Sea level and ocean heat and freshwater content

Abstract

Improving understanding of past and projections of future sea-level change is a multidisciplinary challenge of great importance to the well-being of the World's coastal societies and ecosystems. Priorities include improving the record of past global averaged and regional sea-level change and the contributions to this change. Of particular priority for Australia is improving understanding and modelling of the role of the Antarctic (and Greenland) ice sheet, the role of the ocean in the global-averaged and regional sea-level change, and improving estimates of vertical land motion. A (virtual) sea-level centre involving collaboration of all partners would result in a narrowing of uncertainties.

Background

Sustained observations of ocean heat and freshwater content (the Argo project and ocean repeat sections (GO-SHIP)) are undertaken by the CSIRO Oceans and Atmosphere (OnA) Flagship with some operational activities completed by the Bureau of Meteorology (BoM). In situ observations of sea level are undertaken by the National Tidal Centre (NTC BoM) and various regional and port authorities. These activities are well connected internationally, with Australians prominent in relevant international coordination committees. The one exception is for sea-level observations in the Southern Ocean and within the Australian Antarctic Territory which are not well integrated with NTC activities and the records remain poorly documented and unanalysed. CSIRO OnA and University of Tasmania are also well connected to satellite altimeter missions and run the only southern hemisphere altimeter verification site[1,2].

Together, CSIRO OnA, UTAS and ACE CRC are world leaders in the quality control of ocean temperature and salinity observations[3-5] and the estimation of ocean heat content[5-8], salinity[9,10] and global[11-14] and Australian[15-17] sea level changes, with these products used extensively internationally. ANU is a leader in the interpretation of global[18,19] and Australian[20] paleo sea-level observations and the development of glacial isostatic adjustment (GIA) models[21], with additional work on paleo ice-sheet and sea-level variability at Curtin University[22], UCanberra[23] and UWA[24]. CSIRO OnA and UNSW are world standard in the understanding of global[6,25-28] and regional[29-31] sea level change and its projection for the 21st century[32,33]. ANU and UTAS are leaders in analysis of Global Navigation Satellite System (GNSS) data for the determination of regional and global vertical land movement relevant to tide gauge and altimeter calibration[28,29]; application of radar interferometry to coastal subsidence is fragmented (GA, Curtin, UNSW and ANU) and limited.

ANU and UTAS has expertise in the use of satellite gravity data (GRACE) and ANU is closely connected to the GRACE follow on mission.

Australia has significant expertise in estimating the contributions of glaciers, ice sheets and changes in land water to sea-level change[30-33] with expertise at ANU, Curtin University, UTAS and CSIRO. Australian has world-leading expertise in ice-sheet/ocean interactions within a small group at ACE CRC and AAD[34-36]. Capability in numerical modelling of ice sheets and interactions with the climate for historical rates of sea-level change and future projections is limited and expectations are of reduced permanent staff in this domain, with some offset by short-term (3 yr) posts at ACE CRC/UTAS.

Many of these observational activities are supported by the Integrated Marine Observing System (IMOS) and AuSCOPE. University based funding is typically short-term (≤3 y) and fragmented amongst ARC, ACE CRC, AAD, the former Department of Climate Change, or is an unfunded activity performed by permanent staff.

Relevance

Regional sea-level change directly impacts coastal Australia, where 85% of Australians live. Up to $63 billion of existing (as of 2009) residential buildings are potentially at risk from inundation from a future 1.1 m of sea-level rise, with the value and number of people potentially affected continuing to increase with ongoing coastal development. Coastal ecosystems are at risk from sea-level rise, particularly when they are squeezed between rising sea levels and coastal developments.

The Council of Australian Governments (COAG) and the Natural Resource Management Ministerial Council has identified the coastal zone as a priority for climate change adaptation. Every state has, or has recently had, guidelines for planning in the face of sea-level change though the 21st century. However, there has been little recognition to date that sea-level rise will continue (possibly at a faster rate) after 2100. Despite these guidelines, estimates of historical sea-level change and projections of future change have been controversial in many regions of Australia, with legal disputes between developers, environmentalists, coastal councils and state governments. Coastal councils are in urgent need of improved and continuing advice from the marine science community on the risk from future sea-level change and extreme events, as witnessed by request for briefings from coastal councils and State Governments. They require robust knowledge of global and regional sea-level change, information on vertical land motion and information on shoreline movement.

Globally, sea-level change is a major issue with 140 million people living within 1 m of the current high tide level, many in south and east Asia close to Australia, and with vulnerable populations in Pacific and Indian Ocean island nations. Climate change refugees may be a significant issue during the 21st century. The risks of sea-level rise, particularly longer-term and effectively irreversible rise, are central to international negotiations on climate change mitigation which will have significant impacts on Australia. As a result, the Federal government is in need of sound advice on future sea levels.

As well as being a central component of global and regional sea-level change, ocean temperatures and salinities and the associated heat and freshwater contents are the most fundamental properties of the ocean. These observations are also central to our understanding of how the oceans operate and of course the estimation of ocean currents. The observations are also central to the seasonal to interannual prediction of global and Australian climate[37,38], and to the prediction of sea level up to several months in advance[39-41]. They are also used to evaluate global and regional ocean only and coupled atmosphere-ocean climate models and formulate improved parameterisations of ocean processes for incorporation in these models[42]. Perhaps the most fundamental (and controversial) property of the climate system is its sensitivity to doubling of carbon dioxide concentrations (the equilibrium climate sensitivity) – ocean uptake of heat is central to the evaluation of this sensitivity. Ocean salinity changes are also key observations in understanding changes in the hydrological cycle[9,43].

Science needs

Improving projections of global-averaged and regional sea-level change remains a major scientific priority and challenge, with implications for all regions of the Earth and for international negotiations. The uncertainty of the sensitivity of the climate system and the hydrological cycle to increasing greenhouse gas concentrations (and other human activities) directly impacts the amount and regional pattern of warming, changes in precipitation, winds, and air-sea fluxes heat and freshwater, and as a result impacts both global-averaged and regional sea-level change. Thus changes in ocean heat and freshwater content are an important priority both for sea level and for much broader reasons.

Key scientific questions that Australia is positioned to pursue are outlined below:

- *Past rates of sea-level change need to be better determined.*
  Accurate estimates of global and regional sea levels and rates of variability and change in periods of warmer climate and during the last ice age, over the last few decades, centuries and millennia would provide powerful constraints on what sea levels might be in the future.

- *Uncertainties in the rate at which surface waters and heat are sequestered into the ocean interior need to be significantly narrowed.*
  Climate models approximately reproduce the observed ocean thermal expansion over recent decades. However, the observational record is short, the deep ocean is poorly observed, and discrepancies between observations and simulations remain. Large discrepancies between regional projections from different models suggest that the ocean's dynamic response to climate forcing is poorly understood, requiring critical comparison between improved observations and models.

- *The regional patterns of historical and projected sea-level change need to be better understood.*
  Although models project that by 2100 70% of the world's coastline will experience a sea-level rise within 20% of the global average, coupled atmosphere-ocean models produce complex patterns of sea-level change, with little understanding of the differences between model projections. These patterns also relate to changes in the El Nino Southern Oscillation (ENSO) and other modes of climate variability [30,31,44-48] that have implications for changes in patterns and rates of regional warming and rainfall. Coupled to this problem is understanding smaller regional biases in present day satellite measurements of sea level.

- *Contributions from larger rates of the flow of ice into the ocean from the ice sheets, particularly on the longer term, need to be better constrained.*
  An increased flow of ice from the ice sheets has recently been observed[49,50], in response to melting of the West Antarctic ice shelves from increased ocean heat supply. This increased flow has the potential to make a large contribution to future sea-level rise. However, understanding of changes in ocean/ice-sheet interactions and ice-sheet flow remains rudimentary.

- *Improved estimates of vertical land motion are required.*
  Vertical land motion can result from global scale changes in past and future distribution of mass on the Earth (GIA) as well as local phenomena such as sediment compaction. This requires both paleo observations and ongoing modern geodetic observations (for example continuous GPS observations). Sources of large-scale differences between GIA model predictions and GPS observations need to be understood.

- *Observed global and regional sea-level change needs to be more rigorously attributed to the underlying forcing factors.*
  Recent progress has now provided an adequate explanation for the observed 20th century global-mean sea-level change, with some understanding of the regional distribution[29-31,45-48], but attribution of the regional sea-level change to human influences or natural causes causes remains a challenge.

- *The reason why semi-empirical models project substantially larger rates of sea-level rise than current projections need to be better understood.*

  Semi-empirical models, trained with observed sea levels, project rates of sea-level rise as much as twice currently accepted projections. There is little understanding why these models project a larger rise (there is no indication that it results from our incomplete ice-sheet models). Agreement about these projections and confidence in them is low.

Robust advice to policy makers at local, state and federal levels, and the Australian community at large, and answers to these scientific questions must be underpinned by long time series of key climate variables, demonstrated understanding of the issues, along with robust and verified models for projecting future change. Similarly, constraining climate models and climate sensitivity requires long time series of ocean heat content. This requires sustained funding for sustained observations and is a major challenge given the vast area and depth of oceans in the southern hemisphere, the difficulties of working in the Southern Ocean and Antarctica, and the small size of the relevant Australian and southern hemisphere research community. This implies a need for strong international engagement in the World Climate Research Programme (WCRP), Future Earth (FE), the Global Climate Observing System (GCOS) and the Global Geodetic Observing System (GGOS) to ensure that science priorities important to Australia are addressed.

The implications of sea-level, ocean heat content and hydrological cycle change have huge sustainability, economic and environmental implications. Progress on the above science questions would result in a better informed and thus more rational debate in Australia on the implications of sea-level rise and climate and ocean change. This in turn would lead to improved coastal planning and identification of adaptation options, with less public dispute.

Perspectives

Science Priorities

Sea Level Observations

Australia mostly has a high-quality sea-level in situ observational network that is well connected to international activities (GLOSS) and that needs to be maintained and supported by observations of land motion (see below). The **sea-level observation network on the circumpolar distribution of Southern Ocean islands and in Antarctica needs to be strengthened**. This includes data rehabilitation, quality control procedures and making the network operational.

Australian scientists operate the only southern hemisphere verification site for the NASA/CNES/NOAA/EUMETSAT Ocean Surface Topography Science Team (OSTST) and the ESA mission teams (e.g. Sentinel-3 Validation Team, S3VT). These activities are highly valued by the international communities and need to be maintained . **Continued engagement with the international satellite community is required** to keep abreast of and remain well positioned to benefit from new opportunities. Australia needs **greater investment in the interpretation of satellite gravity observations** (building on our involvement in the development of the GRACE Follow on mission). Analysis of the in situ and satellite observations needs to **focus on the regional distribution of sea-level variability and change**.

Paleo observations

Although the Australian paleo sea-level community is small, it is internationally recognised and Australia contains extensive and detailed geological archives of past climate and sea level. Australian Palaeosea level researchers are working together with international partners and working groups, including PAGES, PALSEA2 and PLIOMAX.

A priority is to achieve decadal to sub-millennial record of sea-level change during warmer than present past interglacial periods to provide baseline rates of rapid sea-level rise following ice-sheet collapse events. Fingerprinting of the origin of meltwater sources is required to identify those ice sheets most sensitive to warming. Sections of the East Antarctic Ice Sheet lack well-dated terrestrial and marine constraints on past ice extent and retreat history[51], limiting reconstructions of past ice sheet behaviour[52]. Consequently, disagreement persists as to even the sign of change of the East Antarctic Ice Sheet since Last Glacial Maximum, generating uncertainty on the present state and mass balance of the ice sheet[53].

Specific high priority projects include:

- **Improved estimates of sea levels** for the past 20 ka, 6,000 years and the last two millennia, using near-surface coring of offshore (150 m) shallow waters[54], micro-atoll coral analysis[55], and saltmarsh studies,
- Sediment coring on the East Antarctic shelf to date the moraines seen in the bathymetric data,
- **Paleo observations to determine the size of the Antarctic ice sheet during the last glacial maximum**,

- more widespread paleo estimates of sea level during the last interglacial.

Ocean observations and modelling

A key requirement is to improve historical and ongoing global observations of ocean temperatures and salinities. To reduce uncertainties in the historical ocean record requires **ongoing data recovery efforts and improved quality-control and bias corrections procedures**[56]. An immediate priority is to **sustain global Argo observations of temperature and salinity of the upper 2000 m of the ocean, to extend this into under ice observation and regional seas, and to continue the GO-SHIP full-depth trans-ocean sections**. **Over the next five years, a plan and the capability to systematically observe the full depth ocean is required**, translating to a sustained observational network over the following five years. This will require improved understanding of sampling requirements, advances in technology, and sustained funding.

Sea-level projections are hampered by model biases, long-term drift and differences in the magnitude and patterns of regional projections[57,58]. Priorities to improve ocean models include **better parameterisation of horizontal and vertical ocean mixing, improved parameterisations of mesoscale and sub-mesoscale processes and higher resolution ocean models**. The Southern Ocean is critical, particularly through high-latitude ocean-ice interactions, down-slope flows, and dense water-mass formation. Australia has the capability to lead both regional observations and focused modelling activities. **Improved representation of the major climate modes influencing the Australian region (ENSO, IOD, SAM, IPO) are required for projecting regional sea-level changes**[59,60]. Ocean reanalysis and a focus on decadal variability will help maximize the benefit from these investments. **Australia's seasonal prediction of sea-level anomalies needs to be continued and be made operational.**

Ice sheet observations and modelling

The East Antarctic ice sheet (Australia's Antarctic Territory) contains more ice (and more grounded below sea level) than west Antarctica but our knowledge of this region's contribution to sea-level change is much less than for west Antarctica. **The key priority is to improve estimates of the past, present and future Antarctic Ice Sheet mass budget and its influence on sea level, especially for the East Antarctic Ice Sheet (Australia's Antarctic Territory).** A major limitation is the lack of observations of the East Antarctic Ice Sheet, specifically in critical regions where the ice sheet is showing rapid change. Research efforts focussed on quantify the processes controlling ice mass loss, using *in situ* and remote sensing observations and numerical modelling, are required. Key priorities are:

- **Characterisation of key processes and sustained monitoring of ice flow/discharge rates and ice elevation changes in areas of dynamic interest,** building on existing strengths in *in situ* observations for calibration/validation of satellite and airborne geophysics measurements.
- **Quantifying the response of the ice sheet to ice shelf changes and projecting future change requires** the development and robust evaluation of coupled ice sheet/ocean/climate/GIA models.

- **Identification of areas susceptible to rapid retreat** using air- and ship-based surveys of Antarctic continental shelf bathymetry and bedrock.
- **Quantification of the climate/ocean processes that transport heat to the ice shelves fringing the Antarctic ice sheet**.

Vertical land motion and GIA observations/modelling

Geodetic observations: **The key priority is to obtain long, continuous time-series of vertical land movement at all (~40) climate-related tide gauges within Australian territories** (including island sites and Antarctica) and adjacent regions using GNSS and radar interferometry. The accuracy of the terrestrial reference frame underpins the accuracy of satellite altimetry and vertical land movement estimates assume the achievement of the GGOS goals of 0.1mm/yr accuracy at the global level.

Modelling geophysical processes: **Regionally-coherent differences between GPS uplift rates and models of GIA need to be explained and their effect within altimeter bias drift estimation better understood**. Understanding these differences is the key modelling priority, through improvement of GIA models and addition of other geophysical processes, notably those due to present-day surface mass changes. For GIA modelling, **improved ice sheet reconstructions for the last deglaciation is most important, particularly for East Antarctica**. Developing GIA models that more realistically model solid Earth processes is also important.

Synthesis

Sea level is an exacting, multidisciplinary science requiring understanding in many different disciplines. Australia is very well respected in this area. Australia has only limited expertise in glacier studies and it is arguable that this is an area where Australia should not attempt to be a world leader.

As well as the individual science priorities for each of these disciplines identified above, scientific priorities in the synthesis of sea-level change include:

- **Quantitative understanding of the contributions to understand historical sea-level variability and change,**
- **Better understanding and improved projections of the regional distribution of sea-level change, and the role of anthropogenic drivers,**
- **A greater focus on the potentially irreversible (on a millennia time scale) changes currently occurring, and**
- **Improved quantification on extreme events and how they are changing (see the separate report on extremes).**

Australian scientists need to continue to strongly engage with international efforts, and also the IPCC assessments of sea-level change and its impacts. There is also a need for closer interaction with coastal communities to make sure that results of the scientific research are incorporated into coastal zone management practices, and impacts and adaptation efforts.

Key infrastructure and capability and funding and coordination requirements/impediments

Sea Level Observations

Sustained funding (currently received through the BoM, IMOS and ACCSP) is required for the ongoing sea-level observational network, the satellite altimeter verification site, the analysis of these observations and linkage with the international community.

To bring the Southern Ocean and Antarctic observations up to the required standard requires **recognition of institutional responsibilities and the resolution of the necessary institutional relationships** (coordination of the BoM and AAD responsibilities) **and additional funding** to ensure the appropriate quality products are delivered.

Paleo observations

A primary requirement is a dedicated mobile Coastal Dynamics Research Facility with the infrastructure to provide a fundamentally new and innovative approach for observing and measuring waves, currents, sea levels, and coastal change over a range of temporal and spatial scales. This facility would be shared across institutions and made available for rapid deployment across the country. Data generated would be fed directly into coastal response models (e.g., BarSim). Such a facility would also provide standardization of coastal data collection methodologies and formats, which in turn allow for greater integration of data for coastal response models. Australian Palaeosea level researchers need to continue to collaborate with international partners and working groups and there is a need for additional personnel and to ensure the compilation and analysis of past sea-level records (e.g. dating, field surveys, instrumentation).

Ocean observations and modelling

Sustained funding of Australian commitments to Argo and GO-SHIP to maintain the in situ ocean temperature and salinity observations currently provided through ACCSP, IMOS and the ACE CRC. However, **additional funding will be required for the design and implementation of a deep ocean observing system**, with international coordination through the GCOS. Ocean temperature and salinity, and ocean boundary currents observations on the continental shelf facilitate are required to understand the transfer of the offshore change to coastal sea level.

Increased computing resources, including the human resources necessary to effectively use the new generation of supercomputers will be required to allow the use of higher resolution ocean models to allow delivery of regional and local sea-level projections and quantification of changes in extreme events. These computing resources are also required for ocean reanalysis and studies of decadal variability.

Ice sheet observations and modelling

Sustained funding and logistics support to access remote regions of the Antarctic ice sheet (ground-based traverse and long-range air support and airborne operations) is needed, including:

- The deployment of improved technological solutions for low-cost, sustained and integrated *in situ* measurements, building on existing capability overseas and in Australia.
- Instrumented boreholes (drilled to both bedrock and ocean) for constraints on paleo grounding line position, ice-sheet basal characteristics ice flow and rheology studies and ice-shelf/ocean interaction studies.

To strengthen capability and provide capacity for estimating sub-basin-scale hydrological and glaciological mass changes to aid regional and global sea-level studies requires building both national and international links within and between the observing and modelling communities to make the best use of satellite and airborne calibration/evaluation studies and model development and applications. Development of GRACE expertise within Australia is needed to benefit from science team involvement in the GRACE Follow-on (2017).

To provide capacity in ice sheet modelling and the development of the next generation coupled climate models required a significant increase in both storage and computing power for running the next generation coupled climate models and processing of satellite observations, including porting code to new types of computer architectures and maintaining state-of-the-art software.

An ability to access continental shelf regions that ships cannot reach, including deep grounding zones beneath ice shelves and fast ice zones, requires airborne deployed ocean instruments and **autonomous underwater vehicles**, building on existing capability overseas and in Australia.

Vertical land motion and GIA observations/modelling

Less than 10 Australian climate-related gauges have GNSS within 1-2 km. **New GNSS hardware deployments are required at all gauges (~30) where vertical land motion is not currently measured. A coordinated oversight of installation of GNSS at tide gauges is lacking and is required** to replace the entirely ad hoc and best-effort basis.

An Australian contribution to an improved reference frame has come through NCRIS funded AuScope. **Funding of ongoing operations of NCRIS/AuScope beyond 2015** and necessary equipment upgrades are required.

A pilot study is required to assess the potential of applying satellite radar interferometry for tide-gauge stability monitoring, including the value of locating radar transponders on tide gauges and assessing coastal subsidence over large regions away from tide gauges. Lobbying of international space agencies is required to routinely collect radar data at each Australian gauge.

GIA model expertise is limited to a few centres globally. Given that GIA expertise is required to interpret paleo and modern ice-sheet changes, and to quantify present and future global sea-level change, there is a **strong need for maintaining capacity in GIA modelling** and strong international engagement. An open source GIA modelling framework is required that allows computationally efficient consideration of complex solid Earth rheologies and structures that can be coupled with ice-sheet/climate models.

To better define past Antarctic ice sheet history there needs to an **appropriate level of support to undertake seafloor mapping and sediment sampling on-board Australia's icebreaker, Aurora Australis (and replacement) and/or the RV Investigator**.

Synthesis

The main requirement for effective synthesis is healthy individual sea-level disciplines. All disciplines are currently feeling significant funding pressures, are struggling to meet existing commitments and have essentially no flexibility to take on new priorities. In particular, funding shortfalls at AAD and non-science prioritisation has resulted in a halving of science project numbers over the last ten years, including a near cessation of deep field activities. Making significant inroads into past ice sheet reconstructions required for GIA modelling and assessment of potential future ice-sheet collapse would require a $40-100M field program. Such efforts, perhaps in international partnership, are required to test new model suggestions of large-scale retreat of East Antarctica before 2200 leading to 2.5 m of sea-level rise.

Built on a solid foundation of healthy individual disciplines, the **main requirements for synthesis are the appropriate human resources, good access to international observations and model simulations** (particularly from the ongoing Coupled Model Intercomparison Projects – limited access has been a major impediment over the last decade).

Continued Australian engagement in internationally coordinated projects such as the WCRP, FE, GCOS and GGOS will be required.

If a significant block of funding was available, **a (virtual) comprehensive sea-level centre involving collaboration of all partners** would result in significant progress and a narrowing of uncertainties. This could be a loose partnership or similar to the Centre of Excellence/CRC models. A cooperative research centre approach would also allow a broadening of the scope of sea-level research to consider impacts of sea-level rise and an effective outreach from the research community to the user community in state governments and local councils. Priorities in such a centre, or with a smaller quanta of new funding would be greater investment in understanding ice sheets – in situ, satellite and paleo observations and modelling and ocean observations, supported by modelling aimed at determining the regional distribution of sea-level rise.

Additional comments

This subtheme has close relationships to several other subthemes. In addition, there are strong links to coastal research areas covered in the Oceans Extreme Theme.

In particular:

- Coastal erosion is a major potential impact of sea-level rise and there is a strong demand to **develop reliable coastal response models**, which can accurately forecast future shoreline positions under rising sea-level scenarios. These models need to include the complexities and feedback processes that characterise coastal sedimentary systems. It is also necessary to consider the impacts on different types of coast – beaches and dunes, estuaries [and mudflats], coral reefs [and reef islands], rocky coasts (fossil dune-eolianite). It needs to begin to recognise geographical variations within these coastal types, building on mapping initiatives like Smartline, and a more probabilistic approach to assessing risk is required (i.e., not one-line on a map but a range of lines to which probabilities can be estimated). Changes in sediment supply and changes in surface waves are also important considerations that need to be linked to sea-level change projections to understand the combined impacts on coastal environments.
- **To understand the impacts of, and adaptation to changing sea levels, there is a need to link to the social sciences**, including coastal population projections and coastal development planning, and the many conflicting interests.

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