Sea-level variability and rise: Understanding the past, implications for the future

John Church
17th NSW Coastal Conference
Wollongong, NSW
5 November 2008

www.cawcr.gov.au

Antarctic Climate and Ecosystems CRC and
The Centre for Australian Weather and Climate Research
A partnership between CSIRO and the Bureau of Meteorology

Sea level rose more than 120 m since the last glacial maximum

• Rates of rise up to 4 m/century
• Our coastal society developed in a time of stable sea level
• At temperature similar to what we expect by 2100

Last glacial maximum

Paleo data constrains estimates of sea-level change over centuries to millenia


Salt marsh sediment cores provide proxy sea-level records for several centuries

Gehrels et al. 2006

Sources: Gehrels et al 2005, 2006, in prep.; Donnelly et al 2004; PSMSL

Salt marsh records indicate an acceleration in the rate of sea-level rise

Gehrels et al. 2008

Estimates of 20th century sea-level change come from island and coastal tide gauges

National Tidal Centre
Satellite altimeters measure global sea levels

Sea-level rise accelerated during the 20th century

Satellite Measurements

Holgate and Woodworth 2004

1.8 +/- 0.3 mm/yr (1960 to 2000)

Church et al. 2004, 2006

Sea levels are currently rising at over 3 mm/yr

Sea level has been rising around the Australian continent

Church et al. 2008

Climate variability affects the regional distribution of sea-level rise

Why does sea level change?

Total sea level change = Mass (water exchange) + Volume change (thermal expansion)

In the IPCC reports GLOBAL SEA LEVEL RISE over the past 40 years (1961-2003) was greater than what would be expected from the SUM of the WATER EXCHANGE BETWEEN OCEAN AND OTHER RESERVOIRS (ice sheets, mountain glaciers, small ice caps, land) and THERMAL EXPANSION?

We have made significant progress in closing this balance.

Domínguez et al. 2008
**Improved Estimates of Global Ocean Heat Content**

(Knight et al. 2005)

Increased rate of warming from 1976/1977
Smaller amplitude of the 1970-1980s decadal signal
Smaller rate of warming for 1993-2003

*Domingues et al. 2008*

**Improved comparison with climate models**

(Knight et al. 2005)

Variability in models with volcanic forcing in good agreement with observations.
Simulated multi-decadal trends tend to underestimate observed warming
(50% smaller in the upper 100 m and 10% smaller in the upper 700 m).

*Domingues et al. 2008*

**Glacier melting contributes to sea-level rise**

(Imposing et al. 2005)

Evidence of a dynamic response of the West Antarctic Ice Sheet

*Lemke et al. 2007*

**The Greenland Ice Sheet is contributing to sea-level rise** (about 0.2 mm/yr for 1993-2003)

(Knight et al. 2005)

Increasing surface melt and a dynamic response of the ice sheet

*Lemke et al. 2007*

**The Antarctic Ice Sheet is contributing to sea-level rise** (about 0.2 mm/yr for 1993-2003)

(Zwally et al. 2005)

Evidence of a dynamic response of the West Antarctic Ice Sheet

*Lemke et al. 2008*

**The Multi-Decadal Sea Level Budget (1961-2003)**

(3-year running mean)

Sum of the trends are in better agreement with updated estimates of sea level.
Different decadal variability is an indication of the uncertainty in the estimates and the unknown variability of the cryospheric and deep ocean contributions.
Satellite altimeter and in situ estimates diverges (temporarily) after 1999.

*Domingues et al. 2008*
Sea-level rise will continue during the 21st Century


Sea level rising near the upper limit of the projections (i.e. about 90 cm rise by 2100)

From coastal observations
From satellite observations
Model projections

Ice-sheet stability a major concern

- Close to a threshold for Greenland melting!
  Surface melt is increasing. For sustained warming above about 3°C, it is likely that the Greenland ice sheet would eventually be eliminated.

- Dynamic instability could lead to faster collapse
  Bottom lubrication and ice shelf collapse

- Evidence for rates of SLR about 1.5 m/century in last interglacial

Sea-level rise and storm surge, tides and waves all affect coastal vulnerability


Sea-level rise increases the impacts of coastal storms

For Fremantle and Sydney, a 1 in 5 year event has already become a 1 in 2 year event during the 20th century.

By 2100, a 1 in 100 year event is likely to happen several times/year!

Extreme Sea Level Modelling – Combining tides and storm surges

Church et al. 2006, 2008
Impact of Corner Inlet work undertaken for Gippsland Coastal Board

- Study undertaken in 2006 estimated extreme sea levels associated with storm tide would increase by ~0.3 m by 2070 under a mid-range sea level rise scenario (~0.6 m under a high scenario by 2070)

Wave and storm surge regions

INTERANNUAL VARIABILITY from reanalysis (C-ERA-40: 1958-2001)

Beach Rotation (e.g., Narabeen Beach, Ranasinghe et al., 2004)

Exploratory work on coastal impacts

Sensitivity of near shore to changes in offshore conditions using wave models

(Hemer et al. 2008)

(Hemer et al. 2008)

(Hemer et al. 2008)
Coastal Megacities will be impacted

By 2100, tens of millions/year will have to respond to coastal flooding; Most vulnerable regions are South and South-East Asia; Africa; Caribbean; Indian and Pacific Islands.

Nicholls, Pers Comm. 2011

Bay of Bengal

Major Surges

1737 300,000 killed
1864 100,000
1876 100,000
1897 175,000
1970 300,000
1971 (tide plus 6m surge)
1991 140,000 (10 Million homeless)

And at least 23 surge events with over 10,000 killed since 1737

These considered lower limits as economic damage adds to eventual total

(Murty, Flather and Henry, 1986 Progress in Oceanography
Murty and Flather, 1994 Journal of Coastal Research)

Developed nations are also vulnerable

Today’s sea level unprecedented during modern civilisation

Sea level is currently tracking the upper limit of these projections

Range of (stable) sea level during development of modern society

20° C rise an order of magnitude larger than previous thousand years

35

Research needs - WCRP Workshop

- Observing sea-level change
- Ice sheet and glacier change and models
- Ocean warming and models
- The regional distribution
- Terrestrial water storage
- Land motion
- Extreme events

The Science Shows:

- Ongoing sea-level rise is virtually inevitable! It is an issue for: Now, the 21st C and the long term.
- Need to adapt
  - Inundation, coastal erosion, wet land loss, aquifer contamination
  - Extreme events – more frequent, more severe.
  - Least developed nations and the poor most at risk. Local and regional planning.
- Need to mitigate to avoid the most extreme scenarios
  - Without significant, urgent and sustained action, we could pass a threshold during the 21st C, committing the world to metres of sea-level rise! Urgent! Short term emission goals critical!
- Environmental refugees
  - Not “if” but “when, where and how will we respond?”
- To minimise costs need to reduce uncertainty
  - Observing, understanding and modelling the oceans and the ice sheets are key!
  - Need to implement/improve early warning systems
- Essential and urgent that science/government/business/community partnerships are strengthened!
Need to understand coastal implications of offshore trends

Sea-level rise increases coastal flooding event frequency

For a 0.5 m sea-level rise, a current 1 in 100 year event is likely to happen several times/year!

Church et al., 2006

The frequency of flooding events has already increased

A 1 in 5 year event becomes a 1 in 2 year event.

For a 0.5 m rise, a 1 in 100 year event could happen several times/year!

Church and White, 2006

The distribution of available sea-level data changes with time

Hunter 2007
An average of the Australian Records

To overcome decadal variability in trends long records are essential. (Note this is relative sea-level rise.)

Church et al. 2006

Ice Sheet Instability II
Greenland and WAIS

• Loss of ice shelves
  Rapid propagation up the ice stream; Antarctic Peninsular and Greenland.

• Penetration of ocean water under the ice
  West Antarctic Ice Sheet and some outlet glaciers in Greenland.

Proxy sea-level records from salt marshes

Can now included wave setup in storm surge models

OSTM - Ocean Surface Topography Mission

Exploring two decades of change in ocean climate
A Global Hydrosphere Mapper

A SAR interferometry radar altimeter
Near-global coverage with 16-day repeat orbit

- Same technique as SRTM – radar interferometry
- Use of SAR to enhance the spatial resolution
- 1 cm measurement precision at 1 km resolution, superb for mapping ocean eddies

History of Satellite Altimeter Accuracy

100 fold improvement in 25 years

Measurement Performance

Christmas Tide Gauge vs. T/P Altimeter

rms = 2.0 cm

Extension of modelling to other mid-latitude coastlines

- E.g. NSW
- North Tasmanian coast

1 in 100 year storm surge
1 in 100 year storm tide

Portland
In the present case, we have applied the precautionary principle. We consider that increases in the severity of storm events coupled with rising temperatures beyond the historical record that planners and others rely on in making decisions will result in more extreme weather conditions. What is the extent of sea-level rise? There is an acknowledged level of uncertainty as to what the conditions will be like and the time period over which climate shifts may occur.

**VCAT decision**

**Conclusion about sea level rise**

1. We conclude that sea-level rise and risk of coastal inundation are relevant matters to consider in appropriate circumstances. We accept the general consensus that some level of climate change will result in extreme weather conditions beyond the historical record that planners and others rely on in making decisions.

2. The relevance of climate change to the planning decision making process is still in an evolutionary phase. Each case concerning the possible impacts of climate change will turn on its own facts and circumstances.

3. Is it Dangerous?

**Key Impacts in the Coastal Zone**

- Sea-level variability
  - inundation
  - storm surges, waves
  - coastal erosion
  - impacts on agriculture and marine ecosystems
  - impacts on terrestrial ecosystems

**Recent VCAT Planning Decision**

- Gippsland Coastal Board vs South Gippsland Shire Council
- Issue of planning permits overturned for the development of 6 blocks of land near Toora north of Corner Inlet in Victoria

What is the extent of sea-level rise?

1. We do not have the benefit of expert evidence other than the CSIRO reports. These reports set out a number of factors which may influence sea-level rise in storm surges, erosion of the coastline and inundation of the subject land. The August 2006 study reports that:

   - Climate change forecasts indicate a possible decrease in the number of storm events, but an increase in their intensity and hence rainfall and other extreme weather conditions. There is an expectation that storm events will be more severe.

   - There is an acknowledged level of uncertainty as to what the conditions will be like and the time period over which climate shifts may occur.
The interannual variability is correlated with climate EF C-ERA40 components vs SOI (All monthly means)

Bounded regions indicate significant correlation at 95% confidence level.

Hemer et al. 2008

INTERANNUAL VARIABILITY

\[ S(z) = 2.22 \times 10^4 \]
\[ S(|z|) = 2.10 \times 10^4 \]
\[ S(\text{dir}) = 0.06 \]

\[ S(z) = 1.36 \times 10^4 \]
\[ S(|z|) = 1.36 \times 10^4 \]
\[ S(\text{dir}) = 0.03 \]

\[ \text{EF}_{\text{C-ERA40}} \]

The interannual variability is correlated with climate components vs SOI (All monthly means).

Bounded regions indicate significant correlation at 95% confidence level.

Hemer et al. 2008

Exposure trends: Gold Coast

Year = 1966
Population = 40,000

A few years ago
Population > 500,000

Source: Prof Rodger Tomlinson,
Climate Change and Coastal
Erosion, June 2005