# PCIC SCIENCE BRIEF: SEA LEVEL RISE OBSERVATIONS AND ACCELERATION

**Three recent journal articles examine the rate of sea level rise and the ability of models to accurately simulate sea level rise at a global and regional scale.**

**Publishing in *Geophysical Research Letters*, Yi et al. (2017) examine the rate at which sea level rise is accelerating and find that the rate of acceleration over the 2005-2015 period is three times faster than it was over the 1993-2014 period and an order of magnitude larger than the acceleration over the 1920-2011 period. They also identify three primary contributors to this acceleration: the thermal expansion of sea water, reduced storage of water on land and the melting of ice on land.**

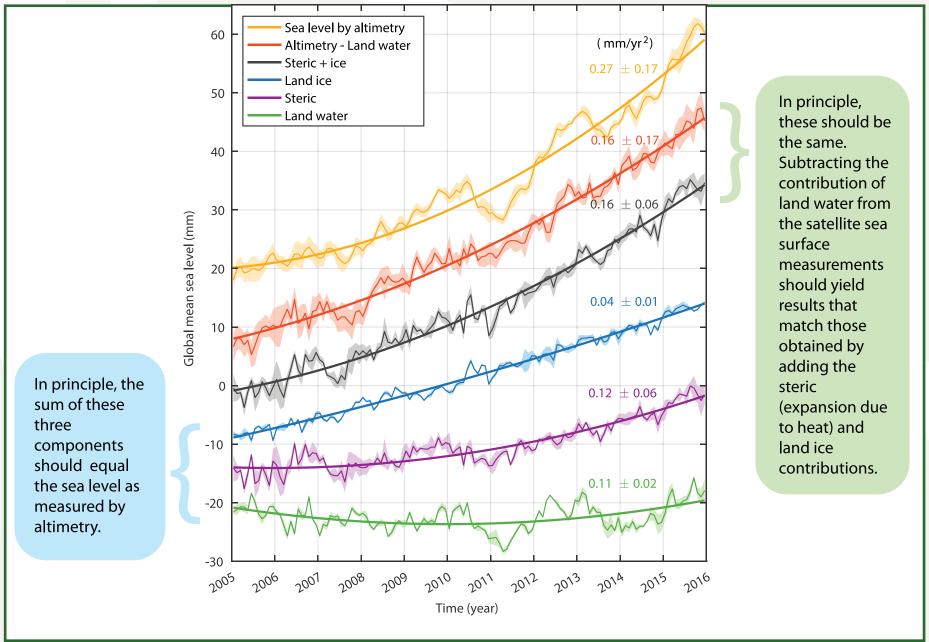


**Figure 1: The changing global sea level over the 2005-2016 period, edited from Yi et al. (2017).**
This figure shows how global mean sea level has changed over time. Time series of the various components are separated on the vertical axis with each denoted by colour as indicated in the inset. Estimated average accelerations for each component over the whole period in millimetres per year squared (mm/y$^2$) are annotated beside the time series in matching colours. The figure is only meant to depict changes and the choice of vertical placement for each component is arbitrary.

**In a pair of articles published in the *Journal of Climate*, Slangen et al. (2017) and Meyssignac et al. (2017) analyze the of climate models to simulate both global and regional sea level rise. They find that simulations can only explain about half (50% ± 30%) of the observed sea level rise. After bias corrections are included for the Greenland ice sheet and the possibility that ice sheets and the deep ocean were not in equilibrium with the 20$^{th}$ Century climate, the models explain about three-quarters (75% ± 38%) of the observed 20th Century sea level rise and all (105% ± 35%) of the observed sea level rise over the period from 1993-1997 to 2011-2015 period. Regionally, climate models underestimate the amount of sea level rise that occured, but do show reasonable agreement for interannual and multidecadal variability. When the same bias corrections are applied, the models come into closer agreement with observations. In addition, they find that the spatial variability in regional sea level rise is largely due to the thermal expansion of sea water and ongoing isostatic adjustment[1] resulting from the end of the last glacial period.**

1. Isostatic adjustment refers to the response of the solid, outer part of the Earth to being placed under a load (such as by water or ice accumulation) or having a load removed from it (such as by erosion or ice loss). In this case, the surface was placed under the load of glacial ice, which was subsequently removed at the end of the last glacial period. This caused the area that was underneath the ice to rise and the area that was on the margin of the ice to sink. This reaction of the crust to the removal of ice at the end of the last ice age continues to this day.

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More than two-thirds of British Columbia's population lives in coastal regions and sea level rise is one of the primary threats that climate change presents to coastal communities[2]. Observational data shows that sea levels have been rising over the instrumental record at an accelerating rate[3] and climate projections indicate that they will continue to rise[3]. In order to plan for sea level rise, it is helpful to know how sea levels are changing in the present day and also how well models can simulate sea level change, so that models can be improved and future projections can be interpreted with an understanding of their associated uncertainties.

Addressing the first question in a recent paper published in *Geophysical Research Letters*, Yi and colleagues examine how quickly global sea level rise is accelerating and which factors contribute most to it. To do this, they use a mix of satellite measurements of both ocean height[4] and the water and ice mass in the oceans and on land[5], and measurements of ocean heat content from floats in the ocean itself[6]. The use of satellite measurements of water and ice mass, combined with float data allows the authors to both determine which factors are contributing to sea level rise and reduce the uncertainty in sea level measurements, allowing for the trend over the 2005-2015 period to be distinguished.

After removing seasonal variations from their data, the authors turn their attention to the large, interannual variability that is driven by the El Niño Southern Oscillation (ENSO)[7]. Because this is natural, internal variability within the climate system, the authors remove it, using satellite measurements of total water stored on land in places such as rivers, lakes and ground water, in order to focus on the long-term climate change signal. They find that the acceleration in sea level rise over the 2005-2015 period is 0.27 $\pm$ 0.17 millimetres per year squared (mm/yr$^2$). This means that each year the rate of sea level increase "sped up" by a further 0.27 millimetres per year. Of this, approximately 0.11 $\pm$ 0.02 mm/yr$^2$ is due to decreasing terrestrial water storage. Once this term is removed, the remaining acceleration in sea level rise is 0.16 $\pm$ 0.06 mm/yr$^2$, which is about three times the average rate of acceleration of 0.055 mm/yr$^2$ over the 1993-2014 period and an order of magnitude greater than the 0.02 mm/yr$^2$, experienced during the 1920-2011 period. Yi et al. find that the primary drivers of this acceleration are the expansion of sea water due to heat, at 0.12 $\pm$ 0.06 mm/yr$^2$ and the contribution from melting land ice, at 0.04 $\pm$ 0.02 mm/yr$^2$. A breakdown of each of these components can be seen in Figure 1, above.

Yi et al.'s results rely, in part, upon the consistency between the results that they obtain from: (1) adding the thermal expansion and ice components, the black curve in Figure 1, and (2) subtracting the land water contribution from satellite altimetry measurements, the red curve in Figure 1. This bolsters their argument that they have removed

2. Three primary climate-related threats to coastal systems are: sea level rise, changes in ocean temperature, and changes in ocean acidity (Wong et al., 2014). Each of these on its own may bring impacts, but occur in tandem with each other and with other anthropogenic influences, such as pollution and coastal development. For a detailed assessment of the possible impacts that these influences may bring to coastal regions, see Wong et al. (2014).
3. A comparison of the average rate of sea level rise since the late 19th Century with the rate of sea level rise over the past 2000 years shows that there was a transition in the rate of sea level rise, with recent sea level rise accelerating at the end of the 19th Century and continuing to accelerate into the present day. This is due primarily to the thermal expansion of the ocean and the influx of water into the ocean from melting glaciers. Projections from climate models indicate that the rate of sea level rise will continue to increase throughout the 21st century. For more information on sea level rise, see Church et al. (2013).
4. The measurement of surface heights by satellites, known as satellite altimetry, is conducted by bouncing photons of various frequencies, such as high-frequency lasers, radar or microwaves—the satellites used for measurements of ocean height use microwaves—off of a planet's surface and measuring the time that it takes them to return to the satellite. The satellites used in the authors' work have their height calculated using both information about the satellites' path in the sky and ground measurements of the frequency of the photons that their instruments emit. For more information, see the National Aeronautic and Space Administration's (NASA) page on satellite ocean height data: https://sealevel.jpl.nasa.gov/overview/.
5. Satellite gravimetry is the measurement of gravitational fields by satellites. In order to do this, two satellites are placed in orbit and constantly measure the distance between each other using microwave signals. From changes in the distance between the satellites, variations in the gravitational field that they are experiencing can be calculated. This allows satellites to measure changes in ice, surface water, ground water and ocean water, as well as the density of rock and movement of magma beneath the Earth's surface. For more information, see NASA's page on the satellite gravity data used by the authors: https://www.nasa.gov/mission_pages/Grace/overview/index.html.
6. The ocean float data comes from a large network of several thousand autonomous floating sensors spread out across the world's oceans that can alter their buoyancy to sink to a depth of two kilometres. They later rise to the surface, making measurements of temperature, pressure and salinity as they do, and then return to the surface, where they transmit their data to satellites. For more information on the float data used by the authors, see the project's page, here: http://www.argo.ucsd.edu/About_Argo.html.
7. The El Niño Southern Oscillation is a climate pattern characterized by periodic variations in the sea surface temperature (SST) across the equatorial Pacific Ocean. It has effects on both local and global weather patterns. For example, El Niño events, characterized by warm SSTs in the eastern or central equatorial Pacific, bring warmer winters to British Columbia with more rain and storms in the southwest and drier weather in the interior.

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the noisy interannual fluctuations in sea level rise that the land water contribution brings. This, in turn, allows them to discern the trend in the rate of sea level rise over the 2005-2015 period.

The authors attribute about three-quarters of the acceleration to the rise in global temperatures during the second half of the study period, which they explain shows the susceptibility of global mean sea levels to global warming.

At this point, a few questions arise: Will this acceleration continue on into the foreseeable future? Will the rate of acceleration continue to increase? The future rate of sea level rise and its possible acceleration depend on global surface air temperatures. Over the timescale of multiple decades, global mean sea level rise is approximately proportional to the rate of change of surface air temperature and, over the shorter timescale in their paper, Yi et al. attribute most of the acceleration in sea level rise to the increase in global air temperatures. The projected rate of warming in surface air temperatures is, in turn, dependent on future greenhouse gas emissions. In scenarios with comparatively lower greenhouse gas emissions, projected sea level rise does not accelerate into the 21st Century. However, in a business-as-usual scenario, with higher emissions, sea level rise may continue to accelerate over the remainder of the century, as heat increasingly penetrates into the deep ocean. It should also be noted that sea level rise is a very long-term response to anthropogenic climate change, with oceans continuing to rise, potentially for thousands of years, after greenhouse gas emissions cease[8].

In a pair of papers published in the *Journal of Climate*, Slangen and Meyssignac and colleagues examine the second question, how well models have been able to capture both global and regional changes in sea level over the 20th Century. They use output from twelve climate models and compare the results to both satellite and tide gauge measurements of sea level. They also use reanalysis data[9], land-water storage estimates and estimates of ice-sheet mass compiled from multiple sources.

The authors find initially that the climate models underestimate the change in sea level over the 20th Century, simulating only roughly half (50% ± 30%) of the observed sea level rise. This can be seen in the upper panel of Figure 2 and is particularly striking early in the century. Over the satellite era, 1993-1997 to 2011-2015, the models perform much better, explaining all (102% ± 33%) of the observed sea level rise.

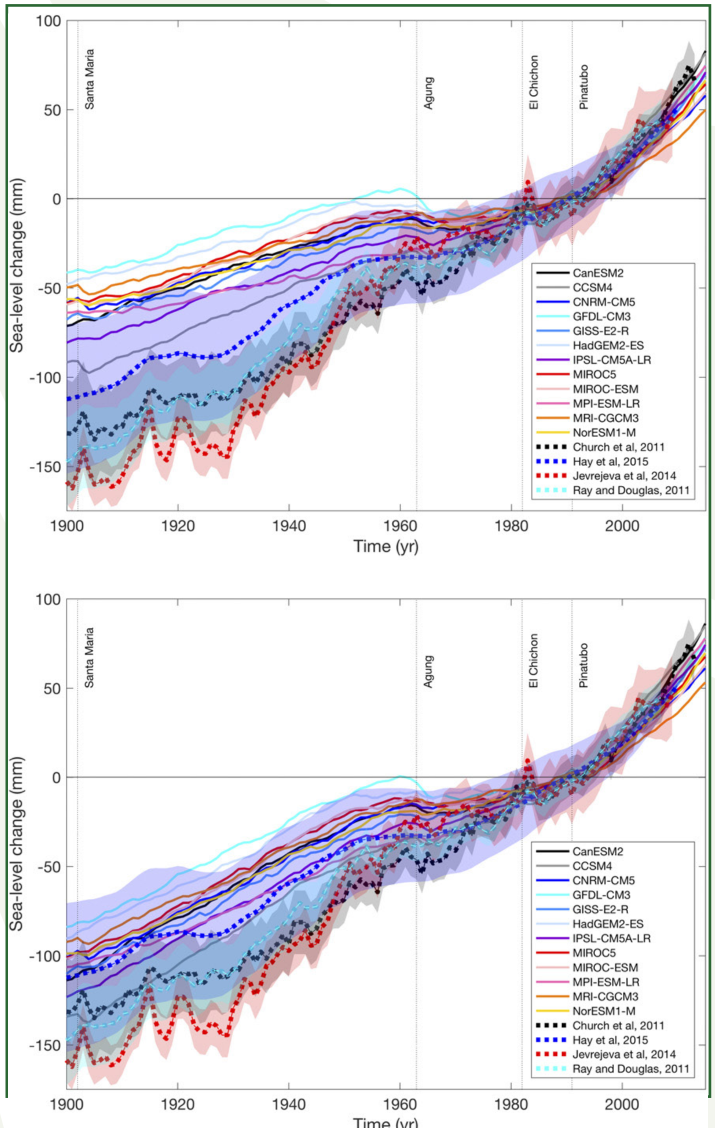


**Figure 2: Simulated and observed sea level change over the 1900-2015 period, from Slangen et al. (2017).**
This figure shows simulated and observational reconstructions of sea level rise before (top panel) and after (bottom panel) the corrections suggested by Slangen et al. Simulations from 12 global climate models are used (solid lines, as denoted by colours indicated in insets) and four observational reconstructions (dashed lines, as denoted by colours indicated in insets). Shading indicates 90% confidence intervals, grey vertical lines indicate major volcanic eruptions. All values are relative to a 1980-2000 baseline period.

8. Though it is very difficult to tell what technologies may be developed or employed to reduce global temperatures—or ocean temperatures in particular—in the far future, in the absence of such interventions, projections from climate models suggest that sea level rise could continue for thousands of years, potentially increasing sea levels by tens of metres, depending on the emissions scenario. For more information on this, see Clark et al. (2016).
9. A reanalysis is a representation of the historical climate that is created from historical observations that are "assimilated" into a model, often a global weather forecast model, that is run in a hindcast mode.

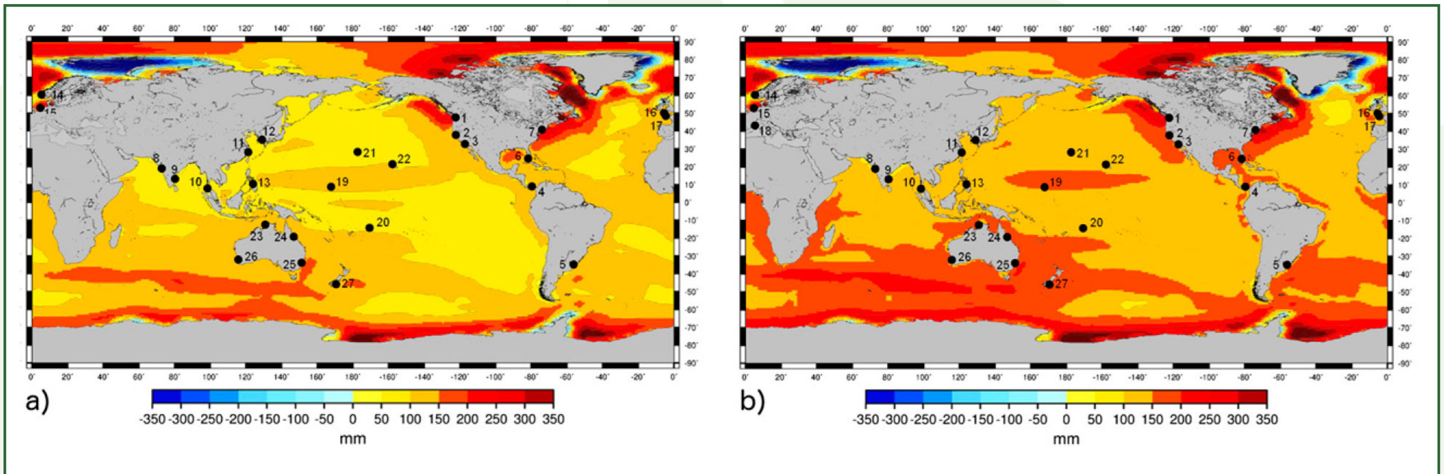


**Figure 3: Relative sea level change for the 1996-2015 period, from Meyssignac et al. (2017).**
This figure shows the average simulated sea level rise for the period of 1996-2015 relative to the 1901-1920 period. Panel a) shows the simulated sea level rise prior to the corrections suggested by Meyssignac et al. and panel b) shows the sea level rise after the corrections are applied. These simulations are from the same 12 global climate models used in Figure 2 and Slangen et al. (2017).

The authors seek to explain this and see if the models can be brought in line with observations. In order to do this, they turn their attention to two areas: what the models do not include in their simulations and internal model variability. All models are incomplete and this leads to biases. The models also have internal variability that doesn't necessarily match the actual short-term states of the Earth system.

The first potential source of the difference that Slangen et al. examine is the models' volcanic forcings. Because several of the models don't include the influence of volcanos in their preindustrial control runs, once the volcanic forcing is introduced in the 20th Century, simulated ocean temperatures fall, leading to an underestimate of the thermal expansion.

The next set of things that the authors examine have to do with ice, biases and the internal variability of the model simulations themselves. The melting of glaciers and the continental-scale glaciers known as ice sheets contributes significantly to sea level rise. However, the model simulations tend to show temperatures that are too cool over Greenland, which is home to the world's second largest ice sheet. Some of this is likely due to internal variability and some is likely due to known biases in the models.

The authors also consider the melt water from the Antarctic ice sheet and the glaciers on its periphery, but find that the former has a relatively small contribution to 20th Centruy sea level rise and is in reasonable agreement with the models, while observations of the latter are too sparse to use.

Finally, ice sheets and the deep ocean take a long time to react to climate signals. Working from geological evidence of a long-term contribution from the Antarctic and the fact that models underestimate thermal expansion from the deep ocean, the authors suggest that the deep ocean and ice sheets may still be reacting to earlier climate change that predates the 20th Century.

Slangen and coauthors estimate the size of each of these effects and suggest corrections for glaciers, Greenland's ice sheet and the potential reaction of ice sheets and the deep ocean to earlier climate signals.

Once these are applied, they find that the models explain about three-quarters (75% ± 38%) of the observed 20th Century global sea level rise and all (105% ± 35%) of the observed sea level rise over the satellite period. This closer agreement between the rate of sea level rise can be seen in the lower panel of Figure 2.

Turning to regional sea level change in their second paper, the same group, led by Meyssignac then use the output of global climate models in concert with a suite of observations to calculate regional sea levels, which are then compared to the direct measurements obtained by 27 tide gauges with long records (more than 70 years in most cases).

In addition to the factors that affect global sea level, regional sea levels are affected by changes to ocean circulation, atmospheric circulation and pressure, as well as changes in Earth's gravitational field and rotation due to changes in glaciers and ice sheets, the "rebounding" of the

Earth in regions that once were covered in glaciers, and changes in landwater storage and depletion.

The authors use climate model output to calculate contributions to regional sea level from dynamic changes in the ocean and atmosphere, glacier mass and the mass of the surface of ice sheets. They also use observations to estimate dynamic ice sheet mass (changing from complex discharging processes such as the calving or "breaking off" of glaciers), groundwater depletion and reservoir storage. Meyssignac et al. then add these to arrive at their estimates for regional sea level changes around the world (Figure 3).

They find that the ability of the augmented model output to capture variability on different timescales varies with the region. For instance, in Asia, the models capture the variability in sea level over decades, but fail to capture it on year-to-year timescales, whereas the models do relatively well at replicating both types of variability along most of the European coast and around most of Australia. As with global trends, models tend to underestimate regional sea level rise, with an average difference of about 0.27 millimetres per year. If the same corrections to the global data that the authors used in the first paper are used, the difference can be reduced ten-fold, to about 0.02 millimetres per year. This comes at a cost, because the application of the corrections leads to better agreement at lower latitudes and greater differences at higher latitudes, such as the northern United States.

In North America, the models match the observations quite well, capturing both year-to-year and multi-decade variability. In the north of the United States, sea level trends are larger and dominated by glacial rebound, whereas closer to the equator, sea level trends are smaller and largely attributable to the global land ice and dynamic ocean contributions (including expansion due to heat).

Taken together, the findings in these papers suggest that sea levels can respond relatively quickly to increasing surface air temperatures and that, with some corrections, models can capture most of the observed sea level rise over the 20th century. The agreement between the model simulations and the observed sea level rise during the satellite era is particularly strong, even before any corrections are applied. Because of this, one may have some confidence in the ability of the models to project future changes in sea level. While research is currently being done to better understand model shortcomings, notably the potential future contributions of ice sheets to sea level rise10, the bigger picture is that the amount of sea level rise that the 21st century will bring will likely be largely dependent on anthropogenic greenhouse gas emissions. These projected changes range from about half a metre to over a metre by 2100, and indicate that sea level may continue to rise for an extended period beyond that.

On the coast of British Columbia, tectonic influences and isostatic adjustment from the loss of glacier ice affect sea level rise and the magnitude of this effect varies regionally. This has caused the province as a whole to experience less sea level rise than the global average and this is likely to continue. Some locations, such as Tofino on the west coast of Vancouver Island, have actually seen sea levels lowering. In general, the province will continue to see rising sea levels, the rate and amount of which will be dependent on future global greenhouse emissions. This will be moderated regionally by tectonics and isostatic adjustment.

Chen, X. et al., 2017: The increasing rate of global mean sea-level rise during 1993–2014. *Nature Climate Change*, **7**, 7, 492–495, doi:10.1038/nclimate3325.

Clark, P.U. et al., 2016: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, **6**, 360–369, doi:10.1038/nclimate2923.

Church, J.A. et al., 2013: Sea Level Change. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Meyssignac, B. et al., 2017: Evaluating Model Simulations of Twentieth-Century Sea-Level Rise. Part II: Regional Sea-Level Changes. *Journal of Climate*, **30**, 21, 8565-8593, 10.1175/JCLI-D-17-0112.1.

Nowicki, S.M.J. et al., 2016: Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6. *Geoscientific Model Development*, **9**, 4521-4545, doi:10.5194/gmd-9-4521-2016.

Slangen, A.B.A., et al., 2017: Evaluating Model Simulations of Twentieth-Century Sea Level Rise. Part I: Global Mean Sea Level Change. *Journal of Climate*, **30**, 21, 8539-8563, 10.1175/JCLI-D-17-0110.1.

Wong, P.P. et al., 2014: Coastal systems and low-lying areas. In: *Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409.

Yi, S., et al., 2017: Acceleration in the Global Mean Sea Level Rise: 2005–2015. *Geophysical Research Letters*, **44**, 23, 11905–11913, doi: 10.1002/2017GL076129.

10. As a part of the sixth phase of the Coupled Model Intercomparison Project (CMIP6), an associated experiment with coupled and stand-alone ice sheet models, Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6), is being conducted. This experiment is being done to reduce the uncertainties in past, present and projected future states of ice sheets and their contributions to global sea level rise. See Nowicki et al. (2016) for more information.