The role of the Southern Ocean in sea level change

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QNLM/OUC
Xianyao Chen and his group
Ocean and climate processes affecting global and regional sea level

Warming (cooling) of the ocean (thermal expansion/contraction)
Change in mass of glaciers and ice sheets (Barystatic)
Changes in liquid water storage on land (Barystatic)

"regional sea level change and coastal impacts" is one of seven Grand Challenges identified by the WCRP
Motivation for CSHOR sea-level project

The Southern Ocean is a key area for improving understanding and projections of ocean heat content and sea level change because:

- It is one of the key areas where heat enters the ocean, resulting in heat storage in the upper ocean and in the abyssal layers, and contributing to sea-level rise through thermal expansion (Purkey and Johnson, 2010; Roemmich et al. 2015; Wijffels et al. 2016).

- Southern Ocean interacts with cryosphere in complicated ways, in particular a warming ocean is critical to the dynamic response of the Antarctic Ice Sheet (Church et al. 2013; DeConto and Pollard 2016).
The role of the Southern Ocean in sea level change

CSHOR sea level project can build up findings from other CSHOR projects to understand and project sea levels regionally and globally.
Achievements and highlights from FY 19-20

- Ocean heat uptake & redistribution in the Southern Hemisphere Oceans based on FAEMIP-type numerical perturbation experiments and decomposition using a theoretical framework (CSIRO, UNSW)
- Analysing CMIP6 sea level output and identifying the linkages between mean state biases and future projection uncertainties in different basins (CSIRO, UNSW)
- Producing high-resolution sea level fingerprints due to land ice mass changes based on NASA/JPL ISSM sea level module with high-resolution unstructured mesh grids (CSIRO, UTAS)
- Global and regional sea-level budget (UNSW, CSIRO)
- Testing impacts of different vertical interpolation schemes on ocean heat content estimate (UNSW)
- Uncertainties of Antarctic Ice Sheet (AIS) mass flux time series; AIS modelling for the future (UTAS)
How do ocean heat uptake and redistribution respond to atmospheric forcing (i.e., wind stress, heat and freshwater fluxes)? We first adopted a theoretical framework by Bindoff and McDougall, which proposed three physical processes: pure warming, pure freshening and pure heave in an isopycnal/diapycnal coordinate.

We then carried out FAFMIP-type perturbation experiments with some atmospheric forcing turned on/off to examine the impacts of individual atmospheric forcing, and compared findings between modelling and theoretical methods.

Both methods indicate key roles of wind and heat flux in the Southern Ocean warming.
Dynamic sea level projections: from CMIP5 to CMIP6

• CMIP5 and CMIP6 ensembles show similar regional sea level distribution, for both present mean and future projection.
• Dynamical downscaling based on high-resolution ocean models provides more regional details.

Grose et al. (including Lyu and Zhang) 2020: Insights from CMIP6 for Australia's future climate, *Earth’s Future*. (highlighted by AGU EOS Research spotlight)
Linkages between model mean state biases and future projections in the combined CMIP5/6 ensemble (CSIRO, UNSW)

- Models with equatorward bias in the westerly winds tend to project larger poleward shift of the westerly winds, larger wind stress curl forcing, and thus larger dynamic sea level changes in the Southern Ocean.

- Most CMIP5 models have equatorward bias relative to observations, which means they might overestimate future projections in this region.

Kewei Lyu, Xuebin Zhang, and John A. Church 2020, Regional dynamic sea level simulated in the CMIP5 and CMIP6 models: mean biases, future projections, and their linkages, *Journal of Climate*
Sea-level fingerprint:
Regional sea level distribution due to gravitational, rotational and elastic responses of the earth system to the melting of land ice

(A) Ice Sheet

B) Melting

Sea surface change
Relative sea level change
Solid surface change

Sea-level fingerprint due to uniform GIS melting

(Tamisiea et al., 2003)
Solving *sea-level fingerprint* using ISSM sea level module with unstructured high-resolution mesh grids (CSIRO, UTAS)

ISSM mesh grids: high-resolution along the coast and at melting sources

Change in ice thickness over the AIS from 2000 to 2100 under RCP8.5 (Golledge et al., 2019)

With unstructured mesh grid, we adopted ISSM sea level module to produce high-resolution and more accurate sea level fingerprints, which can resolve melting resources like AIS at the resolution of 5~10 km, much better than previously available products of ~100 km resolution.

100 km
Typical resolution from others

50 km

25 km

10 km
Adopted in our study

5 km
ISSM sea-level fingerprint due to AIS melting 2000-2100 under RCP8.5: 10 km vs 100 km resolution of AIS

AIS fingerprint (10 km)

AIS fingerprint difference (10 km – 100 km)
Sea level fingerprints due to future projections of GIS and AIS melting (Golledge et al., 2019)

[Graph showing sea level change over time]

GIS sea level fingerprint

AIS sea level fingerprint
Ice sheet modelling based on PISM (UTAS)

How an ice sheet model sees the world

Boundary conditions (air temperature, precipitation, ocean temperature and salinity) simulated using CSIRO Mk3L climate system model

Projected future GMSL contribution of AIS melting up to 2500
Sea-level budget (UNSW, CSIRO, QNLM)

- *Church & White (2011)* sea level reconstruction was updated using the latest observations, taking the time-evolving sea-level fingerprints and local vertical land motion (VLM) into account.
- The updated GMSL reconstruction agrees better with the sum of all contributors after correcting the local sea level observations with estimates of local VLM (not just GIA).
Sea-level budget (historical 1958-2015)

Dynamic sea level plus global mean thermal expansion

Added mass into oceans (e.g., glaciers, GIS, AIS, Terrestrial water)

Glacial Isostatic Adjustment

Inverse barometer effect due to regional changes of surface air pressure

Sum of above components
Sea-level budget (at tide gauges; historical 1958-2015)

Sea level budgets at 170 tide gauge stations can be closed reasonably well, with difference of 0.3±1.3 mm/yr over 1958-2015 between direct TG observations and combined budget terms.
Testing impacts of new vertical interpolation on ocean heat content estimate (UNSW)

- Barker & McDougall (B&M) proposed new vertical interpolation method (Multiply-Rotated Piecewise Cubic Hermite Interpolating Polynomials) that better represent high resolution data, compared with existing Reiniger and Ross and linear schemes (left).

- Based on mapping of one month of data (middle), B&M suggested linear interpolation had global heat content errors equivalent to 5 years of ocean heat uptake, and with large scale patterns.

- B&M interpolation gives global integrals of heat content increase from the 1960s to 2006-2018 (255 ZJ) about 13% larger than linear interpolation.
Publications (15 published, 4 submitted during FY 19-20)

Published


10. Richter, Kristin; Meyssignac, Benoit; Slagen, Aimée; Melet, Argélique; Church, John; Fettweis, Xavier; Marzeion, Ben; Agosta, Cecile; Ligenberg, Stefan; Spada, Giorgio; Palmer, Matthew; Roberts, Christopher; Champollion, Nicolas (2020). Detecting a forced signal in satellite-era sea level change. Environmental Research Letters, https://doi.org/10.1088/1748-9326/ab8966.

11. Richter, Kristin; Meyssignac, Benoit; Slagen, Aimée; Melet, Argélique; Church, John; Fettweis, Xavier; Marzeion, Ben; Agosta, Cecile; Ligenberg, Stefan; Spada, Giorgio; Palmer, Matthew; Roberts, Christopher; Champollion, Nicolas (2020). Detecting a forced signal in satellite-era sea level change. Environmental Research Letters, https://doi.org/10.1088/1748-9326/ab8966.


Book Chapter:


Submitted


In preparation

• Jin, Y., X. Zhang, J. A. Church and X. Bao, Projected sea level changes in the China marginal seas based on dynamical downscaling. Journal of Climate, to be submitted soon.


Outreach, capacity building and collaboration

- **Outreach**: convening sessions and giving talks at national and international conferences (e.g., AMOS, AOGS, COSIMA); being interviewed by leading national media (ABC Radio and ABC Science News).

- **Capacity building**: one postdoc, two PhD students, one honours student. (one more PhD student hopefully starting soon)

- **Collaboration**:
  - intra- and inter-CSHOR project collaboration
  - closely collaborating with Scripps Institution of Oceanography (US) and University of Auckland (NZ) on SO modelling, dynamical downscaling and sea level studies
Outlook for FY 20-21

- **Staffing arrangement for postdoc Kewei Lyu** – University hiring

- **Research activities:**
  - More ocean model experiments, e.g., testing the effects of freshwater/melting on ocean circulation and sea level in the Southern Ocean
  - Analysis of sea level output from available CMIP6 model experiments
  - Refined regional sea level fingerprints associated with melting of land ice, in particular AIS using high-resolution unstructured mesh grid based on updated AIS simulations
  - Analysis of GRACE and GRACE-Follow On time series to produce estimates of Antarctic and Greenland ice mass change (UTAS)
  - Better regional sea level budget closure (UNSW)
  - Working towards next-generation of total sea level projection based on updated & refined components
Better understanding and projecting regional and global sea levels

Global mean sea level rising rate:
1901 to 2010 1.7±0.2 mm yr\(^{-1}\)
1971 to 2010 2.0±0.3 mm yr\(^{-1}\)
Satellite 1993-2010 3.2 ±0.4 mm yr\(^{-1}\)