



A Snapshot of Future Sea Levels: Photographing the King Tide

12 January 2009

Department of
Environment, Climate Change and Water NSW



Front cover, left:

SYDNEY, BOTANY BAY

Tidal waters penetrating back up through the stormwater system, 15 December 2008.

Photo: Warwick O'Brien.

Top right:

SYDNEY, BONDI BEACH

Waves breaking over the ocean baths at the southern end of the beach, 12 January 2009.

Photo: Dennis Gray.

Bottom right:

NEWCASTLE, CARRINGTON

Tidal waters of the Hunter River submerging residential streets, 14 December 2008.

Photo: Bruce Coates.

Acknowledgments

DECCW would like to acknowledge the contributions from all photographers who kindly donated their time to capture images of the peak of the high tide in their local areas.

DECCW would also like to acknowledge the vision and dedication of Phil Watson (Team Leader, Coastal Unit) who made this initiative and report possible. Similarly, Ainslie Frazer (Senior Natural Resource Officer, Coastal Unit) has been responsible for the monumental task of collating and coordinating the thousands of images received.

DECCW would also like to acknowledge the contributions of the many parties that made it possible to coordinate the project, acquire the data and prepare the report, including:

Dr John Church (Chief Research Scientist, Marine and Atmospheric Research, CSIRO)

Dr Kathleen McInnes (Principal Research Scientist, Centre for Australian Weather and Climate Research: a partnership between CSIRO and the Bureau of Meteorology)

Dr Bill Mitchell (Director, National Tidal Centre, Bureau of Meteorology)

Sarah Hesse (Manly Hydraulics Laboratory, Department of Commerce)

Matthew Smith (Manly Hydraulics Laboratory, Department of Commerce)

Gary Batman (Sydney Ports Corporation)

Tony Nusco (Sydney Ports Corporation)

Geoff Withycombe (Sydney Coastal Councils Group)

Chris Tola (Coastalwatch)

© DECCW 2009

This report has been prepared by the Coastal Unit, Department of Environment, Climate Change and Water NSW (DECCW) to summarise the state-wide photographic event which captured impacts of the king tide on 12 January 2009. The report is not to be reproduced in part or whole by third parties without the permission of DECCW.

The Department of Environment, Climate Change and Water NSW has prepared this publication with all due care and attention, but we don't guarantee its accuracy or its application to any particular circumstances. Users of this publication should, as necessary, seek expert advice before applying this information to particular circumstances.

Suggested citation: Watson PJ and Frazer A (2009), *A Snapshot of Future Sea Levels: Photographing the King Tide 12 January 2009*, Department of Environment, Climate Change and Water NSW, November 2009.

Published by:

Department of Environment, Climate Change and Water NSW
59–61 Goulburn Street; PO Box A290 Sydney South 1232

Phone: (02) 9995 5000 (switchboard)

Phone: 131 555 (environment information and publications requests)

Phone: 1300 361 967 (national parks information and publications requests)

Fax: (02) 9995 5999

TTY: (02) 9211 4723

Email: info@environment.nsw.gov.au

Website: www.environment.nsw.gov.au

ISBN 978 1 74232 472 2

DECCW 2009/722

November 2009

Printed on recycled paper

Contents

Foreword: Protecting our coast	1
Summary: About this report	2
Photographing the king tide	2
Ocean water levels and tides	4
What happened on 12 January 2009?	8
How climate change is affecting sea level	10
Impacts highlighted by the photos	18
Implications for photographing future king tides	20
Conclusions	22
What happened on 13 and 14 December 2008?	24
Appendix 1: Synoptic charts	26
References	28

Abbreviations

AHD	Australian height datum – national standard survey datum which approximates mean sea level
CSIRO	Australian Commonwealth Scientific and Industrial Research Organisation
DECCW	Department of Environment, Climate Change and Water NSW
EDT	eastern daylight time (equivalent to eastern standard time)
EST	eastern standard time (equivalent to eastern daylight time)
IPCC	Intergovernmental Panel on Climate Change
TGZ	Tide gauge zero at Fort Denison. The zero on the gauge is approximately 925 mm below AHD.

Foreword: Protecting our coast

The interface between tidal waters and the land holds a very special place within our culture. While supporting most of our population, the coastal zone is dealing with increasing development, tourism and resource use as well as the effects of natural physical processes and climate change.

Clearly we need to take great care in managing the interrelated environmental, social, economic and planning issues within the coastal zone, particularly in response to one of the major threats: sea level rise. In this regard, the photographic event during the January 2009 king tides proved a very successful community effort in gathering a state-wide snapshot of areas currently vulnerable to tidal inundation and raising public awareness about rising sea level.

The enthusiastic response from the community, environmental groups, and local and state government agencies deserves recognition. More than 250 people joined in photographing the foreshores around the peak of the king tide along the State's intertidal margins.

As a national first, the Department of Environment, Climate Change and Water (DECCW) has since fielded many enquiries seeking to expand the program around the country in 2010. Given the success of this as a public awareness campaign, there may be substantial benefits in capturing this valuable data regularly on a national basis.

DECCW is now involved in developing a NSW Climate Change Action Plan. Over the coming years, this Action Plan will provide a blueprint for NSW's response. By giving an insight into the effects of sea level rise, this photographic event highlights the need for us all to take action.

We need the community and all spheres of government to work together to meet the challenges posed by sea level rise. I would like to thank the DECCW Coastal Unit for its leadership in developing this innovative project. This report will undoubtedly be a valuable source of information for coastal zone managers and the broader community alike.

Lisa Corbyn

Director General

Summary: About this report

The summer king tide event forecast for 12 January was the largest predicted tide for 2009 that would be visible during daylight hours. This presented a wonderful opportunity to engage the community in photographing the peak of the king tide along the whole NSW coastline, with two primary objectives in mind:

- identifying areas vulnerable to tidal inundation, capturing the tide level against revetments, seawalls, jetties and other marine infrastructure; and
- raising awareness throughout the wider community about the current projections for sea level rise to the end of the century (approximately 90 cm).

This photographic event proved successful in engaging over 250 people to capture over 4,000 images providing a broad, state-wide snapshot of areas and assets currently vulnerable to the threat of tidal inundation.

The strongest message for the community is that all tide levels reached could well be 90 cm deeper by the end of the century. Alternatively, rare ('king') tide water levels in 2009 are likely to be relatively common water levels by 2100.

This report presents a selection of the photographs taken around the peak of the king tide on 12 January 2009, and some images from the very high spring tide that occurred in December 2008. It presents a summary of the information gleaned from the photographic event, along with general technical information about tides and the current status of information on climate change and rising sea levels.

Photographing the king tide

The idea of photographing the impacts of the January 2009 king tide was initially canvassed only six weeks before the event. We thought we might be successful in covering some high priority sites. However, the enthusiasm of the NSW coastal community rapidly turned the exercise into a state-wide initiative.

More than 250 photographers captured over 4,000 images during the peak of the high tide, covering areas along the open coast and within the estuarine margins of the state. The participants came from a wide cross-section of the community, including staff from NSW government agencies, local government authorities, catchment management authorities, Manly Hydraulics Laboratory, Water Research Laboratory, volunteers from the State Emergency Service, local environmental groups, beachfront and waterfront property owners and a large contingent of the broader community.

The NSW Department of Lands arranged for aerial photography around the high tide at selected locations to augment the on-ground coverage. In addition, the Department of Environment, Climate Change and Water NSW (DECCW) was given access to beach imagery from the monitoring network of Coastalwatch cameras to assist with this unique state-wide photographic exercise. Not surprisingly there was a heavy concentration of photographic coverage in the Sydney Harbour basin, but the state-wide coverage of known vulnerable areas was also significant. (See map of the coverage, opposite.)

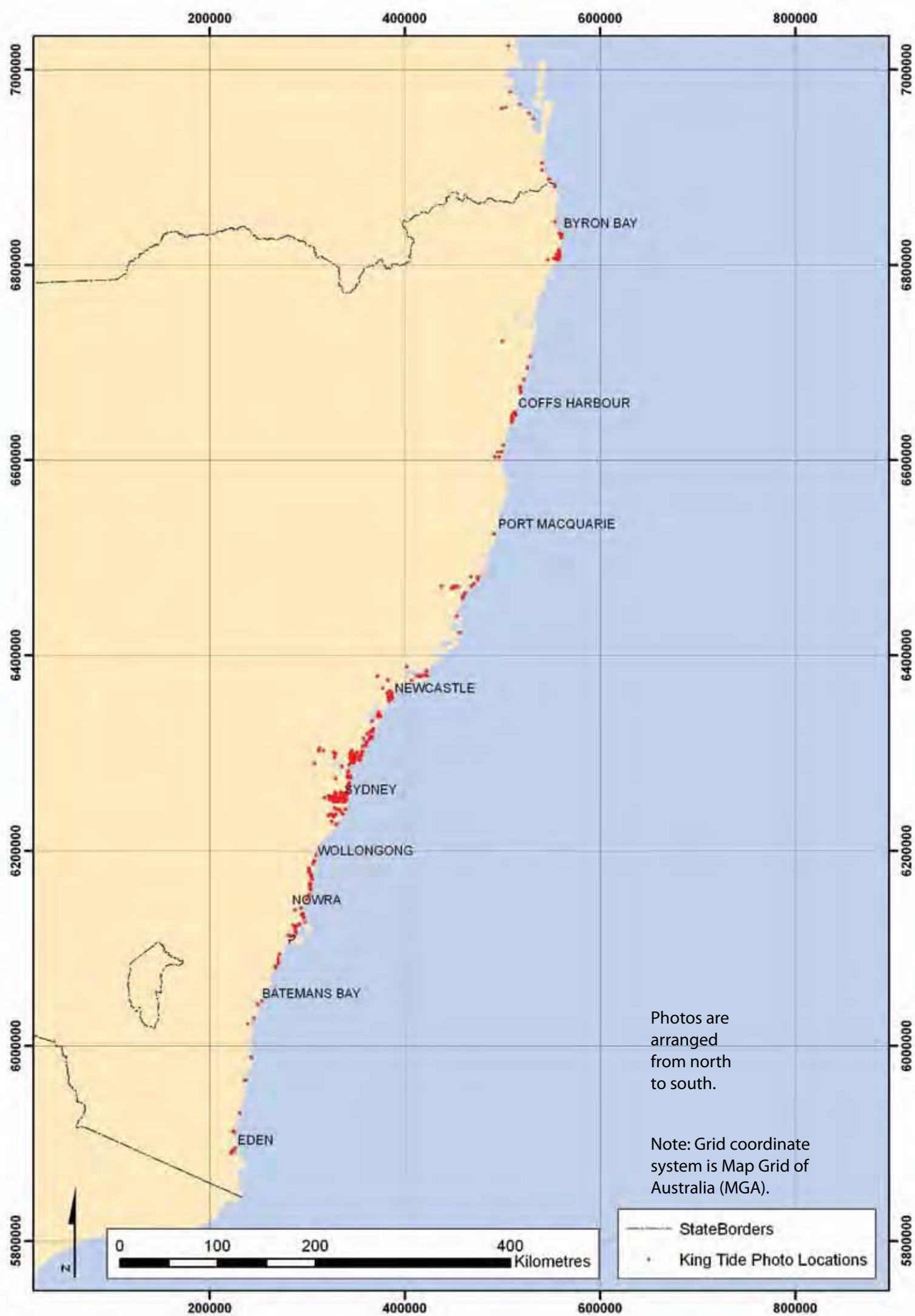
COFFS HARBOUR JETTY

Tidal waters of Coffs Creek penetrating back up through the stormwater system, 12 January 2009.

Photo: Mel Bradbury, NSW Department of Primary Industries.



Photographic coverage of the NSW coastline, 12 January 2009



Ocean water levels and tides

Ocean water levels are continually being influenced by three interacting systems:

- the prevailing weather (e.g. winds, barometric pressure, El Niño and La Niña episodes), and
- oceanic processes (e.g. waves and currents), superimposed on
- the prevailing astronomical tide.

During extreme ocean storms, the combined influences of weather systems, waves and tides have resulted in wave run-up on exposed ocean beaches measured as high as 7 metres above mean sea level at isolated locations. Inside estuaries, where ocean wave penetration is limited, the water levels are comparatively lower, governed generally by weather conditions, local wind-driven waves and the prevailing tide.

We need to understand the contributions of each of these components (particularly during extreme ocean storms) so we can assess probable inundation levels when designing, planning and managing the coastal environment.

There is another force at work here as well. We know beyond doubt that ocean water levels are rising due to climate change. The rare ('king') tide water levels we experience in 2009 are likely to be relatively common water levels by 2100. This is discussed under 'How climate change is affecting sea level'.

The influence of the Sun and Moon

The regular and predictable changes in the ocean level that we refer to as **astronomical tides** are due to the combined influences of the Sun and the Moon and their position relative to the Earth at a given point in time.

Photos of the 2009 king tide

12 January 2009

The water level you see in these images of the 2009 king tide is currently exceeded for only about 22 hours per year (based on long-term data from Fort Denison, Sydney Harbour). However, by the end of the century, assuming sea level will rise by 90 cm, these depicted water levels could be reached or exceeded for approximately 39% of the time, which is equivalent to almost 4.7 months a year.

Similarly, these photos show the impacts of tidal water levels which are projected to be up to 90 cm deeper by 2100.

1 & 2: TWEED HEADS, UKERABAH HISTORIC SITE

Boardwalk submerged.

Photos: Lance Tarvey, DECCW.



The tide is, in effect, a very long and slow-moving wave governed by the complex range of gravitational forces applied by the Moon and Sun which are also modified by the motion of the Earth. The Moon, with a gravitational influence almost twice that of the Sun, is the primary factor controlling the temporal rhythm and height of the tide.

The NSW coast experiences two high and two low tides daily. A tidal cycle (high-low-high or low-high-low) takes approximately 12 hours and 25 minutes. A tidal day therefore is approximately 24 hours and 50 minutes. The reason the tidal day is longer than 24 hours is that the Moon orbits the Earth in the same direction that the Earth spins, and while the Earth takes 24 hours to complete a full rotation, the Moon has moved slightly along its orbit. Thus the Earth has to spin a little further (for 50 minutes) before the same location on the Earth faces the Moon again. For this reason, the same tidal phase (e.g. peak high tide) occurs 50 minutes later each day (MetEd 2006).

Spring tides occur every 14.5 days

So-called 'spring' tides occur throughout the year at regular intervals. When talking about tides, the term 'spring' simply refers to the larger range of tides. The 'spring' tidal range occurs every 14.5 days when the Moon is either full or new and results from the Sun, Earth and Moon falling into alignment, therefore combining their gravitational attractions on the ocean water surface.

'King' tides are the highest 'spring' tides – occurring twice a year

The term 'king' tide is a common term with no particular scientific meaning. It has been coined to describe the highest 'spring' tide. While spring tides occur every 14.5 days, on the full or new phases of the Moon, orbits of the Moon around the Earth and the Earth around the Sun result in distinct variations to the spring tide range.

3: NORTH OCEAN SHORES

Sea water backing up through the stormwater system.

Photo: Brett Miller, Water Research Laboratory.



4: NEAR BRUNSWICK HEADS, FORESHORE OF THE BRUNSWICK RIVER

Water level allowing only limited clearance for a bike track under the Pacific Highway.

Photo: Brett Miller, Water Research Laboratory.



The Moon has a slightly elliptical orbit around the Earth and therefore is closer to the Earth at certain times, increasing its gravitational attraction on the ocean water surface as a result. Similarly, the Earth follows an elliptical orbit around the Sun, being closer during the summer and farthest away during winter, creating distinct seasonal variations in the gravitational pull on the ocean surface.

As a result, in the southern hemisphere the spring tide ranges peak during December, January and February and also during June, July and August. Due to the combined influences of the respective gravitational contributions, the highest spring tide occurring on the new or full moon during these seasons is colloquially termed the 'king' tide.

During the summer months the high spring tides occur during daylight hours and during the winter months the high spring tides occur at night. In NSW, the peak spring tide (or 'king' tide) is usually higher than 2 m above tide gauge zero (TGZ) at Fort Denison in Sydney Harbour.

(This translates to higher than 1.08 m AHD. TGZ is approximately 0.925 m below AHD.)

How we predict tide levels

Tidal predictions are calculated at over 90 locations around Australia by the National Tidal Centre (Bureau of Meteorology). By analysing the water levels observed over a sufficiently long time period we can isolate the contributions made by the Sun, Earth and Moon. The contributions from each particular process or gravitational interaction are known as **tidal constituents**, and each particular location on the planet has site-specific tidal constituents including:

- gravitational and centrifugal forces caused by rotation of the Earth-Moon system
- the Sun's gravitational pull
- changes in the angle of the Earth-Moon-Sun plane

and numerous other and progressively weaker astronomical influences.

In all, the National Tidal Centre considers 114 tidal constituents (specific influences due mainly to the sun and moon) when predicting tides for a specific location.

5: BYRON BAY, BELONGIL BEACH

*Beach and public access at
Manfred Street submerged.*

*Photo: Ben Fitzgibbon,
Byron Shire Council.*



6: BYRON BAY CBD

*Beach submerged at Jonson
Street protection works.*

*Photo: Ben Fitzgibbon,
Byron Shire Council.*



However, tidal predictions are also based on an assumed atmospheric pressure at mean sea level. Local weather including atmospheric pressure systems (the highs and lows shown on weather report synoptic charts) can have a substantial impact on actual water levels. This means that ocean water levels (excluding wave impacts) could differ from the predicted tide level by as much as plus 60 cm or minus 20 cm.

The difference between measured water levels and tidal predictions

Although we can predict the astronomical influences on ocean water levels with great precision, other more local factors can also affect ocean water levels. The difference between the predicted tide and the measured ocean level is referred to as the **tidal anomaly**.

Typical processes and phenomena which can alter ocean water levels relative to the predicted tide include: atmospheric pressure, winds, waves, the El Niño Southern Oscillation (ENSO), ocean currents and temperatures, coastal trapped waves and harbour waves.

The tide gauge at Fort Denison in Sydney Harbour has been recording ocean water levels since 1866 and is the longest continuous record of ocean water levels in NSW. From these records we know that most tidal anomalies are between minus 10 cm and plus 20 cm. The largest tidal anomaly (from 1914 to 2009) was 59 cm recorded in May 1974 during the most significant ocean storm on the historical record.

7: LENNOX HEAD, SOUTHERN END OF SEVEN MILE BEACH

*Wave overtopping
the public walkway.*

Photo: Richard Hagley, DECCW.

8: BALLINA

*Wave overtopping the
breakwater structure
at the entrance to the
Richmond River.*

Photo: Warren Scanlon.

9: BALLINA, TAMAR STREET BUS INTERCHANGE

*Tidal waters of the
Richmond River penetrating
back up through the
stormwater system.*

Photo: Ballina Shire Council.

10: BALLINA, TAMAR STREET

*Tidal waters of the
Richmond River penetrating
back up through the
stormwater system.*

Photo: Ballina Shire Council.



What happened on 12 January 2009?

The peak of the 2009 summer king tide occurred at 0850 hours EST on 12 January. The peak water level was 9 cm lower than predicted, mainly due to a high pressure system over the majority of the NSW coast.

At 0850 hours EST the tide gauge at Fort Denison (Sydney Harbour) measured a peak water level of nearly 2 m above tide gauge zero (1.96 m above TGZ, translating to 1.035 m AHD). This peak was 0.09 m (9 cm) lower than the predicted peak of 2.05 m above TGZ.

Based on analysis of the long-term data from Fort Denison, on average we would expect to reach a water level of this measured peak (1.96 m) for approximately 22 hours per year.

One of the primary reasons the measured water level was lower than the predicted tide at most locations within the NSW ocean water level recording network was due to the influence of a large high pressure system dominating much of the NSW coastline at the time of the king tide (see Appendix 1: Synoptic charts) which had the effect of depressing coastal sea levels.

11: BALLINA, BALLINA QUAYS CANAL ESTATE

Limited clearance between tidal waters and floor levels.

Photo: Ballina Shire Council.



12: BALLINA CBD

Limited clearance between tidal waters and the foreshore along the Richmond River, close to an apartment complex.

Photo: Peter O'Keefe, Ballina Shire Council.





**13: BALLINA, BURNS
POINT FERRY ROAD**

*Tidal waters of the
Richmond River penetrating
back up through the
stormwater system.*

Photo: Ballina Shire Council.

14: WOOLI, RIVER STREET

*Tidal waters of the Wooli
Wooli River flooding the
rear of the Wooli Kiosk.*

Photo: Wayne Jubb.

**15: COFFS HARBOUR,
COFFS CREEK**

*Tidal waters lapping at
the ground-floor level of
commercial premises.*

*Photo: Martin Rose,
Coffs Harbour City Council.*

16: GORDON PARK

*Tidal waters of the Nambucca
River submerging a section of
the public walkway along the
foreshore.*

Photo: Nancy Zek.

**17: PORT MACQUARIE,
HASTINGS RIVER**

*Stormwater drainage canal
completely submerged.*

*Photo: Gordon Cameron,
Hastings Council.*



How climate change is affecting sea level

We know that one of the consequences of climate change is that mean sea level will be significantly higher than it is today. Inevitably this means that low-lying land and coastal areas, particularly land within the tidal zone, will change forever. The natural environment and the built environment will be dealing with:

- inundation by seawater
- higher tides and higher storm surges
- receding shorelines, and
- salt water intruding into freshwater environments.

The obvious questions are – how much, and when? Can we predict critical sea levels and dates, and how accurate are our predictions? What will the social, environmental and engineering consequences be?

Observing and recording king tides gives us an invaluable snapshot of future sea levels. We can see from these

graphic demonstrations of the impact of higher sea levels, and we know from studies, that existing infrastructure, facilities and development will be need to be upgraded, replaced or re-designed. For example:

- Existing gravity-controlled street drainage and stormwater systems that drain to the sea will become less capable over time.
- The boundaries of waterfront properties referenced to the mean high water mark will move successively landward over time, with the land becoming more vulnerable to inundation.
- Seawalls and other coastal defence systems will also have to be incrementally upgraded over time to address the increasing threat from larger storm surges and inundation at higher projected water levels.

(Watson and Lord 2008)

18: WALLABI POINT

Sea water overtopping the berm into Saltwater Lagoon.

Photo: Lisa Reddon and Kirsty Hughes, Mid North Coast Water.



19: DUNBOGAN FORESHORE RESERVE

Limited clearance between the Camden River and the reserve adjoining the roadway.

Photo: Peter Dorman.



What is causing sea level to rise?

There are several processes causing mean sea level to rise over time:

- Ocean temperatures are increasing overall, and as the water warms it expands, increasing its volume – this is the biggest component of sea level rise (about 60%).
- Glaciers, ice caps and ice sheets are melting and losing mass, and permafrost is thawing, causing runoff into the ocean.
- Sediments being deposited into the ocean are building up on the ocean floor; and
- The mass of water stored within the earth as fresh water is changing.

(IPCC 2001)

20: TEA GARDENS,
MYALL RIVER

Tidal waters lapping at the ground-floor level of a café.

Photo: Kevin Haskew.

22: NELSON BAY MARINA

Limited clearance to ground-floor levels.

Photo: NSW Department of Lands.

21. NEWCASTLE,
SHORTLAND ESPLANADE

Waves overtopping the seawall and foreshore pathways.

Photo: Kristy Munro, Newcastle City Council.



What is 'mean sea level'?

Mean sea level is defined as the height of the sea with respect to a land benchmark, averaged over a period of time, such as a month or a year, long enough so that fluctuations caused by waves and tides are largely removed.

Relative, eustatic and isostatic changes

Changes in mean sea level measured by tide gauges are called **relative changes in sea level**, because they can come about either by movement of the land on which the tide gauge is situated or by changes in the height of the adjacent sea surface (both considered with respect to the centre of the Earth as a fixed reference).

We also talk about **eustatic changes in sea level**, meaning global changes in sea level due to water mass added or removed from the oceans (from melting ice sheets, for example). To detect eustatic changes in sea level, the movement of the land needs to be subtracted from the records of tide gauges and geological indicators of past sea level.

Changes in the level of land masses are referred to as **isostatic changes**. Widespread land movements are caused by isostatic adjustment resulting from the slow viscous response of the Earth's mantle to the melting of large ice sheets and the addition of their mass to the ocean since the end of the most recent glacial period ('Ice Age').

We need to take these different contributing factors into account in order to accurately measure changes in sea level and understand how sea level is changing.

23: NORAH HEAD, CABBAGE TREE HARBOUR

Wave run-up penetrating to the base of the escarpment, submerging the beach.

*Photo: Greg White,
Wyong Shire Council.*



24. CENTRAL COAST, BRISBANE WATER, TASCOTT

Limited clearance to the crest of the foreshore revetment protecting the road along Brisbane Water Drive.

Photo: Phil Watson, DECCW



Measuring past sea levels

We measure sea level from several data sources including long-term tide gauge records and more recent technologies including satellite altimetry.

Tide gauge records from around the world show sea levels increasing over the long term

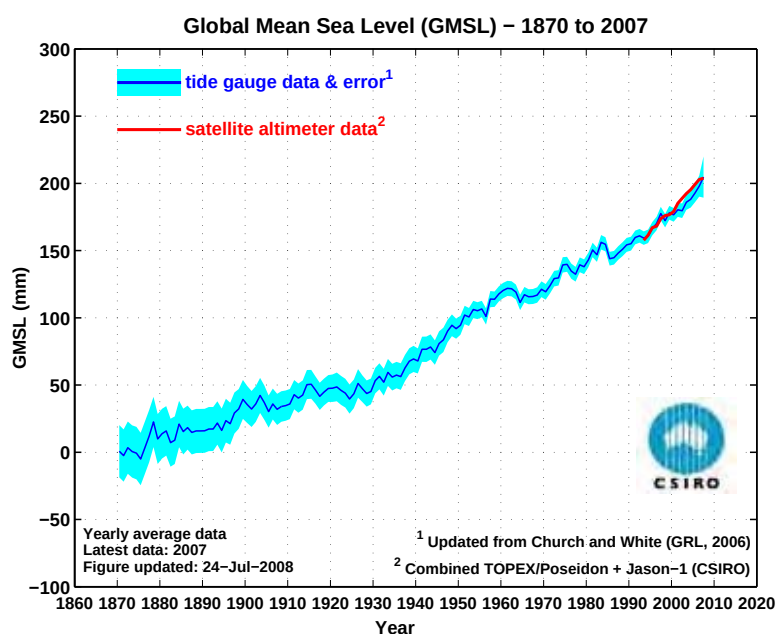
Sea level rise has been evident from very long-term tide gauges stationed around the world, particularly those in northern Europe. The two longest continuous tide gauge records in Australia, Fremantle (from 1897) and Fort Denison (from 1866) show similar trends in increasing sea level over time. Tide gauge records from 1920 to 2000 tell us that the change in relative mean sea level around the Australian coastline was about 1.2 mm/year over that timeframe. (Church et al. 2006)

From detailed analysis of global tide gauge records, the Intergovernmental Panel on Climate Change (IPCC 2007) concluded that the rate of observed sea level rise increased from the 19th to 20th century and that the total 20th century rise was estimated to be 17 ± 5 cm. IPCC (2007) similarly concluded that global average eustatic sea level rise over the period from 1961 to 2003 is estimated at 1.8 ± 0.5 mm/year.

Satellite measurements confirm what we know from the tide gauges

Since 1992 we've been able to measure the altitude of the surface of the ocean using satellites – this is called satellite altimetry. Satellite measurements reveal that global sea level is slowly rising, confirming what we have observed from tide gauges around the world.

When we examine both tide gauge data and satellite altimetry data there is clear evidence that global average sea level has been rising slowly, at an increasing rate.



Source: www.cmar.csiro.au

25. CENTRAL COAST, BRISBANE WATER, DAVISTOWN

*Limited clearance to the top
of the foreshore revetment
and public reserve.*

*Photo: Leon Brooks,
Gosford State Emergency Services.*

26. CENTRAL COAST, BRISBANE WATER, PRETTY BEACH

*Limited clearance between
tidal waters and floor levels.*

Photo: Fiona Lambell.

Projecting future sea levels

The Intergovernmental Panel on Climate Change (IPCC) represents a consensus of the world's leading scientists studying climate change. IPCC has made projections about sea level rise based on a set of possible future scenarios. These scenarios take into account differing world socio-economic conditions and population regimes, and differing levels of greenhouse gas emissions. Considering the different scenarios enables IPCC to generate a range of predictions.

IPCC (2007) projections of global average sea level rise over the 21st century, from the various modelled emission scenarios, range from 18 to 59 cm (at 2090–2099 relative to 1980–1999). A further allowance of 10 to 20 cm is advised for the upper range of sea level rise scenarios in the event that ice sheet flow rates increase linearly with global average temperature change. Importantly, IPCC (2007) advises that larger sea level rises cannot be excluded.

IPCC (2007) advises that while there will be a rise in global average sea level, there will be considerable regional variability in the rate of sea level rise. Recent modelling undertaken by CSIRO (2007) indicates the ocean water levels off the NSW coastline could be of the order of 0-8 cm and 0-12 cm higher than the global average by 2030 and 2070, respectively.

IPCC (2007) continues to build on the reliability of previous sea level rise projections through improved understanding of complex governing ocean-atmosphere relationships, improved understanding of global water budgets, greater diversity and capacity of mathematical models and synthesis of longer and improved measured data from integrated tide gauge networks and satellite altimetry.

Although the international scientific community is continuing to improve our knowledge of climate change impacts and predictions, our understanding of all the complex, interrelated climatic, atmospheric and oceanic processes remains incomplete. Current satellite altimetry

27: CENTRAL COAST, BRISBANE WATER, PRETTY BEACH

*Tidal waters overtopping the
foreshore revetment along
Pretty Beach Road.*

Photo: Fiona Lambell.



28: SYDNEY NORTHERN BEACHES, BILGOLA

*Waves overtopping
and submerging Bilgola
ocean baths.*

Photo: Peter Marshall.



measurements from 1992 to present indicate measured global average sea level rise over this period at approximately 3.2 ± 0.4 mm/year, in line with the upper-bound IPCC (2007) model predictions.

IPCC (2007) advises that sea level rise under global warming is inevitable. Thermal expansion would continue for many centuries after greenhouse gas concentrations have stabilised, for any of the CO₂ emission scenarios assessed, causing an eventual sea level rise much larger than projected for the 21st century. The eventual contributions from Greenland ice sheet loss could be several metres (and larger than from thermal expansion), should warming in excess of 1.9 to 4.6°C or more above pre-industrial levels be sustained over many centuries (IPCC 2007). The long timescales of thermal expansion and ice sheet response to warming imply that stabilisation of greenhouse gas concentrations at or above present levels would not stabilise sea level for many centuries (IPCC 2007).

29: CENTRAL COAST,
PEARL BEACH
*Limited beach width
available above the
wave run-up.*
Photo: Graham Williams.

30: SYDNEY,
FRESHWATER BEACH
*Beach width reduced
at high tide.*
Photo: Debbie Millener,
Warringah Shire Council.

31: SYDNEY, MANLY BEACH
*Beach width and public
access significantly reduced
at the southern end of the
beach.*
Photo: Rafiqul Islam,
Manly Council.

32: SYDNEY HARBOUR,
LITTLE MANLY BEACH
*Foreshore accessways
submerged.*
Photo: Sarah Hesse,
Manly Hydraulics Laboratory.



How much will sea level rise, and when?

Sea level rise estimates for NSW: 40 years and 90 years from 2010

Since 1992 sea level rise has been tracking at or above the worst-case scenario shown in the table below. However, this is a relatively short time frame, and we need to look at the best-case, medium and worst-case scenarios to work out how to cope with rising sea levels.

	Year 2050		Year 2100	
	Estimate of sea level rise ⁽¹⁾ (cm)	Recommended planning allowance ⁽²⁾ (cm)	Estimate of sea level rise ⁽¹⁾ (cm)	Recommended planning allowance ⁽²⁾ (cm)
Best-case scenario	6 ⁽³⁾	10	18 ⁽⁵⁾	20
Medium estimate ⁽⁷⁾	22	25	56	55
Worst-case scenario	38 ⁽⁴⁾	40	94 ⁽⁶⁾	90

Source: After Watson and Lord 2008

Notes:

- (1) Estimates of sea level rise (derived estimates) have been determined from a synthesis of authoritative and up-to-date sources of information regarding sea level rise including IPCC and CSIRO publications. All derived estimates are relative to a baseline of 1990 mean sea level.
- (2) Recommended planning allowances have been rounded to the nearest 10 cm and are provided for guidance only. Given the uncertainty associated with sea level rise (SLR) estimates – the difference between the best-case and worst-case scenarios – planners are advised to use a risk management approach when choosing a planning allowance.

33: SYDNEY HARBOUR, CASTLECRAIG MARINA,
Limited clearance to the carpark.
Photo: Nicola Faith, Willoughby Council.



34: SYDNEY HARBOUR, BALMORAL BEACH
Beach width significantly reduced.
Photo: Helen McParlane.



Since 1992, albeit a relatively short timeframe, SLR has been tracking at or above the worst-case scenario (the upper-bound IPCC trajectory curves).

- (3) SLR estimate derived from Figure 11.12, IPCC 2001.
- (4) SLR estimate derived from Figure 11.12, IPCC 2001, with the addition of 10 cm to estimate the upper-bound regional increase in SLR above the global average based on linearly interpolating upper-bound modelled estimates for 2030 and 2070 (CSIRO 2007).
- (5) SLR estimate from Table SPM.3, IPCC, 2007.
- (6) SLR estimate from Table SPM.3, IPCC, 2007, using the 59 cm advised (relative to 1990 levels). An additional 20 cm has been added to account for the possibility of ice sheet flow rates increasing linearly with increased temperature for upper-bound projections as advised by IPCC (2007). A further 15 cm has been added to estimate the upper-bound regional increase in SLR above the global average based on linearly extrapolating upper-bound modelled estimates for 2030 and 2070 (CSIRO 2007).
- (7) Medium position between best-case (lower-bound) and worst-case (upper-bound) estimates rounded up to the nearest cm.

35: SYDNEY HARBOUR, MILSONS POINT

Base of the south pylon of the Sydney Harbour Bridge.

Photo: Adrian Turnbull, North Sydney Council.

36: SYDNEY, HUNTERS HILL, TARBAN CREEK RESERVE

Retaining wall protecting the foreshore submerged.

Photo: Socs Cappas.

37: SYDNEY, RYDE, KISSING POINT PARK

Carpark adjoining the Parramatta River submerged.

Photo: Peter Mitchell.

38: SYDNEY, MEADOWBANK

Submerged revetment and lighting poles along the foreshore of the Parramatta River.

Photo: Peter Stuart.



Impacts highlighted by the photos

This report contains a brief sample of the photos that were taken during the peak of the 2009 king tide. The extensive array of images, covering the length of the NSW coastline, identify many areas and assets that will become progressively more vulnerable over time as sea level continues to rise.

The key impacts – many of them state-wide – include:

- localised tidal inundation penetrating through stormwater systems and affecting private property, public reserves and local road networks;
- limited clearance between the peak water level and the crest of revetments and seawalls currently protecting waterfront properties, commercial precincts, public reserves and significant public infrastructure;
- widespread submergence of gravity stormwater drainage systems, fixed jetty and wharf infrastructure, as well as public walkways, boardwalks, bicycle paths and carparks situated around the intertidal foreshores of estuaries;
- substantial narrowing of useable beach widths;
- overtopping of beach berm barriers in areas where intermittently open and closed lakes and lagoons are currently closed to the sea;
- increased tidal currents within estuaries and larger rip systems on open-coast beaches;
- inundation and destruction of nesting within endangered bird roosting sites (such as little terns);
- immediate threats to indigenous cultural heritage sites such as middens located with close proximity to intertidal margins;

39: SYDNEY HARBOUR,
BALMAIN

Darling Street Wharf at low tide. The fixed jetty infrastructure has been designed to accommodate high tides.

Photo: Fay Briggs.



40: SYDNEY HARBOUR,
BALMAIN,

Darling Street Wharf at high tide.

Photo: Fay Briggs.



- widespread proximity of tidal waters to sewerage pump stations and associated sewerage infrastructure;
- floor levels of numerous commercial premises and dwelling structures around harbour and estuarine foreshores within 50 cm of the king tide level; and
- wave action submerging and overtopping numerous public ocean bath facilities.

41: SYDNEY HARBOUR,
PYRMONT

Limited clearance to top of decking for fixed jetty infrastructure.

Photo: Steven Morrison.

42: SYDNEY,
DARLING HARBOUR

Limited clearance to hardstand walking areas.

Photo: John Gan.

43: SYDNEY HARBOUR,
MAN O' WAR STEPS

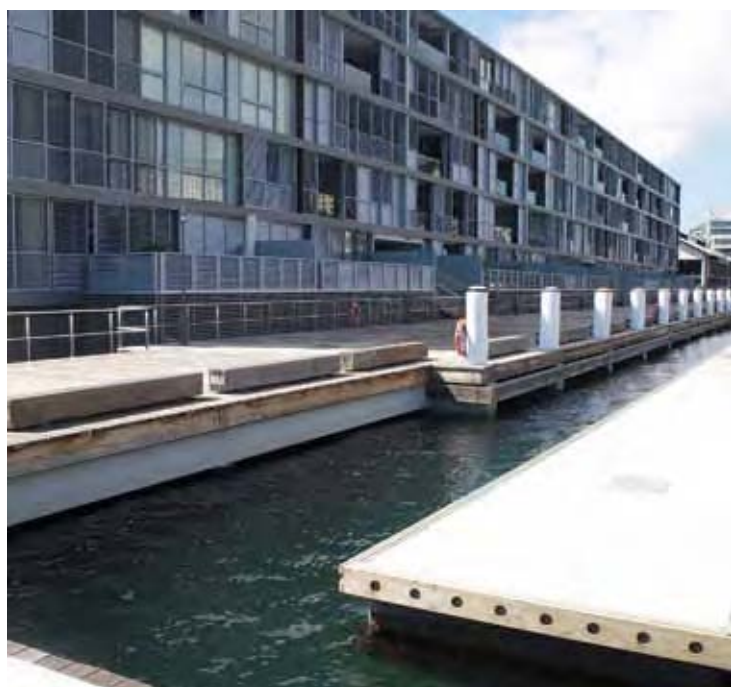
Historic steps submerged.

*Photo: John Hudson,
NSW Planning.*

44: SYDNEY HARBOUR,
DOUBLE BAY, BAY STREET

Tidal waters lapping at the crest of the foreshore revetment.

*Photo: Craig Morrison,
Sydney Coastal Councils Group.*



Implications for photographing future king tides

Despite the short lead time involved with organising this inaugural photographic event, the remarkable level of involvement by the NSW community at large, including local councils and government agencies, coupled with the high level of media interest, clearly demonstrates the value of this initiative.

The peak water levels recorded on 12 January 2009 fell short of the predicted astronomical tide, but the high water levels still exposed numerous areas vulnerable to tidal inundation. The implications are state-wide. Images collected from the photographic event could provide coastal zone managers and the community with a broad-ranging pictorial insight into our current vulnerability and the challenges that lie ahead in managing sea level rise.

Notwithstanding the success of the 2009 exercise, there are opportunities to build on the information obtained, for example:

- **Establishing a database of images, linked to a GIS platform, as a publicly available resource for coastal zone managers.** DECCW is investigating the feasibility of making this available through its website.
- **Targeting areas that were not covered during the 2009 exercise.** The short lead-time for arranging the 2009 photographs meant that some important areas were missed in this first staging of the event. Some areas around the Sydney Basin and Central Coast were covered extensively, but the coverage state-wide was mixed, with the lower and mid-north coast and far south coast experiencing comparatively lower coverage. Similarly, the coverage of various tidal waterways around the State's major river systems was inconsistent.

45: SYDNEY, BONDI BEACH
Waves overtopping and submerging the ocean baths.
Photo: Dennis Gray.



46: SYDNEY HARBOUR, DOUBLE BAY
Limited clearance to the floor of the sailing club premises.
Photo: Craig Morrison, Sydney Coastal Councils Group.



- **Coordinating the state-wide organisation.**
The coverage could be improved by engaging with all NSW coastal councils and catchment management authorities early in the planning process.
- **Seeking national coverage.** During the short lead-in to the 2009 photo event, DECCW was contacted by numerous members of the community in other states wishing to participate. It is obvious that the benefits of the NSW initiative would apply elsewhere, and there is an opportunity to gain a national perspective here.
- **Using measuring sticks to visualise the threat from projected higher sea levels.** Future photographic exercises could generate an even more powerful message if standardised measuring sticks were included in some of the photographs to depict the height of projected sea level rise to the end of the century.

- **Establishing a network of volunteer photographers.**
A state-wide core of volunteers involved in the photo event could provide a network that could be called upon at short notice to capture unusual events such as extreme beach erosion or inundation.

49: SHELLHARBOUR

Submerged fish cleaning facilities at the boat harbour.

Photo: Andrew Williams, Shellharbour City Council.

47: WOLLONGONG HARBOUR

Waves overtopping the breakwater structure.

Photo: NSW Department of Lands.

48: LAKE ILLAWARRA

Submerged pathways along the foreshore.

Photo: Shellharbour City Council.

50: BURRILL LAKE, WEST OF THE PRINCES HIGHWAY

Limited clearance to the top of revetments protecting properties along the foreshore.

Photo: Keith Bourke.



Conclusions

By photographing the king tide, the public was able to gain an understanding of how a relatively rare water level today could be quite common by the end of the century if sea level rise projections prove correct. Those taking part in photographing the peak of the king tide in their local areas had the opportunity to visualise the direct impacts of ocean water levels being 90 cm deeper by 2100.

In addition to capturing a library of images highlighting key vulnerabilities, the event was specifically tailored to raise public awareness about the additional threat from projected future sea level rise. The consensus of scientific information available at present indicates the upper range of sea level rise projections could be close to a metre by the end of the century without significant greenhouse gas mitigation.

Clearly the issue of planning to combat or accommodate sea level rise in coastal communities will present complex challenges for local communities and all spheres of government. Photographing the king tide provides an extremely valuable repository of images and a clear visual perspective on the many current threats and vulnerabilities posed by tidal inundation which will all be exacerbated by sea level rise.

The extent of public engagement and media interest concerning this photographic initiative demonstrates the keen interest within the community regarding coastal zone management issues. This initial exercise provides a solid foundation upon which to build further initiatives and DECCW highly commends the effort and enthusiasm of all the individuals and groups that volunteered their time to take part in this event.



51: NAROOMA,
OLD MUNICIPAL WHARF
*Limited clearance to
the foreshore areas and
roadway next to the wharf.*

*Photo: Greg Watts,
Eurobodalla Shire Council.*



52: BATEMANS BAY CBD
*Limited clearance to the top
of the seawall protecting
commercial premises along
the foreshore.*

*Photo: Lindsay Usher
and Norm Lenehan,
Eurobodalla Shire Council.*

In order to better understand and adapt to sea level rise, the NSW Government has developed a Sea Level Rise Policy Statement. This Policy provides two benchmarks for consistent planning and assessment purposes along the NSW coast: 40 cm at 2050 and 90 cm at 2100, relative to 1990 sea level. A Technical Note is also available to describe the science behind these benchmarks for NSW. Guidelines are also being prepared to assist councils and coastal specialists to implement these benchmarks in coastal hazard assessment, coastal flood assessment and landuse planning. These are available at: www.environment.nsw.gov.au/climatechnage/sealevel.htm.

53: NORTH BATEMANS BAY

Wave run-up submerging low-lying foreshores, close to protection works.

Photo: Lindsay Usher, Eurobodalla Shire Council.

54: MERIMBULA

Limited clearance to the foreshore boardwalk.

Photo: Derek van Bracht, Bega Valley Shire Council.

55: BATEMANS BAY CBD

Limited clearance to the top of the seawall along the foreshore.

Photo: Lindsay Usher and Norm Lenehan, Eurobodalla Shire Council.



What happened on 13 and 14 December 2008?

The peak of an abnormally high spring tide occurred at 0806 hours EST on 14 December 2008. The peak water level was 13 cm higher than predicted, mainly due to a low pressure system in the Tasman Sea north-east of Tasmania.

The dynamic influences of local weather and meteorological conditions on ocean water levels were clearly evident during the high spring tides which coincided with the full moon on the weekend of 13 and 14 December 2008.

At 0806 hours EST on 13 December 2008 the Fort Denison tide gauge measured a peak water level of 2.15 m above TGZ (1.225 m AHD). This peak was 0.13 m (13 cm) higher than the predicted peak of 2.02 m above TGZ.

Based on analysis of the long-term data from Fort Denison, on average we would expect to reach a water level of this measured peak (2.15 m) for approximately 1.2 hours per year.

There was a similar story on the following day. At 0912 hours EST on 14 December 2008 the Fort Denison tide gauge measured a peak water level of 2.17 m above TGZ (1.245 m AHD), 0.12 m (12 cm) higher than the predicted peak of 2.05 m above TGZ. This was the highest recorded water level at Fort Denison during 2008 and, on average, we would expect to reach such a level once every 1.2 years.

One of the primary reasons the measured water level was significantly higher than the predicted tide was due to the influence of a deep low pressure system in the Tasman Sea north-east of Tasmania. This low influenced the entire NSW coast during 13 and 14 December and coincided with the high spring tides.

56: NEWCASTLE,
CARRINGTON

Tidal waters penetrating into Hargrave and Garrett Streets, 14 December 2008.

Photo: Bruce Coates, DECCW



57: NEWCASTLE,
CARRINGTON

Tidal waters of the Hunter River submerging Robertson Street, 14 December 2008.

Photo: Bruce Coates, DECCW



Both the low pressures and the strong southerly winds resulted in higher sea levels, particularly along the southern NSW coast.

Based on analysis of the state-wide ocean water level recording network, the elevation of the measured water level above the predicted peak was comparatively larger towards the southern end of the NSW coast, mirroring barometric pressure gradients and stronger southerly winds evident along the coastline from the synoptic charts (see Appendix 1).

Given the relative rarity of the water levels reached over the course of the weekend, the media reported many areas that were extensively inundated by sea water. Some of the images in this report, from 13 to 15 December 2008, depict the extent of this inundation at isolated locations.

Photos of the December 2008 spring tide

These images of localised flooding from the abnormally high spring tide in December 2008 were also sent to DECCW.

The peak water level recorded in these images (2.17 m) is currently exceeded on average only once every 1.2 years. However, by the end of the century, assuming sea level will rise by 90 cm, the depicted water levels could be reached or exceeded approximately 25% of the time, or alternatively, for a total of almost 3 months per year. Similarly, these photos show the impacts of tidal water levels which are projected to be up to 90 cm deeper by 2100.

58: WOLLUMBOOLA LAKE

Little tern nesting sites destroyed by inundation, 14 December 2008.

Photo: Frances Bray, NPWS volunteer.



59: SYDNEY HARBOUR, FORT DENISON

Water lapping against the western seawall, 13 December 2008.

Photo: Phil Watson, DECCW.



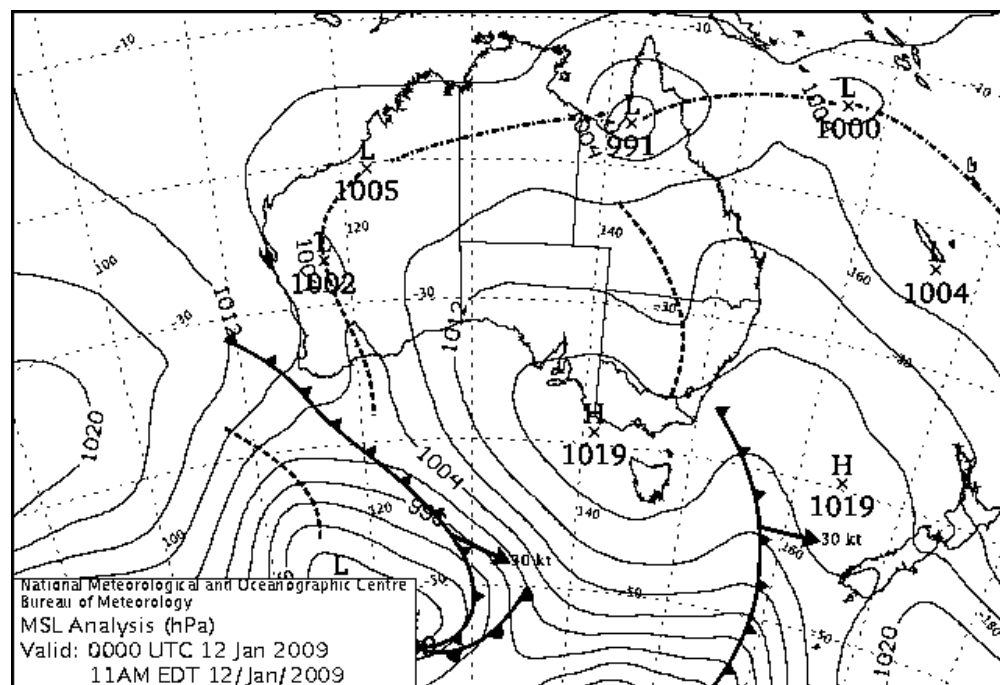
Appendix 1: Synoptic charts

12 JANUARY 2009

Synoptic chart for 1100 hours

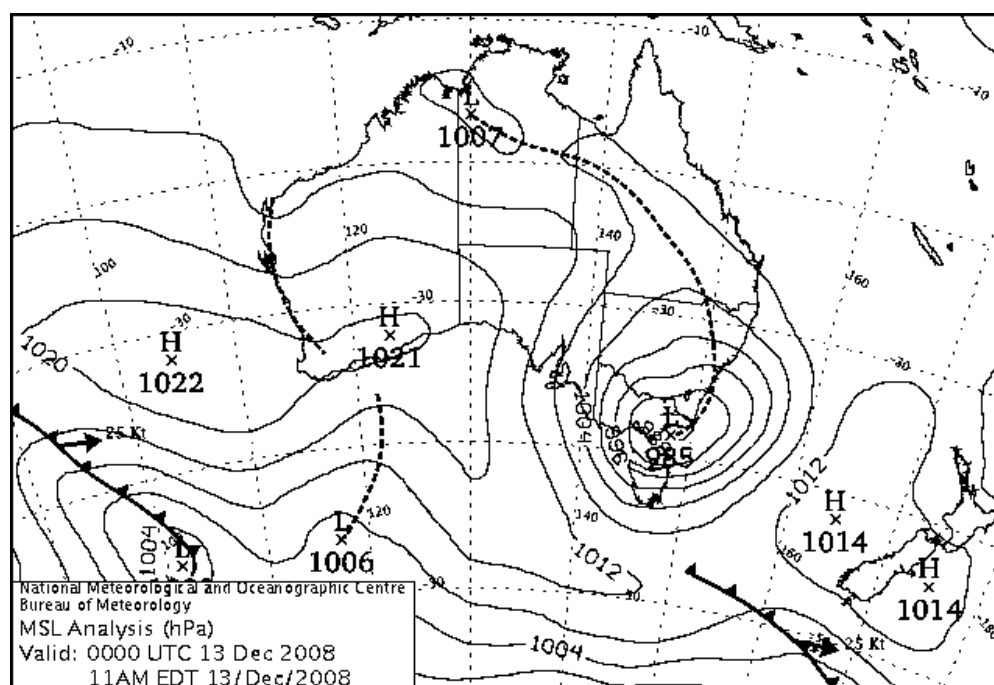
EDT 12 January 2009

(Bureau of Meteorology)



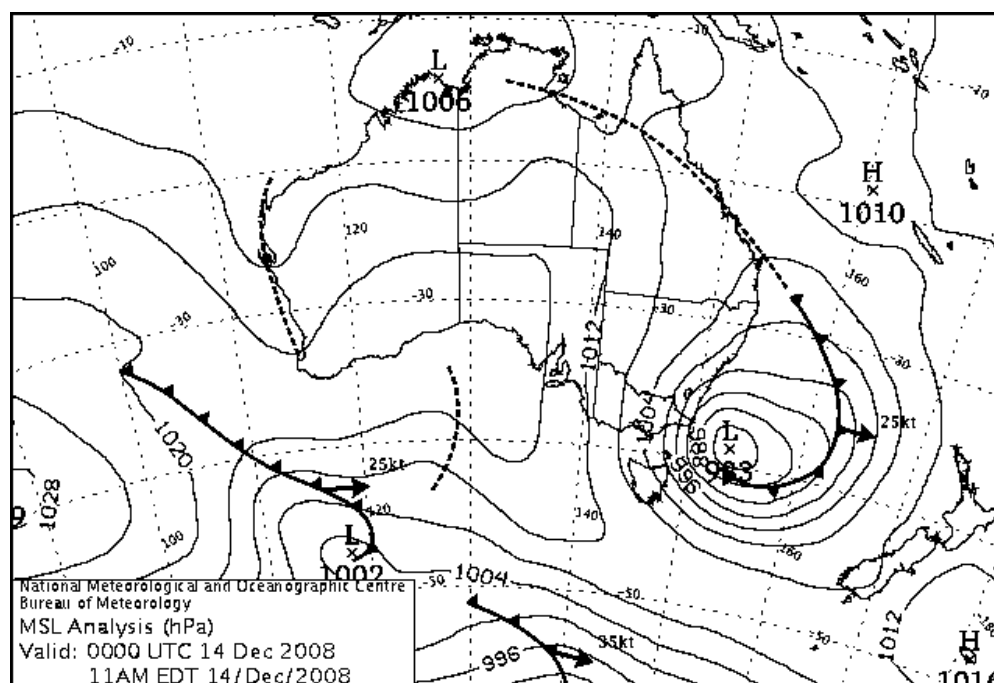
13 DECEMBER 2008

Synoptic chart for 1100 hours
EDT 13 December 2008
(Bureau of Meteorology)



14 DECEMBER 2008

Synoptic chart for 1100 hours
EDT 14 December 2008
(Bureau of Meteorology)



References

Bureau of Meteorology website (BoM 2009),
www.bom.gov.au.

Church JA and White NJ (2006), 'A 20th Century Acceleration in Global Sea Level Rise', *Geophysical Research Letters*, Vol. 33, L01602, doi:10.1029/2005GL024826.

Church JA, Hunter JR, McInnes KL and White NJ (2006), 'Sea Level Rise around the Australian Coastline and the Changing Frequency of Extreme Events', *Australian Meteorology Magazine*, 55: 253-260.

CSIRO (2007), *Projected Changes in Climatological Forcing for Coastal Erosion in NSW*, project undertaken for the Department of Environment and Climate Change NSW, August 2007.

CSIRO Marine and Atmospheric Research Sea Level Rise website (2009), www.cmar.csiro.au/sealevel/

IPCC (2001), *Climate Change 2001: The Scientific Basis*, Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, UK, 944 pp.

IPCC (2007), *Climate Change 2007: The Physical Science Basis, Summary for Policy Makers*, Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

MetEd (2006), *Introduction to Ocean Tides*, report produced by the Cooperative Program for Operational Meteorology, Education and Training (COMET), University Corporation for Atmospheric Research, Boulder Colorado, US, www.meted.ucar.edu

Watson PJ and Lord DB (2008), *Fort Denison Sea Level Rise Vulnerability Study*, report prepared by the Coastal Unit, Department of Environment and Climate Change NSW.

60: SYDNEY HARBOUR,
WEST CIRCULAR QUAY

*Limited clearance to
the crest of the sea wall.*

*Photo: John Hudson,
NSW Planning.*



