

# NSW Sea Level Trends – The Ups and Downs

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## Abstract

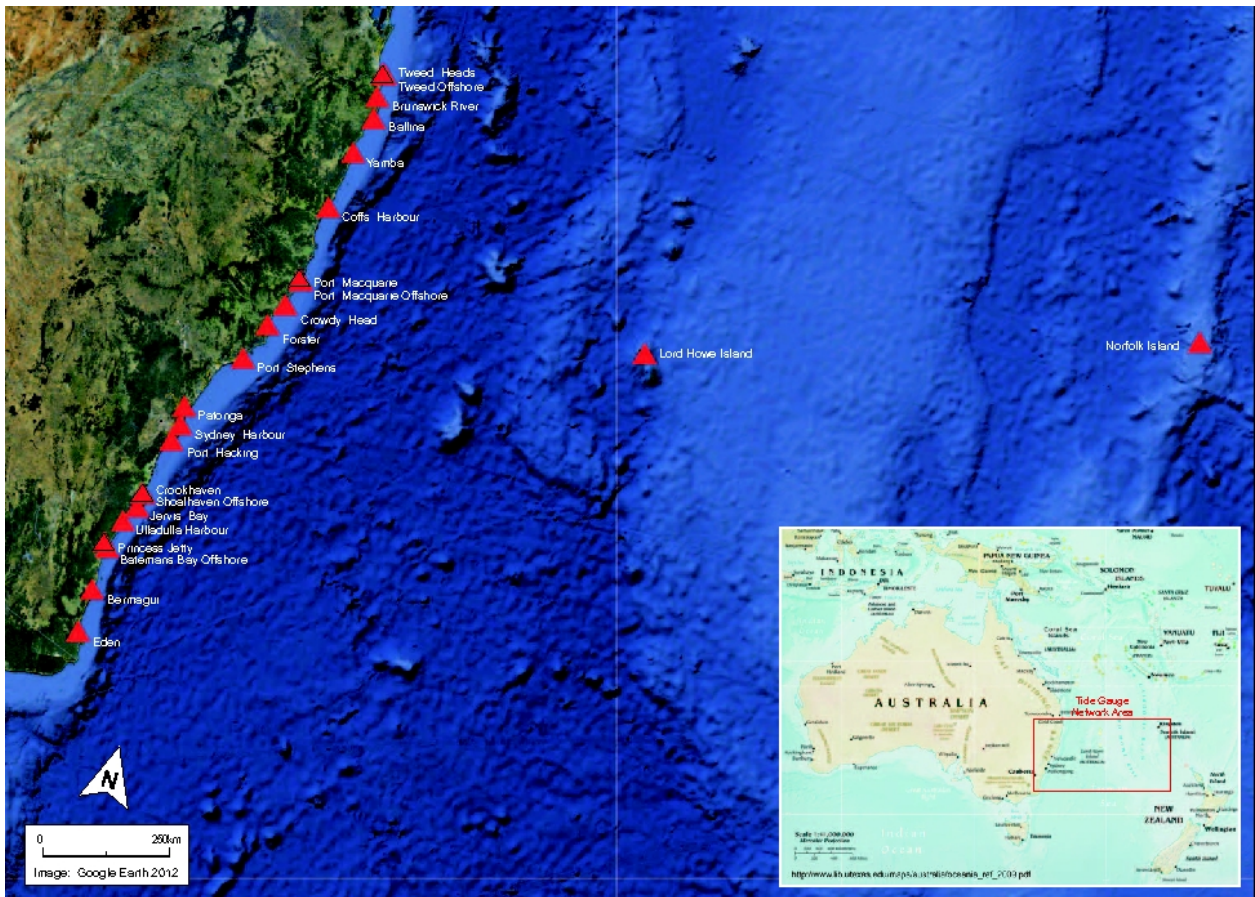
Following the removal of the NSW Sea Level Rise Policy Statement in September 2012, there has been great interest in NSW sea level records to provide often misguided “evidence based” estimates of local/regional sea level trends. One of the great difficulties in climate change and sea level rise planning is that the level of common knowledge on the subject is highly diverse, often biased by urban myths and interspersed by detailed knowledge in particular aspects with poor overall congruence of fact and meaning to a particular issue at hand. This paper will help develop a good understanding of undisputed baseline ocean water level drivers and responses across different timescales to avoid misinterpretation of sea level data. It also will demonstrate how despite over 25 years of highly valuable continuous quality controlled sea level data available for NSW, sea level rise trends based on these and other historical data are not necessarily representative of expected future long-term sea level change.

The paper will describe where sea level data is collected in NSW and how it is measured both today and in the past, including NSW’s longest records from Fort Denison which commenced in 1886 and provide quality controlled sea level data since 1914. The importance of maintaining recording station metadata will be demonstrated, including instrumentation details, datum changes and monitoring intention(s), as the future value of data will be highly dependent on traceability of these metadata. Through the NSW State Government’s recognition of the value of sustaining continuous quality controlled coastal data, the importance of NSW sea level records continues to increase, both in day to day activities and far longer-term. The paper will discuss key factors necessary to ensure that continuous data collection activities can be sustained. This includes understanding both the physical process development and effective communication of the value of these data.

## Background

The NSW Office of Environment and Heritage (OEH) manage an extensive network of automatic water level recorders as part of its Floodplain, Estuary and Coastal Management programs. The coastal data network is operated and maintained by NSW Public Works Manly Hydraulics Laboratory (MHL) under an annual contract with OEH. This paper presents NSW ocean and river entrance water level information collected by NSW Public Works MHL at eighteen coastal and four offshore stations as well as Norfolk Island and Lord Howe Island (see **Figure 1**).

The ocean tide monitoring network features distinctive systems of data capture dependent on available technologies for different locations and different data needs comprising radar, electromagnetic wave staff (EWS), solid state floatwells, vented pressure sensors and/or submersed water level pressure recorders. Data capture systems have continued to evolve as technologies have improved and our understanding and demand of the physical processes being measured continues to mature.



**Figure 1. NSW Ocean and River Entrance Water Level Stations**

Continuous quality controlled water level records exist typically since 1987 with additional historical records at some locations extending for over 100 years (Fort Denison<sup>1</sup>). Despite this extensive and highly valuable data set extending for over 25 years, sea level trends based on these data are not necessarily representative of expected future long-term sea level change. It is vital to understand the various physical processes acting on coastal water levels which operate over different time scales in order to understand observed sea level trends. Average sea levels respond to climatic forcing, amongst other things, and the very notion of a mean sea level is often misunderstood. This situation is further complicated by the fact the earth's climate is not static (whether climate change is natural, anthropogenic or both) and it is invalid to assume statistical stationarity. That is, historical records of sea levels are not expected to be representative of future conditions.

Despite undisputable long-term climate change and sea level rise, there remains great uncertainty with respect to future climate and sea level predictions for decision makers to work to, which means the future climate is uncertain. A risk-based approach underpinned by a good understanding of the dominant physical processes operating is warranted to deal with the inherent uncertainty of sea level rise projections. This emphasises the importance of ongoing monitoring of coastal water levels to improve our understanding and modelling of future projections. Continuous quality controlled local records are vital also to measure the effectiveness of planning decisions through local triggers for adaptation.

<sup>1</sup> The Fort Denison gauge is maintained by Sydney Ports with quality controlled records available since 1914. The data from this gauge is presented also in this paper for direct comparison with the NSW OEH network.

## NSW Ocean and River Entrance Water Levels

### Where We Measure

As shown in **Figure 1**, NSW Public Works MHL monitors ocean and river entrance water levels at twenty four (24) locations along the NSW Coast from Tweed Heads to Eden and including also Lord Howe Island and Norfolk Island.

Gauges are classified according to their location and comprise:

- Offshore Open Ocean (O) stations (**Figure 2**) that have no fixed datum so are not suitable for sea level trend analysis;
- Onshore Bay or Port (OB) stations (**Figure 3**) that are unaffected by rainfall runoff flows and have a fixed datum, but can be affected by harbour seiche (long waves); and
- Onshore River Entrance (OR) stations (**Figure 4**) that can be affected by rainfall runoff but are generally representative of the ocean water levels.



Figure 2. Typical Offshore Open Ocean (O) station



Figure 3. Typical Onshore Bay or Port (OB) station



Figure 4. Typical Onshore River Entrance (OR) station

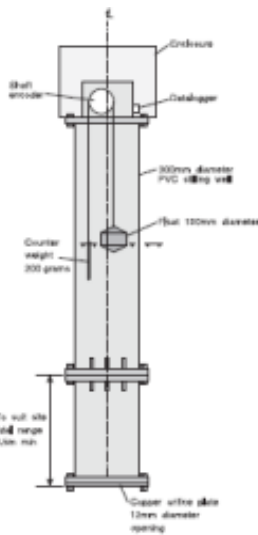
### How We Measure

The ocean tide monitoring network includes radar, electromagnetic wave staff (EWS), solid state Floatwell recorders, vented pressure sensors and submersed water level pressure recorders depending on the measurement location and particular information needs. Each system functions as follows:

*Solid state Floatwell:* the level is sensed by a float within a stilling basin connected to a shaft encoder which is read and stored every 15 minutes. The data recorded is then transferred to MHL via an IP link through a modem between the data logger and MHL's data server. This system has been used successfully for many years at OB and OR locations. Floatwell

systems are progressively being replaced by vented pressure sensors and/or radar installations which do not require stilling basins and utilise higher sample frequencies and numerical filters to remove short period waves from the records. A typical Floatwell installation is shown in **Figure 5**.

*Electromagnetic Wave Staff (EWS):* the water level is sampled continuously by the EWS. The water level is averaged over 60 or 120 seconds to create a 1-minute or 15-minutes time series data file respectively. The data is downloaded from the data logger via an IP link through a modem to MHL's data server or transmitted via radio link to a shore-based receiving station where it can be transferred to MHL via a separate modem connection to the data server. With continuous sampling, the EWS can be used to record both water levels and waves (including local seas and swell). The EWS system can experience long term signal drift, however, with loss of upper and/or lower water level records and hence this system is being phased out from long-term sea level monitoring locations. A typical EWS installation is shown in **Figure 6**.



**Figure 5. Typical Floatwell Station (Bermagui; now a pressure sensor)**

**Figure 6. Typical EWS Station (Port Hacking; now radar)**

*Vented pressure sensors:* the water level is determined by a vented pressure sensor and recorded on a data logger. The sensor is vented to atmospheric pressure and therefore requires no correction for barometric pressure changes. A stilling basin can be used with lower sampling frequencies to remove short period waves from the records or higher sample frequencies with numerical filters can be utilised. The data recorded is transferred to MHL via an IP link through a modem between the data logger and MHL's data server. The photograph in **Figure 5** is representative of a typical vented pressure sensor installation utilising a stilling basin.

*Radar sensors:* the water level is detected by RAdio Detection And Ranging technology. The water level is averaged over 60 or 120 seconds to create a 1-minute or 15-minutes time series data file respectively. The data recorded is then transferred to MHL via an IP link through a modem between the data logger and MHL's data server. With continuous sampling, radar sensors can be used to record both water levels and waves (including local seas and swell). Radar sensors are very stable making this technology suitable for long-term sea level monitoring. A typical radar system is shown in **Figure 7**.



Figure 7. Typical Radar Station (Jervis Bay)

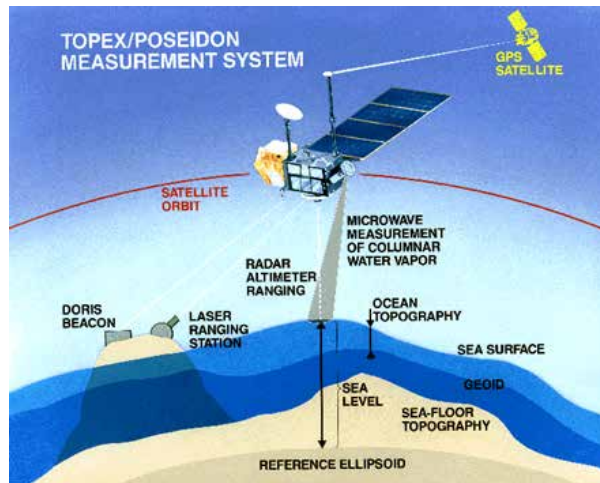


Figure 8. Satellite Altimeter Measurement

*Submersed water level recorder.* the water level is determined by an absolute pressure sensor sealed in a waterproof housing and mounted on the ocean bed. The data requires post-recording correction for water density and barometric pressure changes. The data is downloaded manually from the recorder to the Laboratory's data server after recovery from the ocean bed by divers. This technology has been successfully used at offshore open ocean (O) locations for many years, but do not have a fixed reference datum so are not suitable for sea level trend analysis.

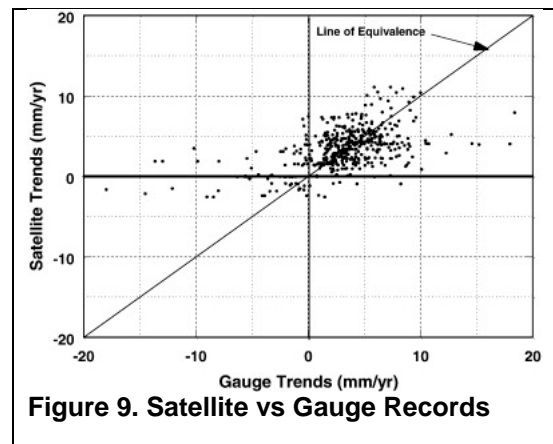


Figure 9. Satellite vs Gauge Records

A typical submersed water level recorder installation is shown in the insert in **Figure 2**.

Although not part of the NSW sea level monitoring network, it is noted that low orbit satellites as shown in **Figure 8** are also used to measure global sea levels (reliably since 1992). This technology is reliant on gauge data for calibration and provides spatially averaged sea levels (typically over 25 km) and therefore cannot be compared directly with gauge data. A comparison of satellite and gauge record sea level trends is illustrated in **Figure 9** after work undertaken by Dean and Houston (2013) which demonstrated trends from 456 gauges agree reasonably well with the global trend average of 3 mm/year from the satellite data. It is noted also that satellite altimeters provide geocentric sea levels (relative to the centre of the earth) with a calibrated accuracy of  $\pm 30$  mm to  $\pm 50$  mm whereas tide gauges provide sea levels relative to a local land datum at a specific location with an order of magnitude better accuracy when fixed by a Global Positioning System (GPS; see Watson *et.al.*, 2012).

A summary of the main attributes of the NSW ocean and river entrance tide station network (including Fort Denison) is shown in **Table 1** including, type, primary sensor, secondary sensors, datum, period of data and comments. Shaded gauges in **Table 1** have some data issues and should be used with caution in any sea level trends analysis.

**Table 1. NSW Ocean and River Entrance Tide Station Summary**

Station	Type	Primary Sensors	Secondary Sensors	Datum *	AHD (m)	Period of Data	Comments
Tweed Heads	OR	Radar	Vented Pressure	TRHD	0.893	Feb 1987-ongoing	In estuary upstream of breakwater, flood influenced
Brunswick Heads	OR	Vented Pressure	Vented Pressure	BRFMD	0.046	Mar 1986-ongoing	In estuary upstream of breakwater, flood influenced
Ballina Break-wall	OR	Vented Pressure	Vented Pressure	LWOST	0.860	Apr 1986-ongoing	In estuary upstream of breakwater, flood influenced
Yamba	OR	Radar	Vented Pressure	IPD	0.895	Jul 1986-ongoing	In estuary upstream of breakwater, flood influenced
Coffs Harbour	OB	Radar	Vented Pressure	CPD	0.882	Aug 1996-ongoing	Harbour seiching, radar installed Nov 2012
Port Macquarie	OR	Radar	Vented Pressure	AHD	0.000	Mar 1986-ongoing	In estuary upstream of breakwater flood influenced
Crowdy Head	OB	Radar	Vented Pressure	CHD	0.911	Jul 1986-ongoing	Harbour seiching, radar installed Apr 2013
Forster	OR	Vented Pressure	Vented Pressure	FHD	1.061	Jul 1986-ongoing	In estuary upstream of breakwater, flood influenced
Port Stephens	OB	Radar	Vented Pressure	PSHD	0.944	Oct 1985 ongoing	Radar installed Nov 2010.
Patonga	OB	Radar	Vented Pressure	AHD	0.000	Jun 1992-ongoing	In estuary upstream of breakwater, flood influenced
Sydney	OB	Radar	n/a	ZFD	0.925	Sep 1987-ongoing	Radar installed Feb 2012.
Fort Denison**	OB	Radar	-	ZCC	0.925	Jun 14 ongoing	Original records since 1886. QC data since June 1914. Sydney Ports operated gauge.
Port Hacking	OB	Electromagnetic	Vented Pressure	ZFD	0.925	Nov 1987-ongoing	Long periods poor data. Avoid using. Radar to be commissioned.
Port Kembla**	OB	Acoustic	-	CD		Nov 57 ongoing	Sporadic data gaps before Nov 1983. NTC took over gauge from PKPA in 1992
Crookhaven	OR	Vented Pressure	Vented Pressure	AHD	0.000	Mar 1992 - ongoing	In estuary upstream of breakwater, flood influenced
Jervis Bay	OB	Radar	Vented Pressure	CD	1.070	Sep 1989-ongoing	Radar installed Mar 2011. Little seiche in harbour.
Ulladulla	OB	Vented Pressure	Vented Pressure	AHD	0.000	Dec 2007 - ongoing	Harbour seiching. Installed for seiche study 2007
Princess Jetty	OR	Radar	Vented Pressure	AHD	0.000	Dec 1985-ongoing	In estuary upstream of breakwater, flood influenced. Upgraded to double sensor +1min data Dec 2012
Bermagui	OR	Vented Pressure	Vented Pressure	BLHD	0.714	Mar 1987-ongoing	Inside harbour in river upstream of breakwaters, flood influenced

Station	Type	Primary Sensors	Secondary Sensors	Datum *	AHD (m)	Period of Data	Comments
Eden	OB	Radar	Vented Pressure	TBHD	0.924	Sep 1986-ongoing	Good data but possible seiche across Twofold Bay. Issue with AHD around Eden.
Norfolk Island	OO	Floatwell	Vented Pressure	LAT	n/a	Sep 1994-ongoing	No datum relationship to NSW
Lord Howe Island	OO	Radar	Vented Pressure	LHIHD	n/a	Aug 1994-ongoing	Radar installed Jun 2012. No datum relationship to NSW
Tweed Heads Offshore	O	Submersible Paroscientific Pressure Sensor and RBR Logger	Aanderaa Submersible Pressure	MSL	n/a	Dec 1982-ongoing	Offshore site, no datum, less accuracy due to barometric correction
Port Macquarie Offshore	O			MSL	n/a	Dec 1984-ongoing	
Shoalhaven Offshore	O			MSL	n/a	Sep 2005-ongoing	
Batemans Bay Offshore	O			MSL	n/a	Sep 2000-ongoing	

\* Datum approximated from conventional terrestrial survey techniques, which generally exclude corrections for movement of land upon which the tide gauge is positioned, including solid earth tides, plate tectonics, glacial isostatic adjustment and localised factors such as aquifer extraction, reclamation and development loadings. In the future, station datum will be determined using a Global Navigation Satellite System (GNSS) Continuously Operating Reference Station (CORS; presently only Fort Denison and Port Kembla are on the CORS network.

\*\* Gauge not operated by MHL

O = Offshore Open Ocean, OO = Onshore Open Ocean, OR = Onshore River entrance, OB = Onshore Bay or port

In deriving stored ocean tide records at OB and OR stations, 120 samples are averaged 1 minute either side of the quarter hour and 60 samples are averaged 30 seconds either side of each minute with records logged 15 minutes on the quarter hour and 1 minute on the minute. Offshore stations are sampled over 40 seconds with records logged every 5 minutes (RBR loggers) or every 60 minutes for some older Aanderaa WLR7 loggers.

## Why We Measure

The NSW ocean tide database has been developed by NSW Public Works MHL to support a number of OEH programs associated with coastal, floodplain and estuary management. These include the operations of ports and marine facilities, water level forecasts, fisheries management, determining property boundaries and developing a detailed understanding of oceanic processes. The monitoring service is available to state, federal and local government as well as other organisations both in Australia and overseas.

In recent times, there has been added focus on sea level rise. However, despite the accuracy and moderate length of these records, sea level trends based on these data are not necessarily representative of expected future long-term sea level change. It is vital to understand the physical processes acting on coastal water levels which operate over different time scales in order to understand observed sea level trends. This includes storm surge, wave setup and other non-astronomical forcing as described in subsequent sections of this paper.

Climate change also involves changes to the coastal wave and wind climates, both in terms of incident energy and direction, as well as the frequency and intensity of coastal storms. While sea levels are the primary focus of this paper, it is important to understand that the combination of these factors influence coastal flooding, coastal erosion and long-term coastal recession. Because the stability of coastal structures is dependent on the incident wave height cubed, a small increase in design water levels can result in large increases in stable armour size, crest height and the depth of toe protection required to achieve serviceability requirements. This is particularly a problem along the NSW coast where significant public and private assets are increasingly in harm's way.

Climate change and sea level rise aside, the NSW ocean tide database has provided effective design water levels along the NSW coast. NSW Public Works MHL uses the Foreman (1977, 1991) tidal harmonic analysis method to calculate the significant tidal constituents and tidal planes from data recorded at the ocean tide stations. From these tidal planes, NSW Public Works MHL investigated the tidal ranges at NSW ocean tide stations (MHL 2005) and concluded that there is a general trend of increasing tidal range from south to north, however there may be local variations from this trend. It was concluded also that nearshore stations located at the entrance of large bays/ports display ranges higher than the closest offshore station, whereas nearshore stations located in river entrances displayed total ranges lower than the closest offshore stations due to bathymetric effects. It is important to recognise such variations when applying data from these ocean tide stations.

It is further noted that the Norfolk Island and Lord Howe Island tidal gauges provide the only data descriptive of some important and unique features of the East Australia Current and their influence on storm surges and other tidal anomalies along the NSW coast as described below.

## **Ocean Water Level Forcing Mechanisms**

The world's oceans rise and fall in a regular harmonic fashion under the gravitational pull of the moon and sun (and to a far lesser extent other planets) which is termed astronomical tides. But other non-astronomical forces also affect water levels around the globe, including meteorological and other influences. It is noteworthy also to recognise that relative sea levels can be notably influenced by land movement on a local or regional scale.

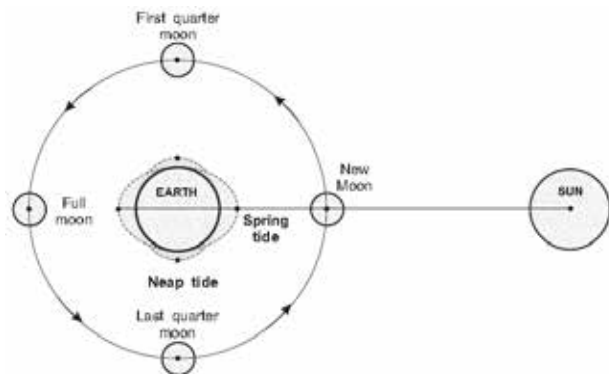
### **Astronomical Forcing**

Astronomical tides along the NSW coast rise and fall twice daily (semi-diurnal tides) which is typical of many other open ocean coasts around the globe. The primary forcing is from the gravitational pull of the moon, being twice that of the sun and the centrifugal force from the earth's surface. The relative positions of the earth, moon and sun affect tide levels, where high tides occur when the moon is either closet to or furthest (on the opposite side) from a particular region on earth. Low tides occur when the moon's relative position is 90 degrees on either side of a particular region on earth, being characterised by the least net gravitational/centrifugal influence.

In developing an understanding of astronomical tides, we need to consider the different time scales which operate. As the earth rotates on its own axis every 24 hours, the moon's relative position creates two high and two low tides each day. But the moon also orbits the earth, in the same direction that the earth rotates, every 28 days, so that the moon effectively reaches the same location on earth every 24 hours and approximately 50 minutes (every 24 hours plus 1/28<sup>th</sup> of a day). Hence, the high (or low) tide each day occurs about 50 minutes later each subsequent day. Interestingly, the moon also rotates on its own axis

every 28 days (being the same period as its rotation around earth) which is why the same face of the moon is always visible from earth.

Within the 28 day lunar cycle, the earth, moon and the sun become in alignment every 14 days (concurrent and opposing), which results in an increased net gravitational/centrifugal effect with a resulting increased tidal range termed Spring tide. During the alternate 14 day period, when the earth, moon and sun are at right angles to each other, a smaller tidal range is experienced and is termed the Neap tide (refer to **Figure 10**).



**Figure 10. Earth – Moon - Sun System**

Further to the semi-diurnal and Spring/Neap tide cycles, the summer/winter cycle affects the magnitude of the earth's tides. Because the earth's rotation is inclined (at 23.5 degrees) relative to its orbit around the sun, and because the earth's orbit around the sun is not circular, but elliptical, the net gravitational/centrifugal force of the sun on earth is maximised during the summer perihelion and winter aphelion when the earth is closest and furthest from the sun respectively resulting in the maximum tides in a year (in early January and July respectively for the southern hemisphere and conversely in the northern hemisphere) commonly termed King tides.

The longer-term astronomical cycle is further complicated by the fact that the planetary orbits are both elliptical, eccentric and inclined resulting in the earth/moon orbital planes re-aligning every 18.6 years which is termed the Tidal Epoch. That is, the plane of the moon's orbit tilts at an angle of about 5 degrees relative to the plane on which earth rotates the sun (the ecliptic plane); not the equatorial plane on which the earth spins which is 23.5 degrees to the ecliptic plane. The moon's orbit relative to the sun completes 360 degrees and returns to the same location every 18.6 years, being  $\pm 5$  degrees relative to the ecliptic or going from 28.5 degrees to 18.5 degrees in north-south orbit every 9.3 years.

Beyond the Tidal Epoch, even longer term astronomical cycles have been identified, including precession of the equinox, where the earth's relative inclination to its plane of rotation around the sun (ecliptic plane) wobbles between 22.5 degrees and 24.5 degrees (presently at 23.5 degrees) about every 41,000 years. This phenomena is mostly related to the relative position of Jupiter's orbit and has been linked to global glaciations (ice ages) that are understood to occur in even longer cycles of some 100,000+ years as first described by Milankovitch in the 1920's (Hays *et al.*, 1976).

All of these astronomical variations modify the daily heights of the high and low tides so the tidal range varies by a slight amount from one year to the next. Changes within the Tidal Epoch are important when calculating average tidal conditions such as mean sea level or mean tidal range. Longer-term changes beyond the Tidal Epoch can be major due to associated glaciation effects with paleo records indicating sea level changes of more than 100 metres, albeit occurring over millennia rather than decadal temporal scales.

## Non-Astronomical Forcing

In addition to long-term glacial cycles occurring over millennia (tens or hundreds of thousands of years), there are other more immediate non-astronomical factors affecting the ocean's water levels which must be understood in assessing sea level records and trends.

Barometric effects due to low and high atmospheric pressure systems cause a relative rise and fall in water levels equivalent to 10 mm change in water level per hectopascal. Wind stress from strong winds blowing over the sea surface can also raise and reduce water levels downwind and upwind, particularly in shallow coastal waters. The combined effects of low atmospheric pressure and strong onshore winds during coastal storms is termed storm surge and can raise coastal water levels in NSW by up to 0.5 metres.

Steric effects result from water density changes caused by changes in ocean water temperature and salinity resulting in seasonal or interdecadal raising or lowering of the sea surface. Steric (and current) effects from warm core eddies of the East Australia Current can raise local sea levels by 0.3 metres to 0.5 metres for sustained periods at Lord Howe Island and Norfolk Island. Ocean Currents can raise/lower sea levels by transporting large quantities of water in/out of an ocean basin during inter-annual and/or interdecadal cycles.

Seiches are long period (minutes to hours) standing waves that occur in bays and harbours from meteorological events. Coastal trapped waves are caused by remote meteorological disturbances and travel along continental shelves. In NSW, these typically originate in Base Strait and propagate from south to north causing sea level fluctuations of up to  $\pm 0.2\text{m}$ .

In addition to these effects, waves breaking along a shoreline can create a superelevation in coastal water levels known as wave setup. Wave setup of up to 1.5 metres has been recorded on the NSW coast during major storms. Tsunamis from seismic activity in the ocean can also generate seiches with amplitudes of up to 0.6 metres having been recorded along the NSW coast following the 1960 Chile earthquake.

The difference between the predicted astronomical tide and the recorded ocean level is commonly referred to as the tidal anomaly or residual and is attributed to the above non-astronomical sea level forcing factors.

## Examples of NSW Tidal Anomalies

**Figure 11** shows typical tidal anomalies recorded along the NSW coast from Tweed Heads to Eden between July 2012 and June 2013. Label 10 in **Figure 11** shows an example of a typical positive anomaly (setup) of between 0.2 and 0.4 metres that took place between 30 March and 5 April 2013 that was caused by an east coast low pressure system coupled with a southward extension of the East Australia Current (warm water) as shown in the inserts in **Figure 11**. Both the low atmospheric pressure system and the warmer ocean waters each contributed to raising sea levels above the astronomical tide levels during this period. A full description of the other tidal anomalies shown in **Figure 11** is documented in MHL (2013).

The sea level and tidal residual (anomaly) at Eden on the NSW south coast is shown in **Figure 12** depicting the arrival and local sea level effects of the March 2011 Tsunami in Japan. While of no comparison to the devastating effects experienced along the Japanese coast, Tsunamis can have significant effects along the NSW coastline, including damage to moorings and other coastal structures from long period seiches and currents despite relatively attenuated amplitudes.

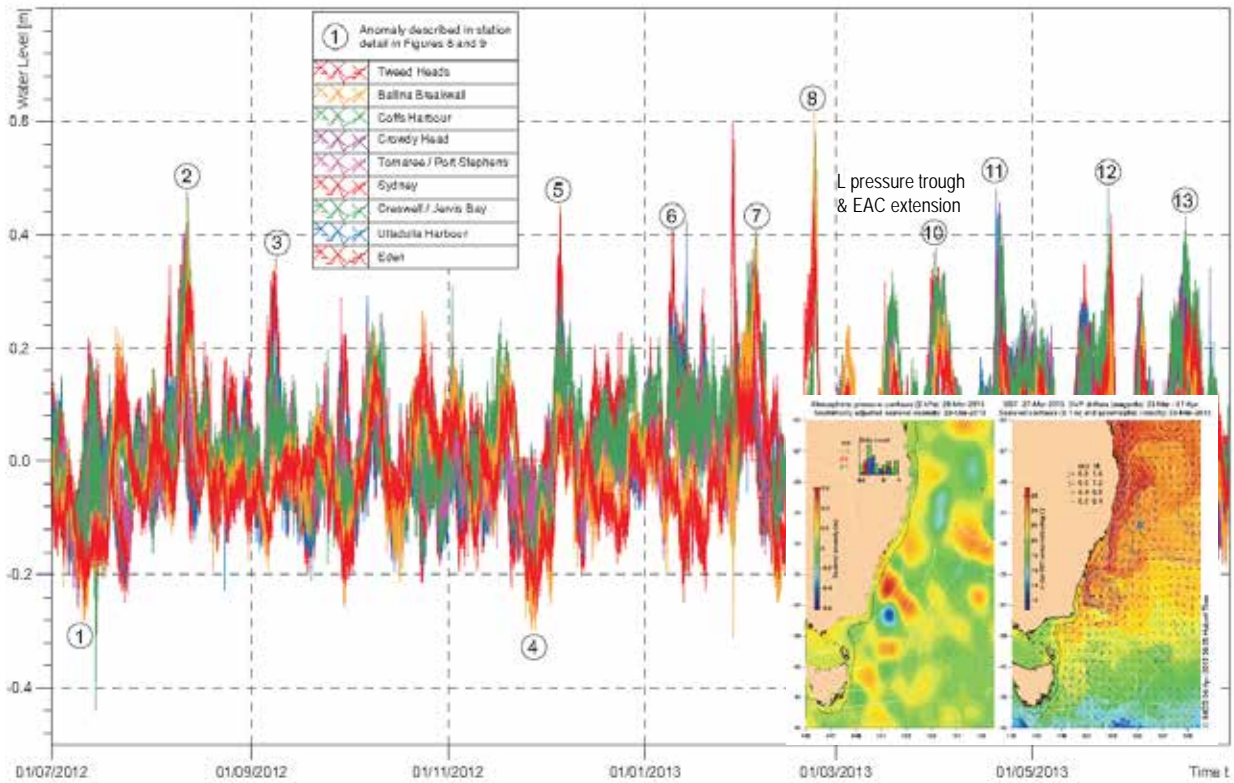


Figure 11. Examples of NSW Tidal Anomalies, July 2012 – June 2013

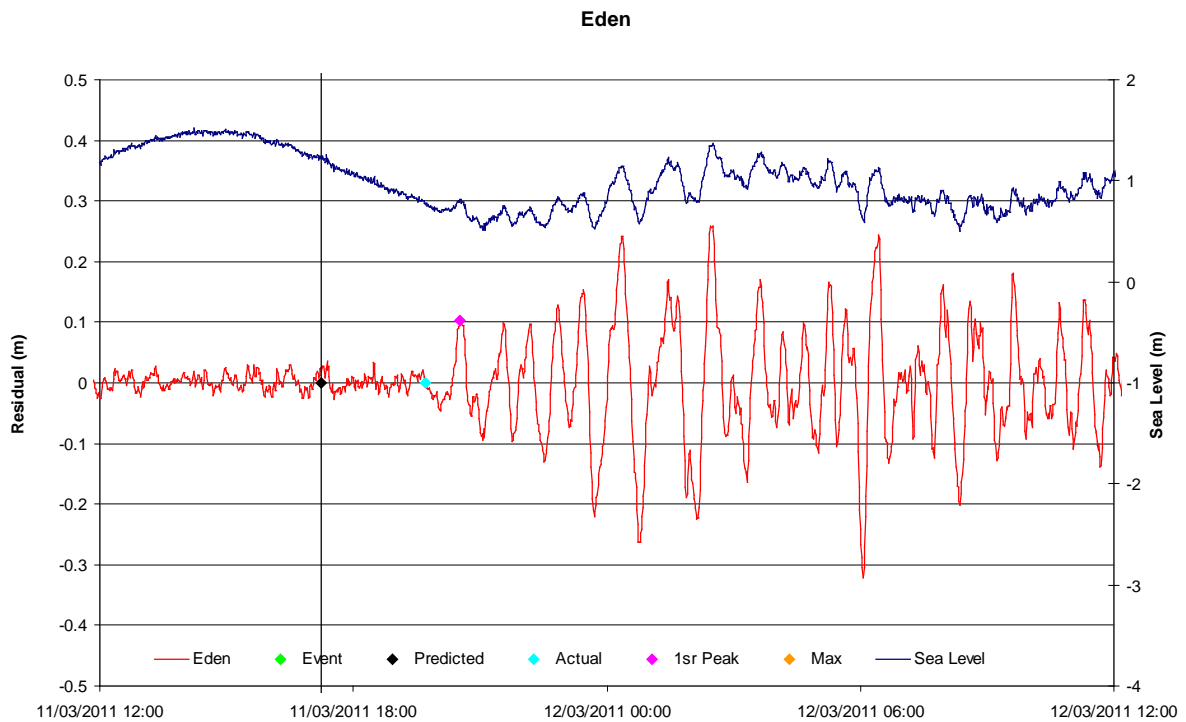


Figure 12. Example of Japanese Tsunami – Eden Gauge March 2011

## Summary of Ocean Water Level Forcing

We can classify ocean and weather variability based on short term daily cycles comprising semi-diurnal tides and weather fronts. Monthly Spring and Neap tidal cycles overarch these with annual “king” tides and seasonal weather cycles. Inter-annually, the El Niño/La Nina (ENSO) cycle affects ocean currents and weather systems episodically in a 3 years to 5 years cycle. ENSO is well known but not so well understood. Interdecadal climate variations as characterised by the Pacific Oscillation Index (IPO) operate in 20-30 years phases or 50-60 years cycles which are still poorly understood but evident in sea level records as described below.

Longer term, over thousands of years cycles, we know that mean sea levels change with changes in astronomical forcing, solar radiation, glaciation and other atmospheric effects. Climate change and associated sea level change, whether anthropogenic, natural or a combination of both, takes place over hundreds or thousands of years with available gauge records being masked by short term variability of at least comparable magnitude.

## Understanding Long-term Sea Level Trends

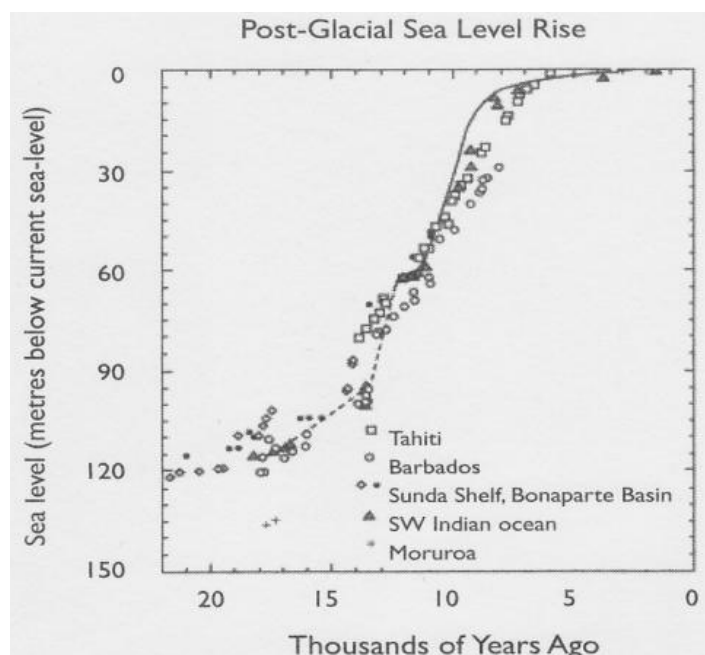
### Paleo and Anthropogenic Sea Level Evidence

It is interesting and important to recognise just how much the climate has changed over time. From undisputed paleoclimatology and geological evidence, sea levels have varied from about 5 to 10 metres higher than present levels some 125,000 years ago to about 120 metres below present levels about 18,000 years ago (**Figure 13**). The main influence on sea levels is from changes in the mass of ice sheets during and since the last glaciation. Sea levels are then indicated to have risen rapidly (by up to 4 metres per century) until about 8,000 years ago to be some 3 metres below present levels. The Holocene still-stand of the past 6000 years is the longest period during which the climate, and so sea level too, has been relatively stable, but even then there has been variability of  $\pm 1$  to  $\pm 2$  metres.

It is well understood that sea level rise has been due to both warming of the oceans and ice melt, but only from land-based ice such as the ice sheets on Greenland and Antarctica, as floating ice such as in the Arctic already displaces its own weight in water. Long-term tectonic factors, including land mass rebound following reduced mass from ice melt and continental plate movements responsible for oceanic basin volume changes are also important factors.

Our coastal society developed in a time of stable sea levels. It is interesting that past sea levels have been higher than today at temperatures similar to what we expect by the year 2100.

Anthropological evidence also



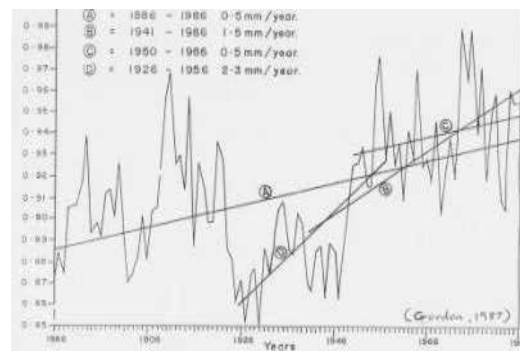
**Figure 13. Undisputed Sea Level Trends during past 20,000 years** (after Carter, “The Counter Consensus” 2010)

suggests strong linkages between the rise and fall of civilisations and climate variability, where civilisations have prospered and expanded during warm conditions and collapsed and/or undergone invasions during cold periods (Gordon, 2013). From an Australian perspective, there has been Aboriginal occupation of Australia for at least 40,000 years and possibly 60,000 years. That is, the indigenous people of Australia have experienced, and adapted to, major climate change, and sea level variability of some 130 metres. Aboriginal dreamtime stories reflect this. For example ‘Sow and Pigs’ reef in Sydney Harbour was once a hill in a valley, and an important spiritual site of the Guringai (Ku-ring-gai) People called Boora Birra. The law legend also tells how Sydney Harbour was created by rising sea levels (Bodkin 2001).

## Historical Sea Level Records

The Global Sea Level Observing System (GLOSS) Core Network (GCN) contains 289 stations including Fort Denison (GLOSS10, 2014).

**Figure 14** shows the type of variability in sea levels at Fort Denison that typically occurs from year to year, mainly due to non-astronomical factors such as El Niño/La Niña (ENSO) and the IPO. It is noted that various sea level “trends” are plausible depending on the adopted record length and start/end of the analysis period.

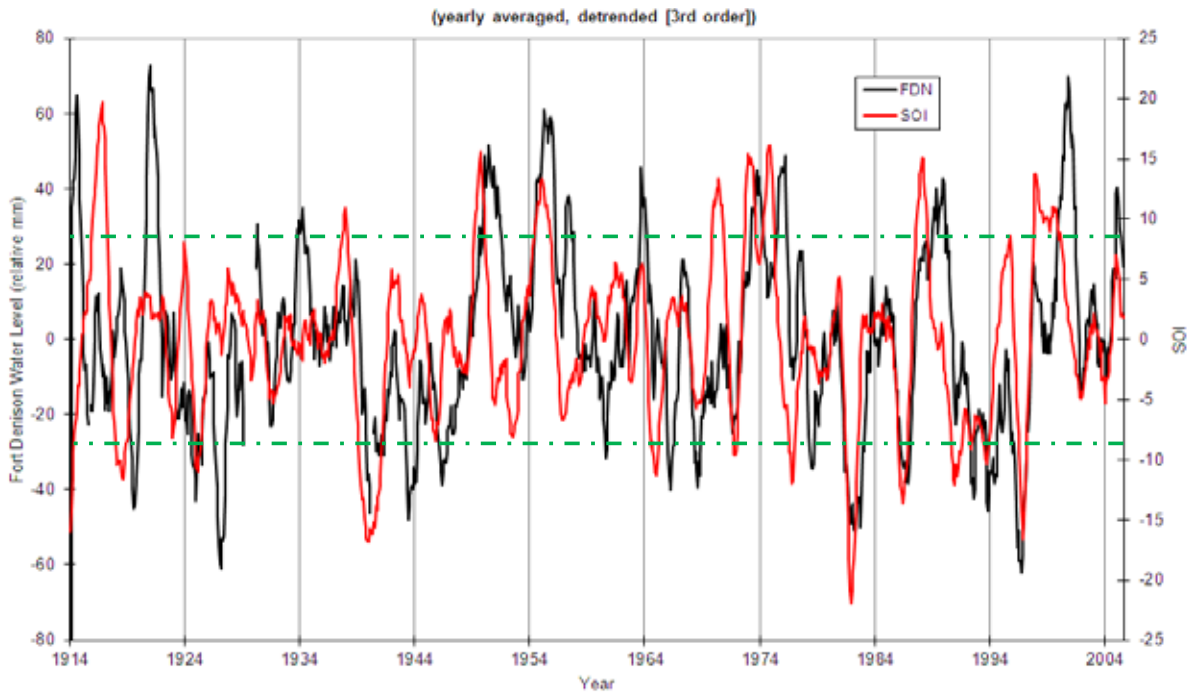


**Figure 14. Fort Denison sea level “trends”**

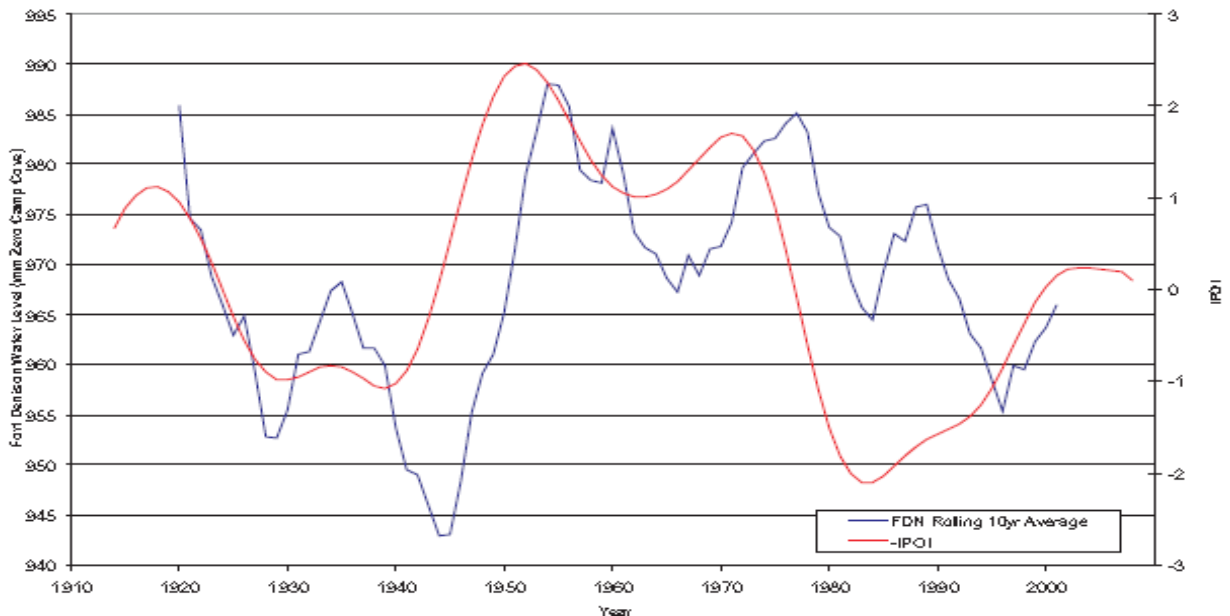
It should be evident by now that sea level change is not linear, and long-term trends can only be confidently assessed if reliable records extend for centuries to average out the effects of both inter-annual and interdecadal influences. The longest continuous tidal records extend back to 1774 in Stockholm, but the quality of early records, particularly with respect to datum shifts and/or land movement is questionable. Similarly, tidal records for Fort Denison commenced in 1886 but quality controlled sea level data exists only since 1914, barely covering two cycles of the IPO. Notwithstanding this, the indicated sea level rise trend at Fort Denison of 1 to 3 mm per year is consistent with the geocentric global average sea level change (IPCC, 2013).

Comparing GLOSS10 station records, there are regional differences in the indicated rate of sea level rise, however, with vertical land motion corrections applied, the regional differences are reduced (IPCC, 2013). Recent trends of accelerated sea level rise from both gauge records and satellite observations could be associated limited records length and interdecadal forcing, although accelerations are supported by climate change modelling (Bindoff et.al., 2013).

**Figure 15** shows the yearly average sea level at Fort Denison (de-trended by subtracting the average rate of sea level rise of 0.9 mm/year from 1914 to 2006) against the Southern Oscillation Index (SOI). Sustained positive values of the SOI (above +8) indicate a La Niña event, while sustained negative values (below -8) indicate an El Niño event. **Figure 15** indicates a strong correlation between average sea levels along the NSW coast and the SOI. Similarly, inter-decadal trends are evident in comparing the 10-year rolling average de-trended Fort Denison sea level with an inverted Inter-decadal Pacific Oscillation (IPO) as shown in **Figure 16**.



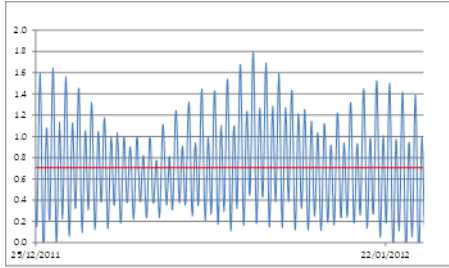
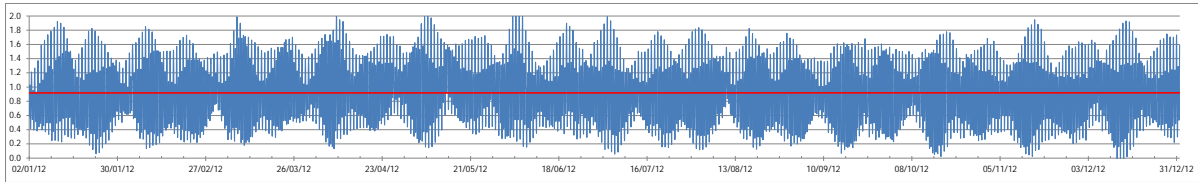
**Figure 15. Southern Oscillation Index (SOI) Correlation with NSW Sea Levels – Fort Denison (FDN), 1914 to 2006; MHL1881**



**Figure 16. Interdecadal Pacific Oscillation Index (IPOI) Correlation with NSW Sea Levels – Fort Denison (FDN) 1914 to 2010**

## NSW Sea Level Trends

**Figure 17** shows a typical annual time series of NSW ocean tides for Port Kembla with the insert showing a typical fortnightly Spring / Neap tidal cycle. The average monthly and average annual sea levels for each of the NSW coast gauges is shown in **Figure 18** (excludes some gauges), depicting both inter-annual and interdecadal variability consistent with both astronomic and non-astronomic forcing attributable to the East Australia Current, ENSO and IPO cycles as discussed above.

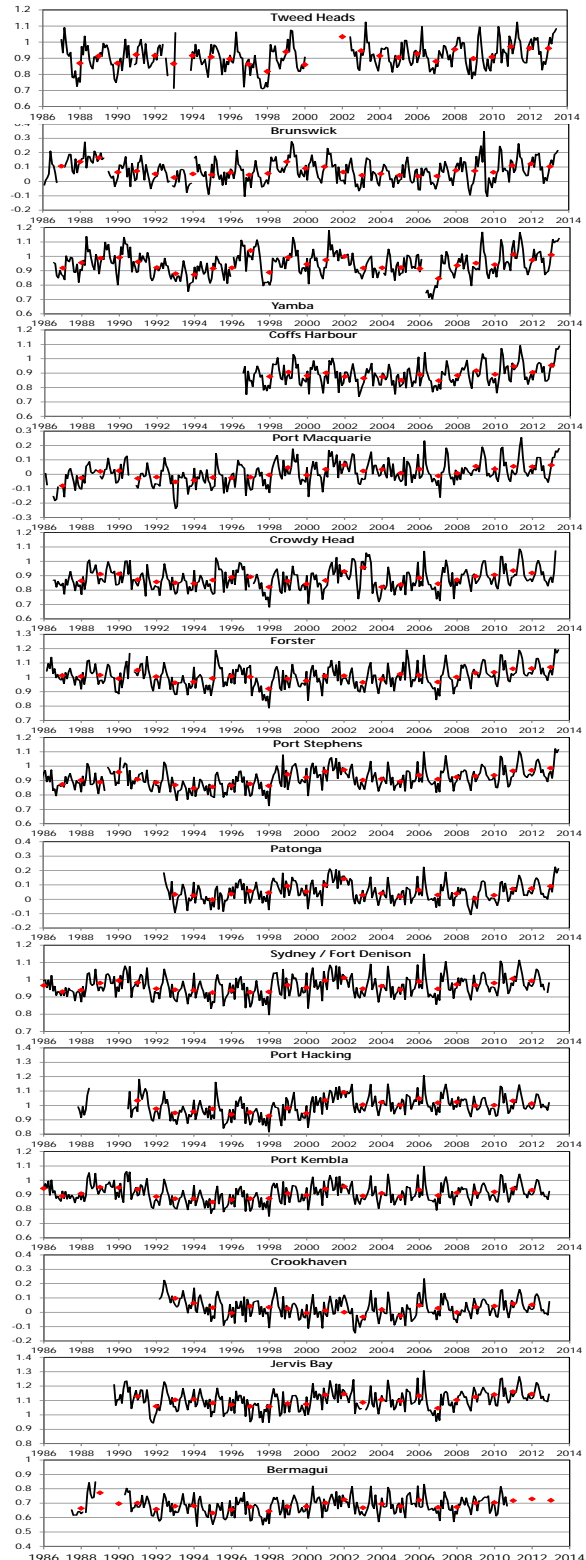


**Figure 17. Typical Annual Time Series of NSW Ocean Tides – Port Kembla 2012 (insert shows fortnightly Spring / Neap Cycle)**

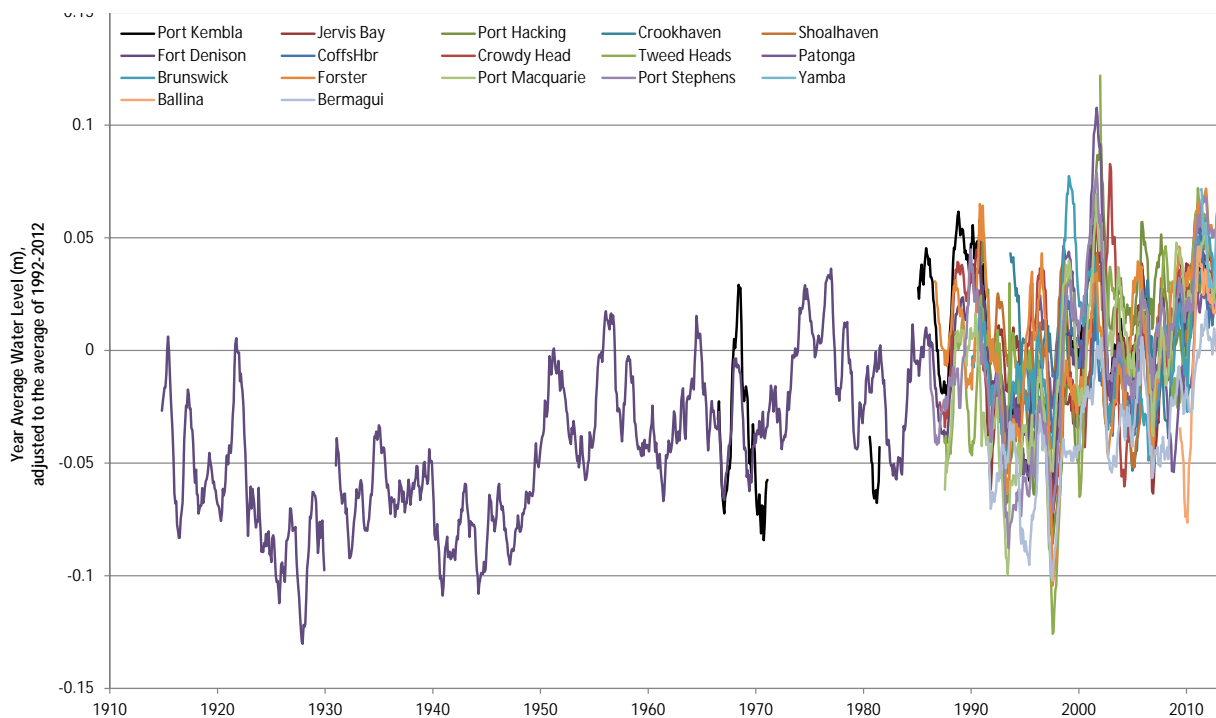
It is important to recall that long-term sea level trends along the NSW coast cannot be determined from the limited gauge record length as records do not even cover one IPO cycle and indicated trends range from -1 mm per to +4 mm per year depending on the start and end dates for the analysis period.

These inter-annual “trends” are not representative of long-term sea level change; however, these trends may be important in assessing local relative sea level change for a particular area. While there is insufficient information available for the accurate determination of land level movement in NSW, this is expected to be relatively small (with the exception of areas affected by mining subsidence) compared to projected sea level rise scenario estimates.

As Fort Denison is the only station to have sufficient data to average out known medium-term ENSO and IPO cycles, **Figure 19** shows yearly average relative sea levels long the NSW coast presented to a common datum relative to the Fort Denison records, depicting common trends, albeit showing some phase / magnitude differences characteristic of physical movement of ocean currents and weather systems along the NSW coast. So, it may be concluded that Fort Denison can be considered to be a good indicator of longer-term historical sea level trends for the NSW coast.



**Figure 18. NSW Monthly and Annual Average Sea Levels (1986 to 2013)**



**Figure 19. “Superimposed” Monthly Average Sea Levels along the NSW Coast (1914 to 2013)**

## Summary and Discussion of Sea Level Trends

Clearly, global sea levels rise and fall over a multitude of time scales, from semi-diurnal, monthly, annual and inter-annual cycles to inter-decadal and inter-millennial progressions that create many traps for the unwary.

Sea levels move up and down due to changes in astronomical and non-astronomical (meteorological/hydrographic/tectonic) forcing with typical variations of  $\pm 0.2$  metres to  $\pm 0.6$  metres, which can mask longer term sea level trends.

Fort Denison has been shown to be a good indicator of longer-term sea level trends for the NSW coast. Consistency between Fort Denison and published global trends in sea level (of approximately 1 mm/year to 3 mm/year) indicate that NSW should consider published sea level rise projections to be representative of that expected for the region.

As with tidal response, however, average sea level change is not uniform around the globe. Sea level change must be considered as being both geocentric and relative. Relative change at a particular location is of most interest to coastal zone managers.

## NSW Ocean and River Entrance Metadata

### What is Metadata

Tide gauge metadata includes information relating to when the original gauge was installed and whether the gauge has been changed, moved or the technology upgraded. Details should include respective tide gauge technology/data capture systems employed over time, details of the location of the gauge and whether it has changed over time. If original tide charts exist, metadata should document where these are located and should identify other issues that may relate to the gauge information including land subsidence, tectonics,

reclamation works, riverine influences or major changes in entrance configuration affecting tidal harmonics (for estuarine locations).

## **Why Store Metadata**

Investigations into sea level changes depend on the accuracy, quality and completeness of available long-term sea level data. Long-term sea level monitoring programs are generally varied through time with shifting priorities and improving technologies. Metadata for the available tide gauges is often limited, inconsistent and hard to find, making the review of available data difficult. A detailed account of Australian tide station metadata is reported by MHL (2012), including summaries of metadata for NSW and 12 national tide gauges. These metadata should always be consulted before undertaking any analysis using tide gauge records.

## **Sustaining Continuous Quality Records**

### **Understanding Value and Needs**

Engineers Australia (1997) demonstrated that engineering and technology-services are particularly dependant on reliable data and to make effective judgements requires reliable data, as information reduces uncertainty and hence ensures that unnecessary capital is not spent in over-design or, conversely, that under-design does not lead to expensive failures. The costs of uncertainty were demonstrated to be significant (tens of millions of dollars) using case studies, including over-design or under-design (failure) of coastal structures.

The NSW ocean tide network supports a wide range of professional and recreational activities on the coast, with multiple stakeholders that individually and collectively place high value on the information utilised for design, planning, emergency management, operation of ports and marine facilities, water level forecasts, recreational and commercial fishing, swimming, property boundary definition and developing detailed understanding of oceanic and coastal processes. Continuity of quality controlled water level records are of increasing value in understanding sea level rise and in particular, to develop effective triggers for future adaptation.

### **Making Information Available**

The NSW ocean water level records and analysis results are available to all key stakeholders, including state, federal and local government as well as other organisations both in Australia and overseas. Online access to information further strengthens the sustainability of these programs by increasing stakeholder breadth and depth and avoiding ineffective data poor judgements.

Data requests can take the form of hard copy requests, verbal requests (telephone or personal communication) and electronic requests (via email or the internet). Typically NSW Public Works MHL receives about 1000 hardcopy data requests each year and over 1.8 million requests via the internet.

## **Funding**

An ongoing, comprehensive and effective data collection program is essential to the future prosperity of Australian businesses and the community. Government has a number of roles including achieving social goals, rectifying market failures, managing macro-economic policy and caretaking of community property. To make effective judgements in all these areas requires reliable data. In recognition of the value of reliable data for multiple stakeholders

and the broader community, the NSW government has provided funding for the collection, archiving and dissemination of NSW coastal and flood data since the late 1980's. Sustainable ongoing funding is dependent on continuing to modernise data networks to achieve cost effective and reliable programs that are well aligned with present and future stakeholder needs.

## Conclusions

Through an understanding of ocean water level measurement systems and the primary ocean water level forcing mechanisms operating across different timescales, this paper aims to avoid misinterpretation of sea level gauge data.

Despite over 25 years of highly valuable continuous quality controlled sea level data for NSW, long-term sea level rise trends based on these data are not necessarily representative of expected future long-term sea level change. Record length, start/end date and averaging methods all have marked effect on indicated "trends". Inter-annual and inter-decadal trends are similar along the NSW coast and Fort Denison records provide a reasonable representation of longer term sea level along the NSW coast.

Despite the many complexities and uncertainties in climate change and sea level rise, there is undisputed change taking place. Whether or not sea level rise is accelerating due to human influence, sea level rise must be considered to make effective planning and design decisions on our coast.

Our understanding of the processes driving spatial and temporal sea level change continue to improve, based on continuous monitoring, which will become increasingly important to identify relative sea level change and to signal local triggers for adaptation.

Given the inherent complexity of processes operating, however, experienced practitioners must be consulted to develop understanding of local processes and relative sea level changes to develop risk based planning benchmarks and implementation guidelines. A risk based toolbox of adaptive strategies is best suited to deal with the uncertainty, noting sea level rise adaptation should occur at a local / regional scale.

## Acknowledgements

The authors wish to acknowledge the support of the Office of Environment and Heritage (OEH) for their vital role in sustaining the NSW ocean water levels program. It is emphasised also that many officers from MHL should be acknowledged for their contributions towards continuous quality records and efficient network operation, in particular Phil Clark, Ben Cox and John Vaubell (field) and David Griffin, Andrew Judge and Adriaan Worlee (data).

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