Australia, and in the Torres Strait Islands.

9. Please describe the projected change to sea levels between now and the conclusion of the 21st Century consistent with each of the Representative Concentration Pathways (**RCPs**) and Shared Socioeconomic Pathways (**SSPs**) as used by the Intergovernmental Panel on Climate Change (**IPCC**).

10. Please describe the projected nature, frequency, and intensity of extreme sea level events between now and the conclusion of the 21st century consistent with each of the RCPs and SSPs.

Tipping points

11. Please explain the relevance, if any, of 'tipping points' to sea levels and extreme sea level events.

12. Please describe the respective risk of reaching tipping points and the corresponding consequences for sea levels and extreme sea level events consistent with the RCPs and SSPs.

ANNEXURE B

John Alexander Church

Dr John Alexander Church AO FAA FTSE
Climate Change Research Centre, University of New South Wales, Sydney, NSW 2052, Australia
Mailing Address: [redacted]
Email: [redacted]
Born: [redacted]

Education:

1972	B.Sc. (Hons.), Physics, Queensland University
1979	Doctor of Philosophy

Selected Professional Experience:

1979 – 1984	Postdoctoral Fellow, CSIRO Fisheries and Oceanography
1984 – 1993	Research Scientist/Senior/Principal Research Scientist (CSIRO Oceanography)
1988	Visiting Scientist, Woods Hole Oceanographic Institute, USA.
1990 – 1997	Leader, Climate Program and then Climate and Ocean Processes Program (CSIRO Oceanography)
1991 – 2003	Leader, Southern Ocean Processes Program, and Polar Waters Program, Antarctic Cooperative Research Centre.
1993 – 2003	Program Leader, Oceanography Program, Australian National Antarctic Research Expeditions.
1994	Science Adviser, Department of Environment, Sport and Territories.
1997	Visiting Research Scientist, Southampton Oceanography Centre, UK.
1997 – 2003	Project Leader, Southern Ocean Processes Project, CSIRO Marine Research
2003 and 2004	Deputy Chief, CSIRO Marine Research (Oct 2003-Jan 2004, Apr-Jun 2004).
2003 – 2010	Chief Research Scientist, CSIRO Marine and Atmospheric Research and Leader, Sea-level Rise Program, Antarctic Climate and Ecosystems CRC.
2010 – 2016	CSIRO Fellow, CSIRO Marine and Atmospheric Research.
2013	Visiting Research Scientist, Southampton Oceanography Centre, UK.
2017 – 2021	Professor, Climate Change Research Centre, University of New South Wales
2022 – Present	Emeritus Professor, Climate Change Research Centre, UNSW

Awards and Recognition Since 2003

November 2004	Fellow, Australian Academy of Technological Sciences and Engineering
	Fellow, Australian Meteorological and Oceanographic Society
June 2006	Roger Revelle Lecture and Medal, Intergovernmental Oceanographic Commission
January 2007	Medal for Research Achievement, CSIRO
August 2007	Eureka Prize for Scientific Research
November 2007	Finalist, Tasmanian of the Year
2007	Contributed to the reports of the IPCC, which was awarded the Nobel Peace Prize in 2007
January 2008	Clarke Lecture and Medal, Australian Meteorological and Oceanographic Society
February 2009	Founding Member Tasmanian Climate Action Council
2013	Church, J. A., and White, N. J. 2006. *Geophysical Research Letters*, 33, L01602, selected as one of the best 40 papers across all fields published in Geophysical Research Letters over the last 40 years.
May 2012	Fellow, Australian Academy of Science
Sept 2014	Fellow, American Meteorological Society
February 2017	Bruce Morton Medal, Australian Meteorological and Oceanographic Society
January 2019	BBVA Frontiers of Knowledge Award in Climate Change.

November 2020	Fellow, American Geophysical Union
February 2021	Jaeger Medal, Australian Academy of Science.
January 2022	Officer of the Order of Australia.
December 2022	James Cook Medal, Royal Society of New South Wales.
May 2023	Prince Albert I Medal, International Association for the Physical Sciences of the Ocean.
June 2023	Axford Medal of the Asia Oceania Geoscience Society.

Selected Program Membership and Scientific Committees:

1987 – ~2010	Principal Investigator for the NASA/CNES TOPEX/POSEIDON and Jason Satellite Altimeter Missions
1990 – 1996	Co-Investigator, NASA/EOS Interdisciplinary Investigation
1989 – 1993	Member, World Ocean Circulation Experiment Core 1 Working Group.
1992 – 1998	Member, Scientific Steering Group, World Ocean Circulation Experiment.
1994 – ~2005	Co-Principal Investigator, ESA ERS-1/2 Satellite Mission
1994 – 1998	Co-chair, Scientific Steering Group, World Ocean Circulation Experiment.
1994 – 1998	Member, CLIVAR Scientific Steering Group.
1998 – 2001	Co-convening Lead Author for the Chapter on Sea Level in the IPCC Third Assessment Report.
1999 – 2006	Member Joint Scientific Committee, World Climate Research Programme
2000 – 2004	Officer, Joint Scientific Committee, World Climate Research Programme
2004 – 2006	Vice-Chair, Joint Scientific Committee, World Climate Research Programme
2006 – 2008	Chair, Joint Scientific Committee, World Climate Research Programme
2005 – 2010	Intergovernmental Oceanographic Commission, Scientific Advisory Committee
2010 – 2013	Co-convening Lead Author for the Chapter on Sea Level in the IPCC Fifth Assessment Report.
2011 – 2014	Lead Author, the IPCC Fifth Assessment Report, Synthesis Report.
2018 – 2021	Chair UK Transient Tracer-based Investigation of Circulation and Thermal Ocean Change (TICTOC) Project Advisory Committee.
2020 – 2023	Member, Australian National Committee for Antarctic Research.

PhD/MSc Students

Rosemary Morrow 1992, PhD, University of Sydney
APS Wong 1999, PhD, University of Tasmania
Mauricio Mata 2000, PhD, The Flinders university of South Australia
Catia Domingues 2005, PhD, The Flinders university of South Australia
Kieran Helm 2008, PhD, University of Tasmania
Ann-Maree Catchpole, 2009, MSc, University of Tasmania
Benjamin Galton Fenzi 2009, PhD, University of Tasmania
Kewei Lyu 2015, PhD, Xiamen University
Quran Wu, 2018 PhD, Xiamen University
Jinping Wang, 2021 PhD, Ocean University of China
Yi Jin, 2021 PhD, Ocean University of China
Ruhai Wang – Co-Supervision of PhD Student (from 2022), Xiamen University, China.

Postdoctoral Supervision

R. Schainger 1992-1994; Mark Hemer, 2006-2008; Catia Domingues, 2007-2010; Aimee Slangen, 2013-2016; Damien Irving, 2016-2021, Taimoor Sohail 2020-2022; Kewei Lyu 2018-2022, Saurbah Rathore, 2022-2023.

Research Grants

Awarded regular grants during my career at CSIRO (including grants for research in the Pacific, Vietnam and Malaysia), and significant ocean research vessel time.
Since moving to UNSW in 2017, awarded an ARC Discovery Project grant (ARC Discovery Project, DP190101173, $419 000; ARC Centre of Excellence in Antarctic Science *SR200100008. $25 m*).

Publications:

Edited Books	3;
Refereed papers and book chapters	>190 (including 22 in Nature, Nature group or Science); Hirsch Index 60 (Web Of Science), 85 (Google Scholar)
Career Citations	Over 14,600 in Web Of Science at July 2022; not including book chapters, edited books or IPCC Contributions; >70,000 in Google Scholar)
Other reports	>110

Invited talks: International profile resulted in more than 10 invited talks for a number of years.
Numerous radio, newspaper and TV interviews/articles on weather and climate.

PUBLICATIONS — JOHN CHURCH

Books

Siedler, G., Church, J. and Gould, J. Editors, 2001. Ocean circulation and Climate, Observing and modelling the global ocean. *International Geophysics Series*, **Volume 77**, Academic Press, San Diego, 715 pages.

Church, J.A., Woodworth, P.L., Aarup, T and Wilson, Editors, W.S. 2010. Understanding Sea-level Rise and Variability, Wiley-Blackwell Publishing, Chichester, UK. (427 pp; ISBN: 978-1-4443-3452-4 (paperback); 978-1-4443-3451-7 (hardback).

Siedler, G., Griffies, S., Gould, J. and Church, J. Editors, 2013. Ocean circulation and Climate, A 21st Century Perspective. *International Geophysics Series*, **Volume 103**. (ISBN: 978-0-12-391851-2)

Refereed and Invited Manuscripts

A1. Milford, S.N. and Church, J.A. 1977. Simplified circulation and mixing models of Moreton Bay, Queensland. *Australian Journal of Marine and Freshwater Research* **28**, 23-24.

*A2. Boland, F.M. and Church, J.A. 1981. The East Australian Current 1978. *Deep-Sea Research* **28A**, 937-957.

A3. Church, J.A. and Forbes, A.M.G. 1981. A non-linear model of the diurnal and semi-diurnal tides in the Gulf of Carpentaria. *Australian Journal of Marine and Freshwater Research* **32**, 685-697.

A4. Church, J.A. and Forbes, A.M.G. 1983. Circulation in the Gulf of Carpentaria. Part I. Direct current observations in the south east corner of the Gulf of Carpentaria. *Australian Journal of Marine and Freshwater Research* **34**, 1-10.

A5. Forbes, A.M.G. and Church, J.A. 1983. Circulation in the Gulf of Carpentaria. Part II. Residual currents and mean sea level. *Australian Journal of Marine and Freshwater Research* **34**, 11-22.

*A6. Rothlisberg, P.C., Church, J.A. and Forbes, A.M.G. 1983. Advection modelling of vertically migrating shrimp larvae. *Journal of Marine Research* **41**, 511-538.

A7. Church, J.A. and Boland, F.M. 1983. A permanent undercurrent adjacent to the Great Barrier Reef. *Journal of Physical Oceanography* **13**, 1747-1749.

A8. Church, J.A., Andrews, J.C. and Boland, F.M. 1985. Tidal currents in the outer Great Barrier Reef. *Continental Shelf Research* **4**, 515-531.

A9. McDougall, T.J. and Church, J.A. 1986. Pitfalls with the numerical representation of isopycnal and diapycnal mixing. *Journal of Physical Oceanography* **16**, 196-199.

*A10. Freeland, H.J., Boland, F.M., Church, J.A., Clarke, A.J., Forbes, A.M.G., Huyer, A., Smith, R.L., Thompson, R.O.R.Y. and White, N.J. 1986. The Australian Coastal Experiment: The search for Coastal Trapped Waves. *Journal of Physical Oceanography* **16** 1230-1240.

*A11. Church, J.A., Freeland, H.J. and Smith, R.L. 1986. Coastal trapped waves on the east Australian Continental Shelf. Part 1. Propagation of wave modes. *Journal of Physical Oceanography* **16**, 1929-1943.

A12. Church, J.A., White, N.J., Clarke, A.J., Freeland, H.J. and Smith, R.L. 1986. Coastal trapped waves on the east Australian Continental Shelf. Part II: Model verification. *Journal of Physical Oceanography* **16**, 1945-1958.

A13. Church, J.A. and Freeland, H.J. 1987. The energy source for the ACE coastal trapped waves. *Journal of Physical Oceanography* **17**, 289-300.

A14. Zedel, L.J. and Church, J.A. 1987. Real-time screening Techniques for Doppler current profiler data. *Journal of Atmospheric and Oceanic Technology* **4**, 572–581.

*A15. Church, J.A. 1987. The East Australian Current adjacent to the Great Barrier Reef. *Australian Journal of Marine and Freshwater Research* **38**, 671–683.

A16. Huyer, A., Smith, R.L., Stabeno, P.J., Church, J.A. and White, N.J. 1988. Current off southeastern Australia: Results from the Australian Coastal Experiment. *Australian Journal of Marine and Freshwater Research* **39**, 245–288.

A17. Church, J.A., Joyce, T.M. and Price, J.F. 1989. Current and density observations across the wake of hurricane Gay. *Journal of Physical Oceanography,* **19**, 259–265.

A18. Church, J. A., Cresswell, G.R. and Godfrey, J.S. 1989. The Leeuwin Current, in Poleward Flows on Eastern Ocean Boundaries, Springer Verlag Lecture Notes on Coastal and Estuarine Studies, Ed. S.J. Neshyba et al., 374pp.

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A21. Bryden, H.L., Roemmich, D.H. and Church, J.A. 1991. Ocean heat transport across 24°N in the Pacific. *Deep-Sea Research.* **38**, 297-324.

*A22. Church, J.A., Godfrey, J.S., Jackett, D.R. and McDougall, T.J. 1991. A model of sealevel rise caused by ocean thermal expansion, *J Climate.,* **4**, 438-456.

A23. Burrage, D.M., Church, J.A. and Steinberg, J.A. 1991. Linear systems analysis of momentum on the continental shelf and slope of the central Great Barrier Reef, *J. Geophys. Res.*, **96**, 22 169-22 190.

*A24. Bindoff, N.L. and Church, J.A., 1992. Warming of the water column in the southwest Pacific Ocean. *Nature*, **357**, 59-62.

*A25. Morrow, R., Church, J.A., Coleman, R. Chelton, D. and White, N. 1992. Eddy momentum flux and its contribution to the Southern Ocean momentum balance. *Nature*, **357**, 482-484.

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A39. Wong, A.P.S., Bindoff, N.L. and Church, J.A. 2001. Freshwater and heat changes in the North and South Pacific oceans between the 1960s and 1985-94. *Journal of Climate*, **14**(7), 1613-1633.

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A42. Church, J.A. and Gregory, J.M. 2001. Sea level Change. (pp 2599-2604) In Encyclopedia of Ocean Sciences, Eds J. Steele, S. Thorpe and K. Turekian, Academic Press, London.

A43 IPCC, 2001: Climate Change 2001:The Scientific Basis, Summary for Policy Makers. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y Ding, D. J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell and C.I Johnson (eds.)]. Cambridge University Press, 98pp. (Final Report based on a draft prepared by Daniel L. Albritton, Myles R.Allen, Alfons P.M. Baede, **John A. Church**, Ulrich Cubasch, Dai Xiaosu, Ding Yihui, Dieter H. Ehhalt, Christopher

K. Folland, Filippo Giorgi, Jonathan M. Gregory, David J. Griggs, Jim M. Haywood, Bruce Hewitson, John T. Houghton, Joanna I. House, Michael Hulme, Ivar Isaksen, Victor J. Jaramillo, Achuthan Hayaraman, Catherine A Johnson, Fortunat Joos, Sylvie Jousamme, Thomas Karl, David J. Karoly, Hasroon S Kheshgi, Corrine Le Quéré, Kathy Maskell, Luis J. Mata, Bryant J. McAveney, Mack McFarland, Linda O. Mearns, Gerald A. Meehl, L. Gylvan Meira-Filho, Valentin P. Meleshko, John F.B. Mitchell, Berrien Moore, Richard K. Mugura, Maria Noguer, Baruhani S. Nyenzi, Michael Oppenheimer, Joyce E. Penner, Steven Pollonais, Michael Prather, I. Colin Prentice, Venkatchala Ramaswamy, Armando Ramirez-Rojas, Sarah C. B. Raper, M. Jim Salinger, Robert J. Scholes, Susan Solomon, Thomas F. Stocker, John M.R. Stone, Ronald J. Stouffer, Kevin E. Trenberth, Ming-Xing Wang, Robert T. Watson, Kok S. Yap and John Zillman).

A44. Albritton, D. L., et al. 2001. Technical summary. A report accepted by Working Group I of the IPCC. In: Climate change 2001: the scientific basis: contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change. J. T. Houghton, and others (Editor). New York: Cambridge University Press. p. 21-83.

A45. Rintoul, S. R., Church, J., Fahrbach, E., Garcia, M., Gordon, A., King, B., Morrow, R., Orsi, A. H. and Speer, K. 2001. Monitoring and understanding Southern Ocean variability and its impact on climate: A strategy for sustained observations. In: Observing the Oceans in the 21st Century. Eds: C. J. Koblinsky and N. R. Smith. GODAE Project Office, Bureau of Meteorology, Melbourne, Australia. pp. 486-508.

A46. Gould, W.J., Toole, J.M., Church, J., Rintoul, S., Wijffels, S., Talley, L., Robbins, P., Johnson, G.C., Imawaki, S., Suginohara, N., Hanawa, K., Koltermann, P., Osterhus, S., Freeland, H., Clarke, A., Mercier, H. 2001. Hydrographic section observations. Pages 351-360, in: Observing the oceans in the 21st Century, Chester J,. Koblinsky and Neville R. Smith (eds.), Godae/Bureau of Meteorology, Melbourne, Australia.

A47. Church, J.A., 2001. How fast are sea levels rising? *Science*, **294**, 802-803.

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A50. Rintoul, S.R., Sokolov, S. and Church, J. 2002: A 6 year record of baroclinic transport variability of the Antarctic Circumpolar Current at 140°E derived from expendable bathythermograph and altimeter measurements. *J. Geophys. Res.*, **107** (C10), 3155, doi:10.1029/2001JC000787.

A51. Gregory, J. and Church, J.A. 2002. Changes in sea level. *Weather*, 57(8), 287-295.

A52. P.J. Mason, M. Manton, D.E. Harrison, A. Belward, A.R. Thomas, D. K. Dawson, A. Allali, J. Church, R. A. Clarke, J. Eeyre, C. Folland, W. J. Gould, W. Haeberli, S. Harrison, T. Karl, T. Maurer, D.E. Parker, M. Proffitt, S. Quegan, A. Simmons, K. Trenberth, M. Verstaete, 2003. The Second Report on the Adequacy of the Global Observing System for climate in support of the United Nations Framework Convention on Climate Change. GCOS-82, WMO/TD Number 1143, 74pp.

A53. Du Yan, Wang Dongxiao, Xie Qiang and John Church, 2003. Harmonic analysis of sea surface temperature and wind stress in the vicinity of the maritime continent. *Acta Meteorologica Sinica*, **17(Suppl.)**, 226-237.

A54. Watson, C., Coleman, R., White, N., Church, J. and Govind, R. 2003. Absolute Calibration of TOPEX/Poseidon and Jason-1 using GPS Buoys in Bass Strait, Australia. *Marine Geodesy (Special Issue on Jason-1 Calibration/Validation, Part 1),* **26 (3-4)**, 285-304.

A55. McDougall, T. J., Church, J. A. and Jackett, D. R., 2003: Does the nonlinearity of the equation of state impose an upper bound on the buoyancy frequency? *Journal of Marine Research*, **61**, 745-764.

*A56. Church, J.A. White, N.J., Coleman, R., Lambeck, K. and Mitrovica, J.X. 2004. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. *Journal of Climate*, **17 (13)**, 2609-2625.

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A60. White, N.J., Church, J.A. and Gregory, J.M. 2005. Coastal and global averaged sea-level rise for 1950 to 2000. *Geophysical Research Letters*, **32(1)**, L01601, dio:10.1029/2004GL021391.

A61. Aoki, S., Bindoff, N.L. and Church, J.A. 2005. Interdecadal water mass changes in the Southern Ocean between 30°E and 160°E. *Geophysical Research Letters*, **32** (7), L07607, 7607-7607 Apr 14 2005.

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*A63. Church, J.A. White, N.J. and Arblaster, J. 2005. Significant decadal-scale impact of volcanic eruptions on sea level and ocean heat content. *Nature*, **438**, 74-77 (doi:10.1038/Nature04237).

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