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

www.cawcr.gov.au

John Church

17th NSW Coastal Conference
Wollongong, NSW
5 November 2008

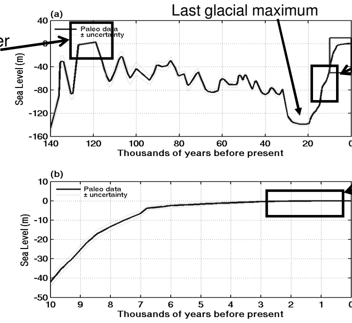
Australian Government
Bureau of Meteorology

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

CSIRO

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

- Sea level higher than today,
- rates of rise about 1.5 m/century
- At temperature similar to what we expect by 2100



- Rates of rise up to 4 m/century
- Our coastal society developed in a time of stable sea level

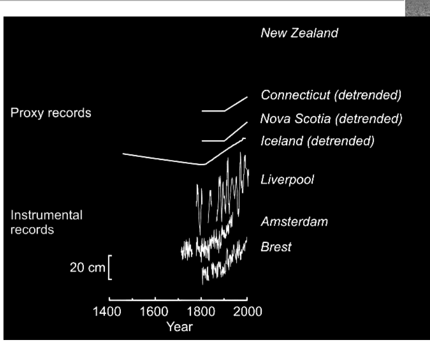
Church et al. 2008

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

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

Gerhels et al. 2008

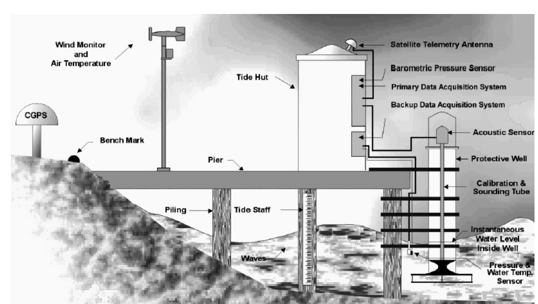
Salt march records indicate an acceleration in the rate of sea-level rise



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

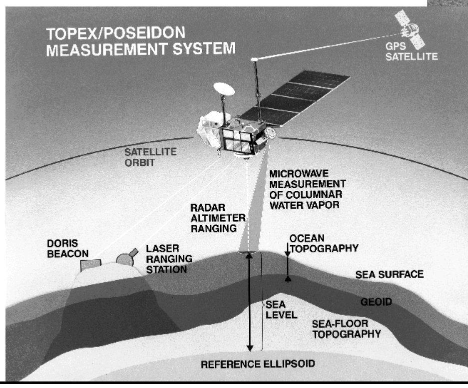
Gerhels et al. 2008

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

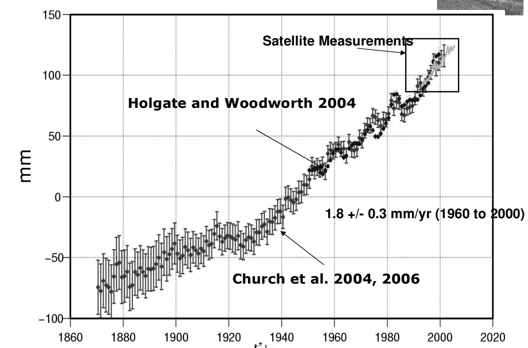


National Tidal Centre

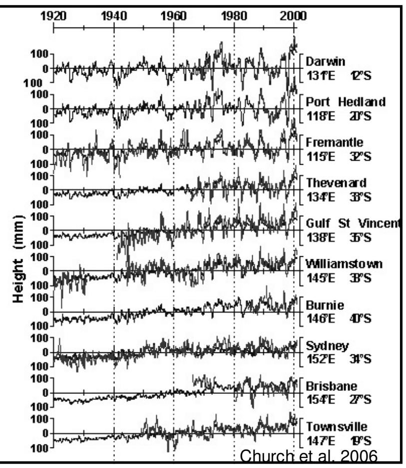
Satellite altimeters measure global sea levels



Sea-level rise accelerated during the 20th century



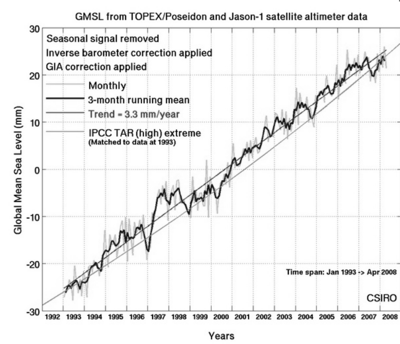
Sea level has been rising around the Australian continent



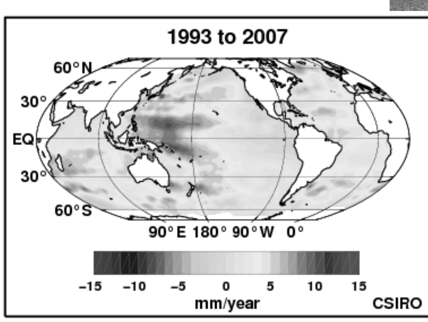
Church et al. 2006

Church et al. 2008

Sea levels are currently rising at over 3 mm/yr



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)

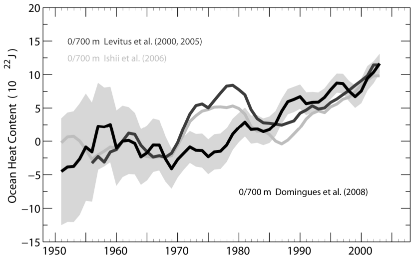
In the IPCC reports GLOBAL SEA LEVEL RISE **over the past 40 years (1961-2003) was greater than what would be expected from the SUM of the** WATER EXCHANGE BETWEEN OCEAN AND OTHER RESERVOIRS **(ice sheets, mountain glaciers, small ice caps, land) and** THERMAL EXPANSION**?**

We have made significant progress in closing this balance.

Domingues et al. 2008

Improved Estimates of Global Ocean Heat Content

(3-year running mean)



Levitus et al.
Ishii et al.
Domingues et al.

Smaller amplitude of the 1970-1980s decadal signal

Increased rate of warming from 1976/1977

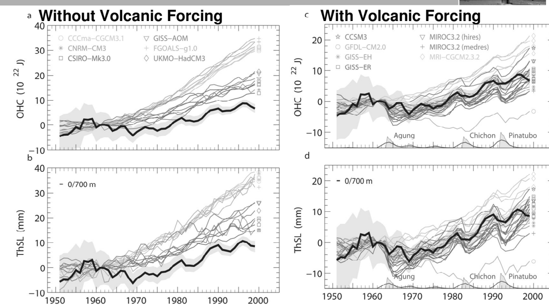
Smaller rate of warming for 1993-2003

Domingues et al. 2008

Australian Government Bureau of Meteorology

CSIRO

Improved comparison with climate models



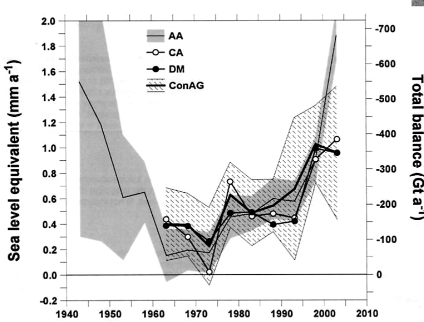
Variability in models with volcanic forcing in good agreement with observations.
Simulated multi-decadal trends tend to underestimate observed warming
(30% smaller in the upper 300 m and 10% smaller in the upper 700 m).

Domingues et al. 2008

Australian Government Bureau of Meteorology

CSIRO

Glacier melting contributes to sea-level rise



Kaser et al. 2005

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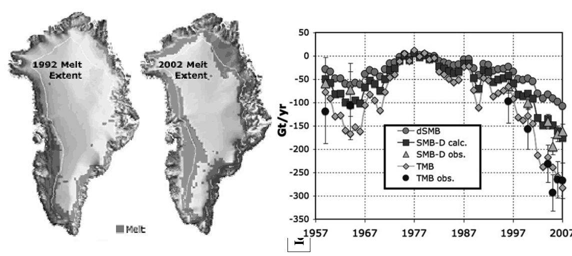
The Greenland Ice Sheet is contributing to sea-level rise (about 0.2 mm/yr for 1993-2003)



Increasing surface melt and a dynamic response of the ice sheet

Lemke et al. 2007 Rignot et al. 2008

Australian Government Bureau of Meteorology

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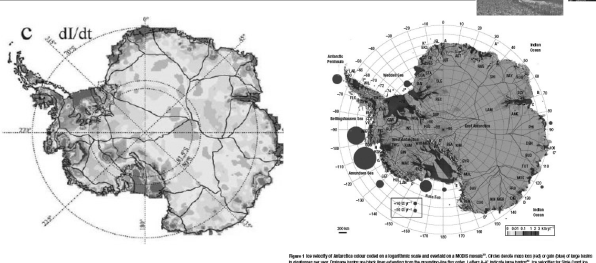
The Antarctic Ice Sheet is contributing to sea-level rise (about 0.2 mm/yr for 1993-2003)



Zwally et al. 2005

Evidence of a dynamic response of the West Antarctic Ice Sheet

Lemke et al. 2008 Rignot et al. 2008

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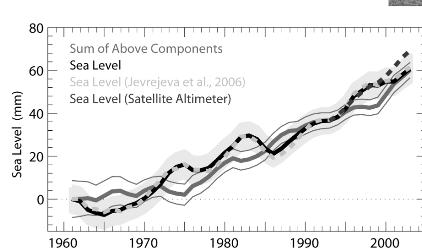
The Multi-Decadal Sea Level Budget (1961-2003)

(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

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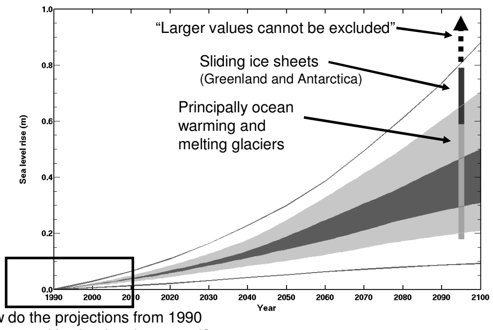
Sea-level rise will continue during the 21st Century



How do the projections from 1990 compare with what has happened?

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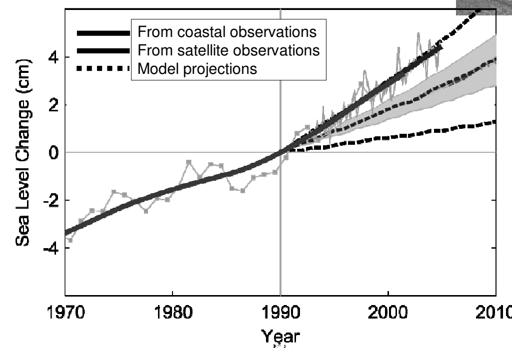
IPCC 2001; IPCC 2007

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



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Rahmstorf et al. 2007

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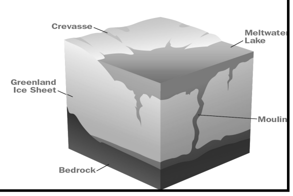
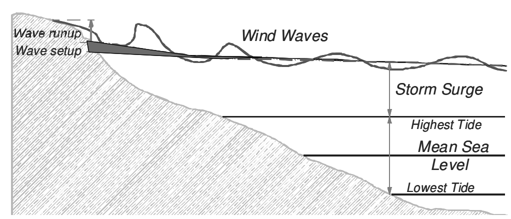
Ice-sheet stability a major concern

- **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



K. L. McInnes et al. *Impact of Sea-level Rise and Storm Surges on a Coastal Community*, Natural Hazards 30: 187–207, 2003

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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!

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Church et al. 2006, 2008

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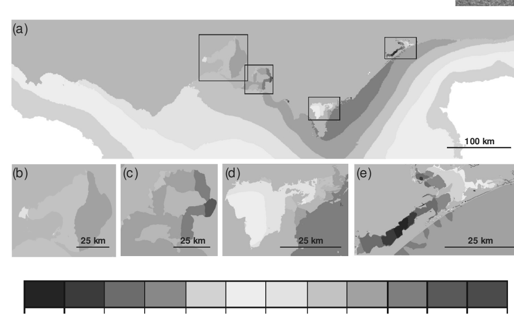
Extreme Sea Level Modelling – Combining tides and storm surges



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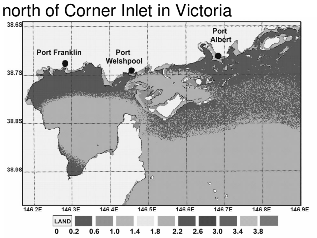
Impact of Corner Inlet work undertaken for Gippsland Coastal Board

- 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



- 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)

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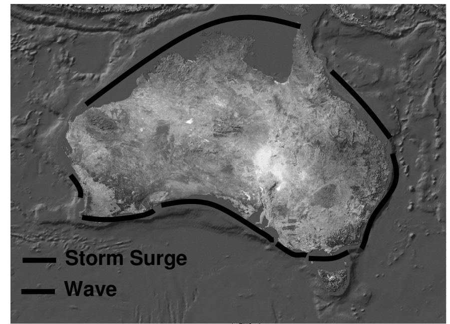
McInnes 2008

Wave and storm surge regions



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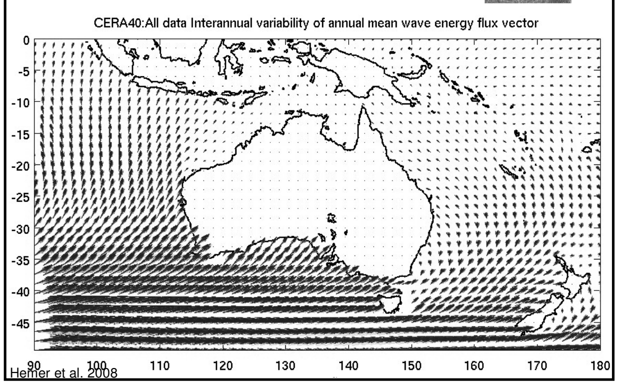
McInnes 2008

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



Hemer et al. 2008

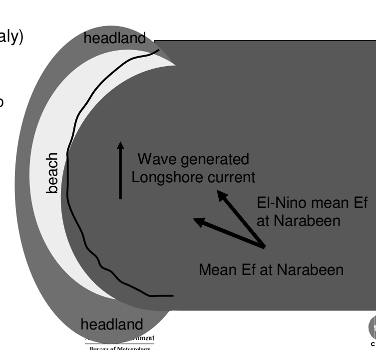
Beach Rotation
(e.g., Narabeen Beach, Ranasinghe et al., 2004)

"El-Nino" conditions (negative SOI anomaly)

Efu and Efv display Negative correlation to SOI.

Therefore,

El-Nino leads to Positive anomalies of Efu and Efv.



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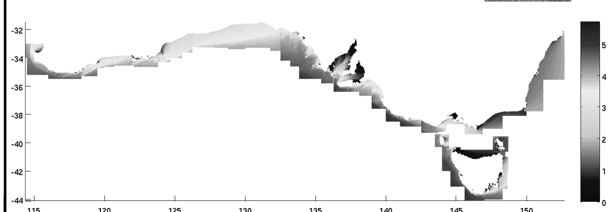
Exploratory work on coastal impacts

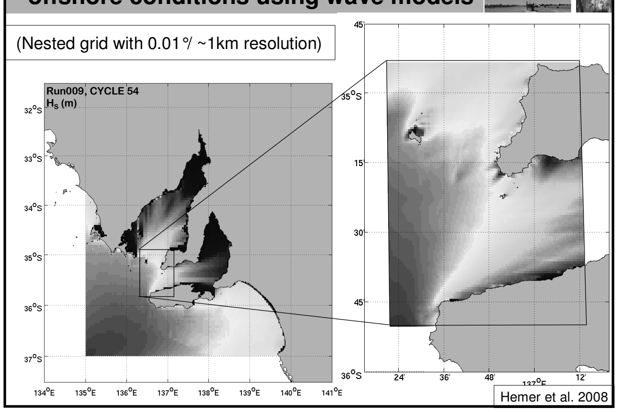


Significant wave height (m)

Hemer et al. 2008

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

(Nested grid with 0.01°/ ~1km resolution)

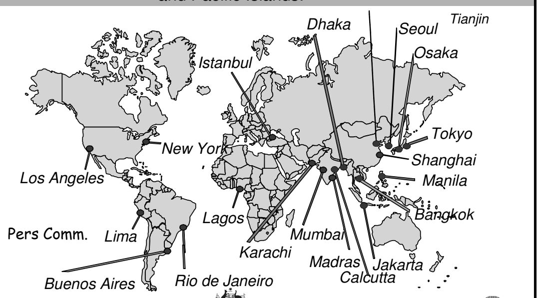


Hemer et al. 2008

Coastal Megacities will be impacted

(sea-level rise and land sinking)

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



Nicholls, Pers Comm.

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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)

Lowe et al. 2008

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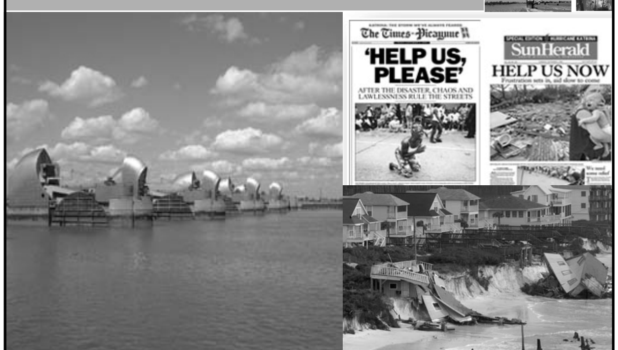
Developed nations are also vulnerable



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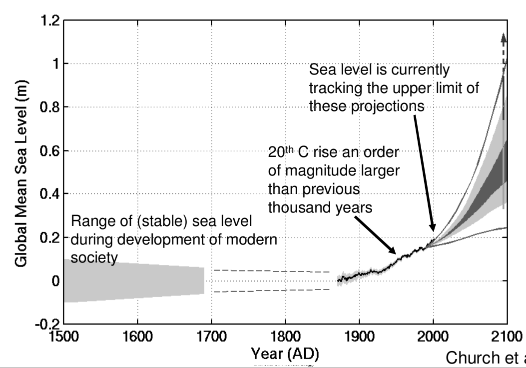
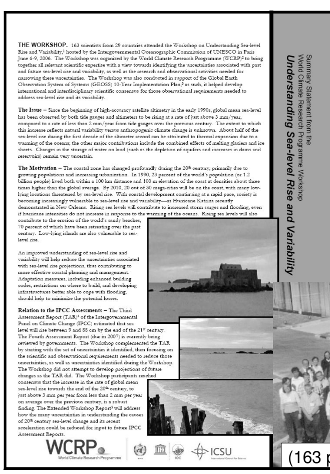
Today's sea level unprecedented during modern civilisation



Church et al. 2008



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

(163 participants, 29 nations)

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!**

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

CSIRO

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Thank you

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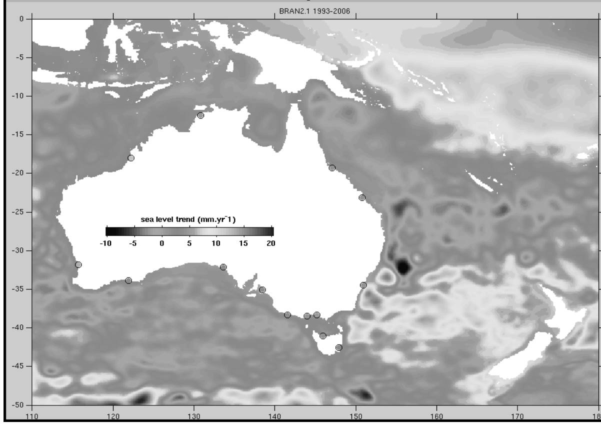
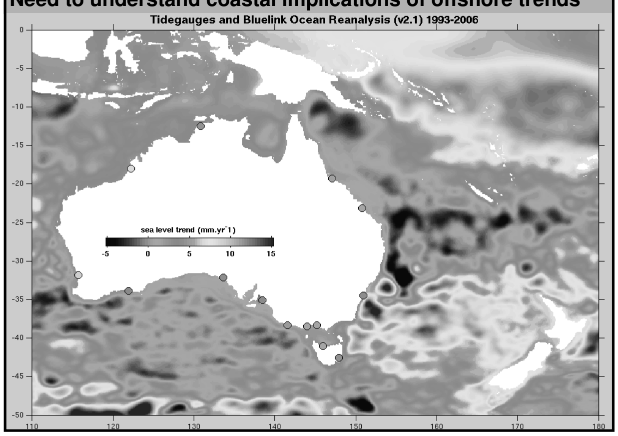
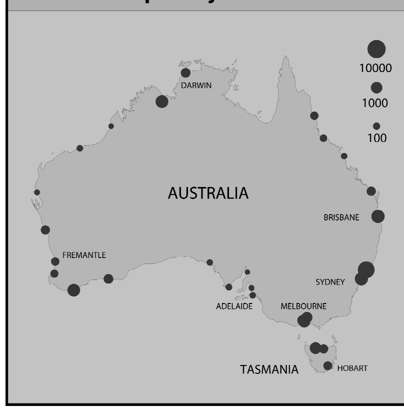
Need to understand coastal implications of offshore trends



Need to understand coastal implications of offshore trends



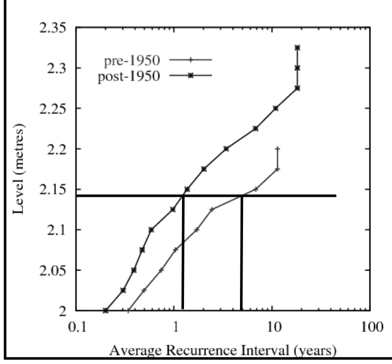
Sea-level rise increases coastal flooding event frequency



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

Hunter 2007

The frequency of flooding events has already increased

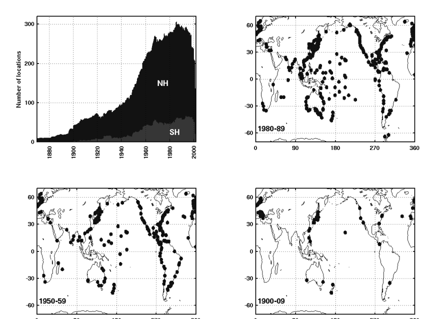


A 1 in 5 year event becomes a 1 in 2 year event.

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

Church et al., 2006

The distribution of available sea-level data changes with time



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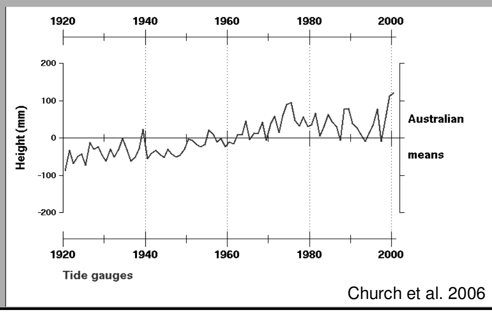
Church and White, 2006

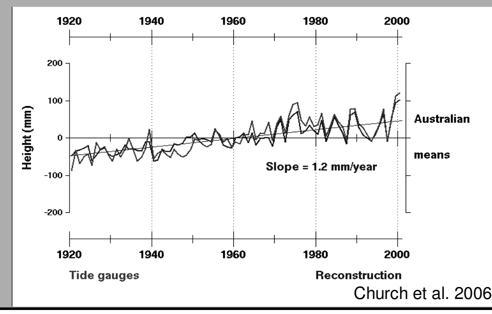
An average of the Australian Records



Church et al. 2006

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.

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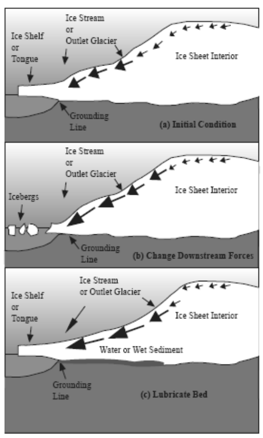
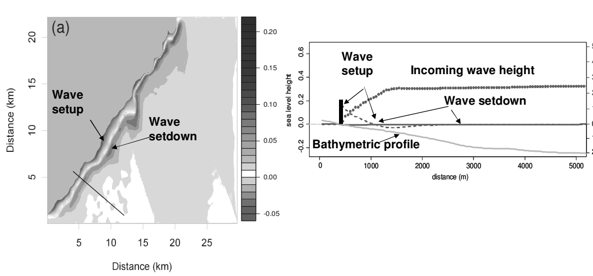


Proxy sea-level records from salt marshes

Can now included wave setup in storm surge models



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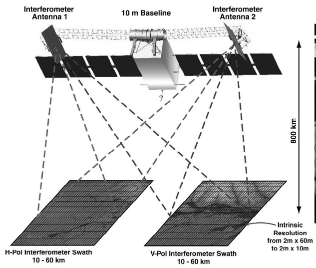
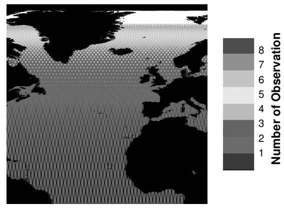
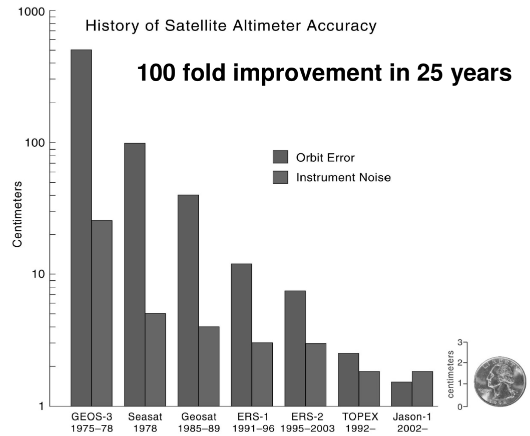
A Global Hydrosphere Mapper

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

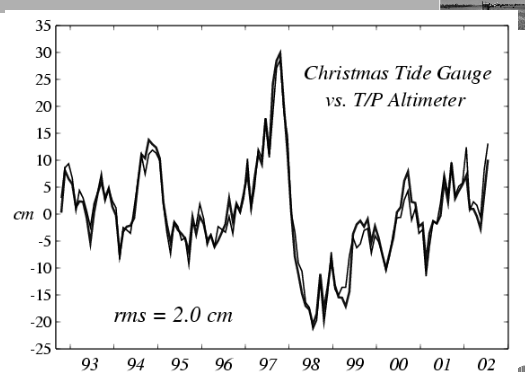




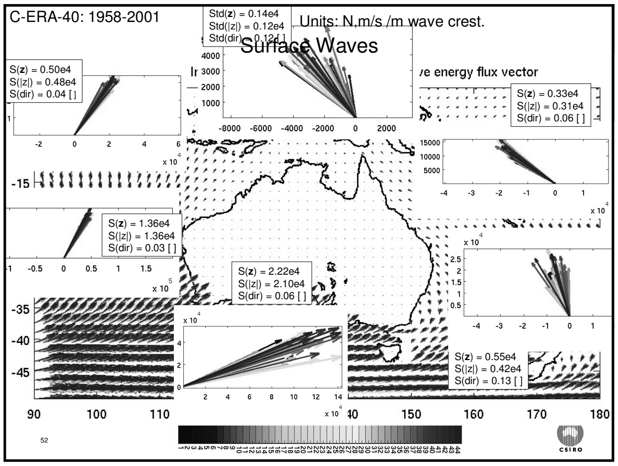
- **Same technique as SRTM – radar interferometry**
- **Use of SAR to enhance the spatial resolution**
- **1 cm measurement precision at 1 km resolution, superb for mapping ocean eddies**



Measurement Performance



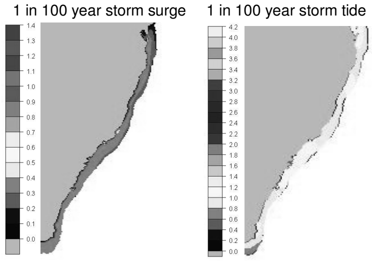
R. Cheney/NOAA



Extension of modelling to other mid-latitude coastlines

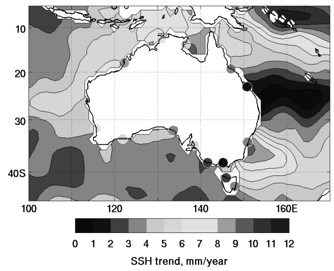
- E.g. NSW
- North Tasmanian coast

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

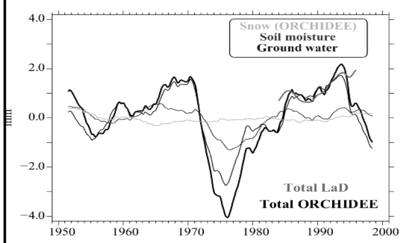


Portland

Contours: Satellite altimeter data, Jan 1993 -> Dec 2007
Dots: NTC tide gauges, early 1990s -> Dec 2007
Corrected for GIA Not corrected for Inverse Barometer effect



Land water storage effects global sea level



Milly, P. C., D., A. Cazenave, and M. C. Gennero (Proc. Natl Acad. Sci, 2003)

Ngo-duc T., K. Laval, J. Polcher, A. Lombard and A. Cazenave (GRL, 2005)

- greatest variation is associated with ground water, followed by soil moisture
- no significant trend was detected
- strong decadal variability driven by precipitation, strong decrease in the beginning of 1970s
  - agreement between ORCHIDEE and LaD. *(Land Dynamics LSM of GFDL)*

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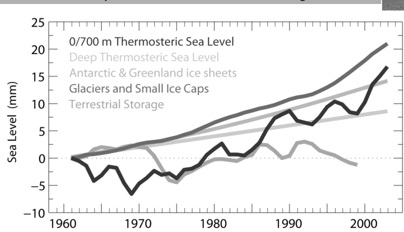
Components of the Sea-level budget



Deep ocean **(Antonov et al., GRL, 2005; Kohl et al., JPO, 2007).**
Ice sheets **(linearly increases towards the 1990s estimates, as compiled in Lemke et al., IPCC, 2007)**
Glacier and small-ice caps **(Dyurgerov and Meier, 2004).**
Terrestrial storage **(Ngo-Duc et al., GRL, 2005).**

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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 rises 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.
- [redacted]
- 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.

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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 assessing future potential impact.

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 [redacted]

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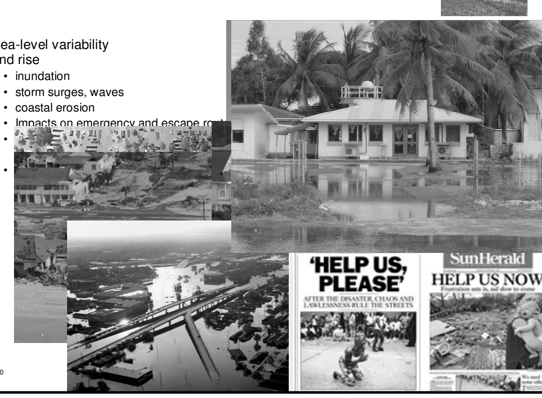
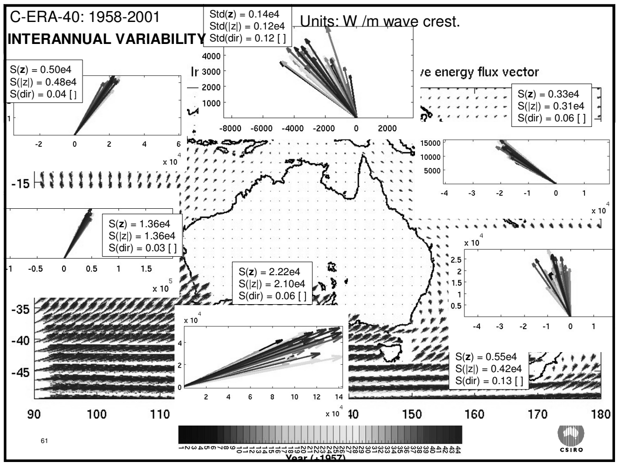
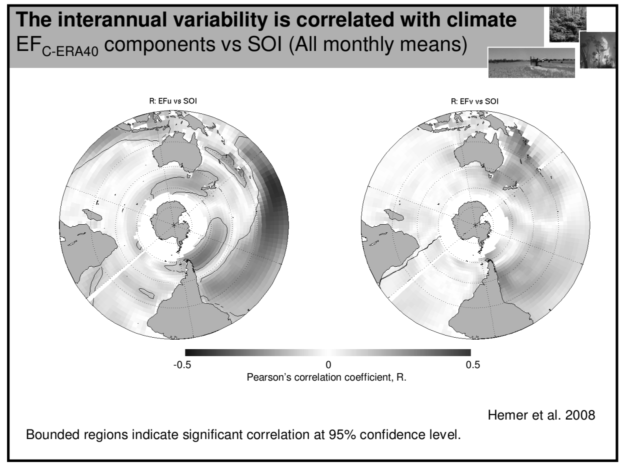
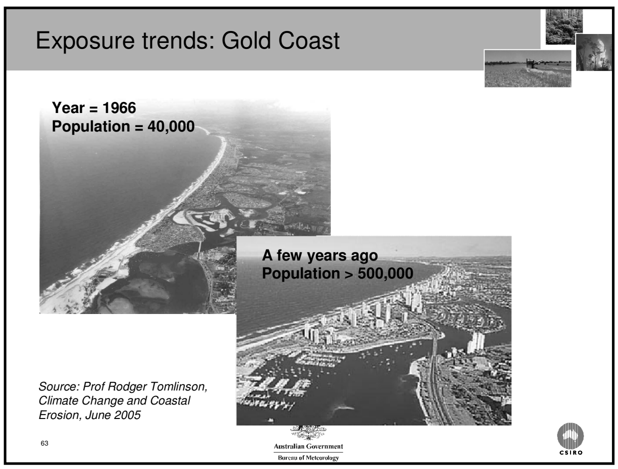
Is it Dangerous?
Key Impacts in the Coastal Zone

- Sea-level variability and rise
  - inundation
  - storm surges, waves
  - coastal erosion
  - Impacts on emergency and escape ro




C-ERA-40: 1958-2001
INTERANNUAL VARIABILITY
Units: W /m wave crest.
Std(z) = 0.14e4
Std(|z|) = 0.12e4
Std(dir) = 0.12 [ ]
S(z) = 0.50e4
S(|z|) = 0.48e4
S(dir) = 0.04 [ ]
S(z) = 0.33e4
S(|z|) = 0.31e4
S(dir) = 0.06 [ ]
S(z) = 1.36e4
S(|z|) = 1.36e4
S(dir) = 0.03 [ ]
S(z) = 2.22e4
S(|z|) = 2.10e4
S(dir) = 0.06 [ ]
S(z) = 0.55e4
S(|z|) = 0.42e4
S(dir) = 0.13 [ ]
90
100
110
150
160
170
180
-15
-35
-40
-45
61


The interannual variability is correlated with climate
EF C-ERA40 components vs SOI (All monthly means)
R: EFu vs SOI
R: EFv vs SOI
-0.5
0
0.5
Pearson's correlation coefficient, R.
Hemer et al. 2008
Bounded regions indicate significant correlation at 95% confidence level.


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
63
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