The Factors Contributing to the level of Confidence in the Tidal Predictions   Accuracy of Tidal Predictions

1 Introduction

1.1 Terms of Reference

The Association of Australian Port and Marine Authorities (AAPMA) Hydrographic Surveyors and the Permanent Committee on Tides and Mean Sea Level (PCTMSL) conducted concurrent meetings at Cairns on 22 to 23 April 2005. The members of the PCTMSL working group were invited to attend the surveyors meeting for the discussion of their agenda item 8, “Need for Operational Tide Gauges in Ports”.

At the conclusion of the discussions that centred on the accuracy of the secondary port tidal predictions, Captain Nairn, Hydrographer RAN and chair of the AAPMA Hydrographic Surveyors meeting, referred the following questions to the PCTMSL working group members:-

1. What are the factors that contribute to the level of confidence in the tidal predictions?
2. What is the level of confidence in tidal predictions of secondary and standard ports?

Note:- Where the context permits the words:-

“prediction” includes harmonic and non-harmonic processes of tidal prediction; and,

“readings” includes observations or predictions of tidal times, heights and streams.

1.2 Introduction

The height of the sea level changes in response to a number of stimuli. The obvious stimuli are the gravitational forces that maintain the sun, moon, and earth in their orbits. The relative positions of these bodies and the associated gravitational forces are continuously changing. The daily tides are the result.

Because the orbits of the bodies are precisely known, the variations in the forces can be used as a basis for predicting the tidal times and heights (stream vectors) known as the gravitational tide.

The water level along the coast and in the coastal estuaries and streams also responds to forcing by the atmosphere and other natural events such as fresh water flooding, tsunami, and shelf waves.

Obviously the tide does not occur at the same time or height everywhere.

Accordingly it is necessary to observe the tidal times and heights, at each place where tidal information of any kind is required. Obviously it is not practicable to observe the tides at all places. As a result the tidal times and heights are recorded only at convenient places along the coast, usually at a tidal station situated within a port.

After a suitable period of tidal recording is obtained, it is possible to prepare predictions of future tidal times and heights, based upon the observed readings. Once tidal predictions are available, it is not essential to continue recording the tides. However, depending on how critical is the use of the tidal times and heights, prudence may dictate that the observing program should continue indefinitely.

1.3 Tidal Prediction

Tidal predictions are a representation of the tide as it actually occurs. They are a hind cast or forecast based on a series of observations at the place, that is, tidal prediction is an extrapolative process using one of the so called harmonic or non-harmonic methods.

1.4 Standard Ports

A standard port (may also be called reference tidal station) is a place where tide or tidal stream constants have been determined from observations, and which is used as a standard for comparison of simultaneous observations at a subordinate station. (IHO 1994)

The predictions for Australian standard ports are exclusively prepared directly from tidal observations by the harmonic method. Refer to Appendix 1 for an outline of the method.

1.5 The level of confidence

In order to have confidence, it is necessary to assess and quantify the difference between the predicted and actual tide. For the purposes of this report, the statistics of the difference between the predicted and actual tide (non-tidal residuals) are accepted as being a measure of the "level of confidence" referred to in the terms of reference.

2 What are the factors that contribute to the level of confidence in the tidal predictions?

2.1 Discussion

All tidal information as a degree of uncertainty that will lower the confidence in the tidal predictions:-

1. Carefully recorded information has the least uncertainty;
2. Harmonic tidal predictions have a higher level of uncertainty; and,
3. Tidal predictions based on non-harmonic processes (such as the ratio process) have the highest level of uncertainty.

Tidal predictions are necessarily based on tidal observations recorded at the tidal station. The precision of all prediction methods depends upon the precision of the observed readings used to generate the necessary the harmonic constituent constants.

As already indicated, tidal prediction is an extrapolative process the success of which is dependent upon the causal agent (in this case the gravitational tides of the ocean) and the factors (the tidal constituent constants, and the environment) relating the cause to the effect (the tidal predictions) remaining unchanged.

Any change to the factors relating the cause and effect invalidates the prediction process and the results from it.

2.1.1 Gravitational Tides

For practical purposes it is accepted that the gravitational tides remain unchanged.

2.1.2 The Real World Tides

It is possible for the tidal regime (as measured by the tidal constituent constants) at a place to change under the influence of natural or anthropogenic modification to the waterway adjacent to the tidal station.

For the purposes of this paper, the tide may be considered as a progressive wave. As such it interacts with its environment, that is the depth and shape of the waterway, through which it travels. This interaction (the so called shallow water effect) distorts the sinusoidal shape of the time series of tidal heights that is indicated by the theory of the gravitational tides. Fortuitously, while the environment in the vicinity of the tidal station remains substantially unchanged, the shallow water effects also remain constant and can, to a large extent, be included in the tidal prediction process.

2.1.3 The Effect of Calculation Processes

Different calculation processes will always produce different time and height predictions. The only way to achieve consistent predictions is to use one calculation process.

Because the harmonic process is based on tidal theory, this is the most accurate tidal prediction process available to calculate the times of high and low water and tidal heights at intervening times. It is the method of choice and it used to prepare the official standard port tidal predictions for the Australian National Tide Tables and similar state government official tide table publications.

2.1.4 Consistency

Any inconsistency between tide tables raises doubts in the mind of the uses, particularly mariners to whom tide tables are critical input to the safe operation of ships. As an imperative of their profession, mariners are highly risk averse. Any inconsistency reduces their confidence in the tidal predictions.

There are international precedents for the concept that there should be only one tide table for each place this. In order to avoid publication of inconsistent tidal predictions the IHO urges agencies to share them.

2.2 Contributing factors

There are factors that increase (conversely diminish) the confidence one may have in the tidal predictions.

2.2.1 Factors diminishing confidence

These are the factors that the tidal analysist must consider when preparing tidal predictions.

Clearly there is some variability associated with the predictions prepared by any method. Any unexplained variation serves to diminish the confidence in the tidal predictions.

All of the following factors result in poorly performing or inconsistent tide tables:-

1. The observations used as the basis of the tidal predictions:-

    a. Their accuracy;

b. The degree to which they are typical of the average tidal conditions at the station (i.e. they are not unduly affected by storm tide, fresh water flood, etc);

c. The period of observations available for use as the basis of the predictions;

d. The degree to which the tidal station is subject to meteorological effects, storm tide and so on.

2. Changes to the environmental conditions that modify the tidal height and flow, principally the water depth in the vicinity of the tidal station and the depth and/or width of the waterway connecting the station to the open sea. Any such change violates the requirement that the factors used in the prediction process must remain truly constant.
   Environmental changes are discernable in the tidal record as changes over time to the:-

   a. "Shallow water" effects; and,

   b. The "shallow water" constituent constants.

3. Imperfections in the tidal harmonic model used:-

   a. The number of tidal constituents that can be resolved from the available tidal recordings;

   b. The appropriateness of the constituents selected to form the tidal model, including any constituents inferred, or selected as "related" constituents;

   c. How well the shallow water effects are represented; and,

   d. How well the seasonal variation of mean sea level is represented.

2.2.2 Factors increasing confidence

The following factors tend to counteract the uncertainty engendered by any unexplained variation. They contribute to an increase in the confidence in the tidal predictions prepared by either the harmonic or non-harmonic methods:-

1. The availability of tidal recordings for the execution of regular checks of the predicted tide times and heights;

2. Rigorous operation of the tidal recording station;

3. Quality assured preparation of the "Official" tidal predictions for the port;

4. Regular testing and reporting on the variability between the observed and predicted tidal times and heights; and,

5. Adherence to the concept of only one tide table for each port tidal station (that is, 100% consistency of the tidal predictions is maintained).

3 What is the level of confidence in tidal predictions for standard ports?

As indicated above the level of confidence achieved in standard port tidal predictions is expressed through the statistics of the non-tidal residuals.

Tidal prediction (given the tidal constituent constants) is the converse of the analysis process. Accordingly any consideration of the level of confidence in the tidal predictions commences with an examination of:-

1. The observations that were analysed to produce the constituent constants;
2. The environmental conditions (mainly depths) in the vicinity of the port tidal station; and,
3. The tidal model used to calculate the:-
    a. Tidal constituent constants: and,
    b. Resultant predictions.

Note In order to ensure consistency is critical that the same model be used in both the tidal analysis and prediction processes.

3.1 The Observations upon which the Predictions are based

There are three matters to consider. They are:-

1. The rigour with which the readings are checked and the station is calibrated;
2. The degree to which the observations are typical of the tidal regime at the place (The meteorological effects on tides); and,
3. The number of tidal constituent constants that may be drawn from the available observations.

3.1.1 Accuracy

The accuracy of tidal recordings depends upon the rigour with which the readings are checked and the station is calibrated. Refer to Appendix 3 Calibration of Tidal Stations.

By way of example, the daily water level check readings from the Brisbane Bar undertaken for the month of July 2005 gave the following calibration parameters:-

Instrument Reading = 1.004*Tide Board Reading + 0.002 with the following standard errors:-

Multiplying factor 0.009; and;

Additive constant 0.010.

These readings from the calm conditions at Brisbane Bar have a spread of 4 centimetres relative to the recorder reading.

It is expectable that the variation will be larger at more exposed sites.

Given that the height of the tide board is set correctly, the mean offset of the recorded readings relative to chart datum (also called the elevation of the chart zero of the recorder) has a span of +/- 2 centimetres.

In addition to water level checks, it is necessary to ensure that:-

1. The tide board at the station is correctly graduated and that its zero is set exactly at the height of chart datum;

2. The tide gauge clock is set exactly to local standard time;

3. The relationship between the recorded and actual readings is linear; and,

4. Any instrumental biases (height, time, or non-linearity) are removed from the recorded readings.

Clearly the observational accuracy achieved at any other station will depend upon the environmental conditions and the rigour with which it is operated and calibrated.

3.1.2 Meteorological effects on tides

The water level responds to forcing by the atmosphere, e.g. the so called "inverse barometer effect" associated with the changing barometric pressure. Weather events, strong winds, large barometric pressure changes, cyclones, tropical lows, extra tropical lows, and the like, also impact on the sea level by imposing wind stress on the water surface resulting in:-

1. High wave conditions (with the associated wave set up); and,

2. A super elevation of the water surface known as storm surge.

Because it is not possible to make refined and detailed forecasts of the weather and shelf waves for more than about a week or so in advance, the sea level variations associated with it are regarded as an unpredictable, random and a normal part of the daily tides.

Other natural events such as fresh water flooding and tsunami are obvious in the sea level record and can be removed from it.

Meteorological conditions that differ from the average will cause corresponding differences between the predicted and the actual tide.

> "Meteorological conditions which differ from average will cause corresponding differences between the predicted and the actual tide. Variations in tidal heights are mainly caused by strong or prolonged winds and by unusually high or low barometric pressure. Tidal predictions are computed for average barometric pressure.
> Low pressure systems tend to raise sea levels and high pressure systems tend to lower them. The water does not, however, adjust itself immediately to a change of pressure. It responds, rather, to the average change in pressure over a considerable area.
> The effect of wind on sea level and therefore on tidal heights and times is variable and depends on the topography of the area in question, in general, it can be said

> that wind will raise the sea level in the direction towards which it is blowing. A strong wind blowing straight onshore will "pile up" the water and cause high waters to be higher than predicted, while winds blowing off the land will have the reverse effect.
>
> (Anon 2005a)

Each tidal station is subject to different and wide-ranging weather conditions. The southern parts of Australia are subject to strong and frequent cold fronts evidenced:-

1. As strong winds – Diagram 3 Hourly Wind Speeds (m/s) – March 2005

2. Very large pressure variations typical of the passage of the weekly cycle of pressure systems across Australia in - Diagram 4 Hourly Atmospheric Pressure (hPa) – March 2005

The weather conditions in the northern latitudes are more benign and the associated weather effects on the tidal heights are not particularly severe.

Except in extreme cases it is not possible to illustrate graphically the effect of the weather on the tidal heights themselves. See Diagram 15 Cyclone Althea – Townsville 24 December 1971 for an example of an extreme case.

However the non-tidal residuals reveal the effect of the weather on the sea level. Figure 2 details the non-tidal residuals associated with the weather conditions depicted in figures 3 and 4. The frequency of the and magnitude of the non-tidal residuals is visibly correlated to the frequency and strength of the weather events.

Superelevation of the water level by freshwater flood is an indirect effect related to the weather. The flood may last for a number of days if not weeks or longer.

In conclusion, it is important for the tidal analysist to know the degree to which the sea levels used as the basis of the tidal predictions are typical of the average tidal conditions at the station (that is the observations do not include large and or frequent atypical meteorological effects such as storm tide, fresh water flood, etc).

3.1.3 Period of observations available for use as the basis of the predictions

Because of its origin in the varying gravitational forces of the moon, sun, and earth system the tide is a periodic phenomenon. Tidal analysis sets out to decompose the tidal height time series into a polynomial composed of simple harmonic functions, each with a frequency (speed number) provided by tidal theory. These simple harmonic functions, known as tidal constituents are used to prepare the tidal predictions.

Tidal heights result from a natural continuous – analogue - process. The necessary digitisation process:-

1. Produces a series of discrete samples separated in time by "h" hours; and,

2. Introduces the phenomena known as aliasing.

The sampling interval “h” limits the highest frequency (i.e. the nyquist frequency) that can be defined for the series to ½ h cph. Any frequencies higher than the nyquist frequency will “fold back” into the lower frequencies contaminating them and any subsequent calculations, such as the tidal analysis and predictions. (Schahinger and Lennon 1984).

The nyquist frequency sets the upper bound of the constituent constants that may be reliably deduced from a given set of observations. Observations made by digital recording systems at a time separation of 10 minutes (nyquist frequency of 3cph or 72 cpd) are more than adequate for tidal analysis which is usually undertaken using readings that are filtered to and decimated to 1 hour apart (nyquist frequency ½ cph or 12 cpd).

The lower bound is set by the tidal frequency that completes one cycle in the period of readings that is available, for example:-

1 year	1 cycle per year. The constituent constant Sa representing an annual cycle of the mean sea level
185 days	2 cycles per year. The constituent constant Ssa representing a semi-annual cycle of the mean sea level
28 days	13 cycles per year. The constituent constant Mm representing a monthly cycle of the mean sea level
Note:-	There are other limitations that impact the selection of constituents. For a discussion see 3.3.2 Number of Constituents.

3.2 Changes to the environmental conditions

Changes to the environmental conditions, principally the water depth in the vicinity of the tidal station and the depth and/or width of the waterway connecting the station to the open sea, modify the tidal height and flow. These changes to the tidal regime are discernable in the tidal record as changes to the “shallow water” effects and as changes to the factors used in the prediction process.

Any change to the tidal regime violates the requirement that the factors used in the prediction process must remain truly constant.

The impact of a change to the environmental conditions is illustrated by the change to the tides of The Broadwater resulting from the creation of the Gold Coast Seaway.

Prior to 1985, The Broadwater drained to the ocean through the Southport Bar. The Gold Coast Seaway was constructed during 1984 and 1985 and the bar was finally closed in mid 1985. The development was finalised in early 1986.

It is known that the development of the Gold Coast Seaway resulted in a change in both the time and range of the tide. (Department of Harbours and Marine 1986, 1987, and 1988).

The impact of the changes on the tidal predictions for The Broadwater is illustrated by the non-tidal residuals at the Runaway Bay tidal station for the observations of 23 January to 4 March 1979. The predictions used to prepare Figure 7 are based on an analysis of the 1979 observations. These predictions fit the observations well. On the other hand the non-residuals depicted in figure 8 were prepared using predictions constituents based on observations from 1987 – a year after the Seaway development was finalised. These latter residuals are poor – illustrating that at least the time of tide had changed. Examination of the tidal constituent constants based on the 1979 and 1987 observations revealed both a change of range and time. The tidal regime at Runaway Bay had changed as a result of the change in the waterway between it and the open sea.

Although the Gold Coast changes were well known, it is possible for subtle changes to the tidal waterways of coastal Australia to occur and to go unnoticed.

Those of us responsible for tidal predictions need to be watchful for changes to the environmental conditions that may change the tidal regime at the tidal station.

3.3 The Impact of an Imperfect Knowledge of the Tidal Model

The tidal model is a mathematical representation of the tidal times and heights. Refer to Appendix 1 The Harmonic Method for an outline of it. During the 1920', Dr A T Doodson developed the model that is used by the National Tidal Centre, Maritime Safety Queensland and other agencies across Australia. His model has been augmented by the inclusion of additional constituents to accommodate the hydrodynamic effect of the shallow water on the tidal wave as it travels though the estuaries and along the coast. In relation to the harmonic method alone, the factors that give rise to or diminish confidence are associated with imperfections in the tidal harmonic model used in the analysis and prediction scheme employed are:-

The selection of constituents that best represent the tide at a particular place (inclusive of shallow water / interaction constituents, seasonal variation in the mean sea level, and any constituents inferred, or selected as "related") or its converse the omission of critical constituents;

1. The number of constituents available for calculation of the predictions; and,

2. How well the shallow water effects are represented in the tidal model.

3.3.1 The selection of constituents to best represent the tide

Desirably the tidal predictions would be based on all of:-

1. The constituents of gravitational origin provided in the tidal model developed by Doodson,

2. The shallow water constituents developed to allow for the modification of the tide as it flows through the shallow and confined coastal waters; and,

3. The meteorological (sometimes called radiational) constituents that represent the seasonal weather effect on sea levels.

The ability to analyse for, and subsequently predict from, all constituents is limited by the quality, sampling interval and duration of the available tidal readings. The constituents are selected on the following frequency criteria:-

1. Highest frequency. The nyquist frequency limits the constituent that may be selected to the one with a frequency equivalent to twice the sampling interval; and

2. Lowest frequency. This constituent is limited by the duration of the available readings. Its frequency is equivalent to one cycle in the data set.

Between the limits spectral analysis in combination with the Rayleigh Criteria or the Rayleigh Criteria alone may be used as a basis for the selection.

Diagram 1 Weipa Tidal Spectra shows a typical spectrum of the tidal observations and of the non-tidal residuals. The difference between the two spectra shows how much of the energy in the tidal observations is explained by the tidal predictions or, in other words, how effectively the tidal predictions represent the tide.

The spectra of the non-tidal residuals assists the selection of constituents for inclusion in the analysis / prediction process by showing if there is energy in the tide that is not explained by the predictions.

Unfortunately it is not always possible to extract sufficient constituents from the available readings to adequately represent the tide. It is therefore necessary to consider which constituents must be included in the representation and what is the effect of those that are not included.

3.3.1.1 Inclusion of Critical Constituents

Those tidal constituents that may be included are governed by the data sample interval, the duration of observations available for analysis and the related Rayleigh Criteria. For any given data set, this may preclude the determination of significant constituents.

At this point a list constituents based on the highest, the lowest, and the nyquist frequency can be determined. It is necessary to determine those constituents that will ultimately provide the best representation the tide.

Amplitude is a ready indicator of the significance of a constituent and so some guidance in the selection of those likely to be present in the readings may be obtained from:-

1. The Doodson's expansion of the tidal potential tidal;

2. The amplitudes resulting from the analysis adjacent tidal station readings; and,

3. A spectral analysis of the observations or of the non-tidal residuals.

It is at this point when some judgement as to reliability of the tidal predictions comes in to play. The decision to include or not include constituents will ultimately impact on the reliability of, and thus confidence in, the tidal predictions.

By way of example, application of the Rayleigh Criteria precludes the direct determination of the constituents P1 and K2 (among others) in the analysis of 35 days of readings. About 180 days of observations are required in order that they may be directly determined.

The constituents P1 and K2 have significant amplitude in the tides of the east coast of Queensland. An allowance must be made for them by way of the process known as "inference" in which the amplitude and phase of P1 and K2 are "inferred" using certain assumptions and the known amplitude and phase of P1 and K2 at an adjacent place where the tidal form is similar to the port under analysis.

Constituents for which values are "inferred" may also be known as "related constituents". Caution is required when selecting the inferencing port to ensure that the form (shape and range) of the tide at the inference port and secondary port are similar.

As indicated above, it is necessary to have at least one year of observed tides in order to determine the low frequency constituents (Sa [annual] and Ssa [semi-annual]). These constituents are used to represent the seasonal variation of mean sea level that is predicted by tidal theory but which is more closely related to the seasonal changes in the weather.

In Australian waters the magnitude of the seasonal variation can reach 0.3 metres (DoD various years). Accordingly the low frequency constituents must always be considered for inclusion in the preparation of standard port tidal predictions. Their omission can seriously impair the accuracy of the tidal predictions.

A significant number of Australian ports are situated in relatively shallow estuaries. As a result the tides are modified be the hydrodynamics of the waterway. It is necessary to include "shallow water constituents" into the tidal model in order to achieve the highest possible accuracy in the tidal predictions. Each estuary is different. Accordingly the applicable "shallow water constituents" differ from place to place and it is not possible to make a general comment on which constituent to include.

3.3.2 Number of constituents

Tidal theory indicates an almost infinite number of constituent constants are required to model the tide. However the practicalities of tidal analysis limit the number of constituents that are available for prediction of the elevation of HAT and LAT. Accordingly it must be recognised that:-

1. There will be some part of the tide which is un-modelled and therefore not included in the predicted tide levels; and,

2. The interaction between the tidal observations and the analysis/prediction process and the level of confidence applicable to the predictions.

The principal long period cyclicities in the tidal record are related to the relative positions of the sun, moon, and earth. Doodson calls them orbital elements Foreman calls them Astronomical arguments:-

Element		**Approximate Period**
s	mean longitude of the moon	1 month
h	mean longitude of the sun	1 year
p	mean longitude of the lunar perigee	8.8 years
N	negative of the mean longitude of the lunar ascending node	18.6 years
p'	mean longitude of the solar perigee (perihelion)	21,000 years

The fifth major cyclicity in the tides, the period of the p' element, is too long to have practical effect - its rate of change is too small to be detected in the available recordings. This element is usually omitted from consideration.

Because of the cyclical nature of the tides it is necessary to analyse data spanning one or more complete cycles in order that the result is not biased. It is of course possible to model the cyclicity and to some extent to make allowance for an incomplete cycle in that way and to use any data span of one month or more. Typically the numbers of constituents that can be evaluated are:-

Span of Observations	**Number of Constituents**
1 month	35 (some of which must be inferred using some assumptions and the constituents from an adjacent tidal station.)
1 year	112
19 years	112 plus many more

From the limited testing that has been undertaken, it is conclude that:-

1. The best determination of the elevation of the LAT and HAT is derived using as many tidal constituent constants as can be deduced from the available tidal observations; and,

2. Acceptable determinations of LAT datum can be obtained from predictions based on observations extending over 3 months or more provided that long term values (necessarily regional) are used for the seasonal variation in mean sea level (represented by the constituents Sa and Ssa).

The analysis of observations of less than one year requires that certain constituents be inferred. There is a risk that the inferred constituent constants will bias the LAT calculations if the form (shape and range) of the tide at the inference port and secondary port are not very similar.

The following tables from Peddersen 2001 are illustrative of the effect that the number of constituents has on the tidal predictions. While the study applies only to the semidiurnal tides at Gladstone and the calculation of HAT and LAT, it shows that as the number of constituent constants was reduced then the range of tide became larger. Effectively the height of high tide was higher as the length of the constituent set was reduced. (A copy of the study report at Appendix 2.

Table 1 LAT calculations using analysis from observed data subsets

	12 month (69 constants)	6 month (52 constants)	3 month (40 constants)	2 month (40 constants)	35 day (38 constants)
HAT	4.78	4.80	4.80	4.88	4.90
Z00	2.31	2.31	2.32	2.35	2.36
LAT	0.00	0.00	0.00	0.00	0.00

Table 2 LAT calculations using constituent subsets from NTF long term analysis 1985--1999

	All available constants (15 years of data & 118 constants)	6 month (52 constants)	3 -2 month (40 constants)	35 day (38 constants)
HAT	4.75	4.82	4.84	4.86
Z00	2.30	2.32	2.34	2.35
LAT	0.00	0.00	0.00	0.00

The best determination of LAT datum (and by analogy the tidal predictions) is going to be derived using as many constituents that may reasonably be drawn (including inference and estimation of the seasonal variation of the mean sea level) from the available observations.

3.4 *Impact of the weather*

The non-tidal residuals are an indicator of the weather effect on the tidal predictions and a measure of the confidence that can be placed in the predictions. The residuals are qualitatively and quantitatively assessed at the completion of each tidal analysis prior to the preparation of the predictions.

In Queensland, the low frequency non-tidal residuals are very similar at places up to several hundred kilometres apart if not further. If the weather event and its associated sea level disturbance are big enough the storm surge will be detected the full length of the coast. Accordingly we know what to expect as far as the weather effects on the tidal predictions.

Cyclonic storm surges are fortunately very rare events in Queensland waters. Provided that period of the surge is very short compared to the data period, experience is that the effects of a cyclonic surge is imperceptible in the tidal analysis and thus has no effect on subsequent tidal predictions. See Appendix 4 (Peddersen 1994)

Storm surges such as those experienced by the southern states and illustrated in the Diagram 2 Six Minute Residual Water Levels (m) – March 2005 do not occur in Queensland waters. These surges, that are associated with the cycle of pressure systems that cross Australia, travel to Queensland as trapped shelf waves. Examination of more extensive records than those depicted in Diagram 2 shows shelf waves are infrequent and of small amplitude.

There are obvious high and low frequency signals in the non-tidal residuals (Diagram 2).

Owing to the cause and effect relationship between the barometric pressure and wind speed, the latter is used to represent the weather in these discussions.

Because of the high correlation between the wind speed (Diagram 2) and the non-tidal residuals the meteorological effect on the tide is accepted as being the low frequency (generally lower than diurnal).

There is frequently but not always a strong correlation between the high frequency non-tidal residuals at adjacent places some distance apart. This leads to some conjecture as to their cause:-

1. It is possible that the tidal constituents being used for the predictions are not fully representing the tide. It is expected that residual due to this cause would be cyclical and on going. There are occasionally larger unexplained non-tidal residuals that last for less than a day. These markers are frequently detected on adjacent stations; and,

2. There is anecdotal evidence that the tidal range is changing. A systematic change in the tidal range produces cyclical non-tidal residuals the amplitude of which synchronises with the seven-day spring/neap tide cycle.

3.4.1 Sea Level Change

There are various estimates of the change of the sea level that is attributed to the “so called” “Greenhouse Effect” climate change. Sea levels are measured relative to the land (relative sea level rise) or relative to the earth centre (absolute sea level rise).

It is now recognized that the relative sea level is:-

1. Rising; and,

2. Episodic with a decadal time scale, i.e. there are times when the rise is relatively rapid and time when it is not and occasionally falling.

The National Tidal Centre includes an allowance of 0.0003 metre rise per annum into the Australian standard port tidal predictions.

Another estimate is provided by Dr. J Church of the CSIRO. He estimates the rise to be 0.0012 metres per annum over years 1920 to 2000. (Church 2004).

However the rate of rise remains a matter of ongoing research.

4 Assessment of the Level of Confidence in the Tidal Predictions

As previously indicated, it is necessary to assess and quantify the non-tidal residuals in order to have confidence in the predictions

Australia is fortunate to have a National Tidal Centre that undertakes both a qualitative and quantitative assessment of the accuracy of the official tidal predictions for Australia as a part of its quality assured tidal analysis and prediction process.

However the responsibility for assessment also falls to the observers and users of tidal predictions. These persons need to make ongoing checks, such as those referred to in Section 3.1.1 Accuracy, in order to ensure that they:-

1. Are confident that the tidal predictions are sufficiently accurate for the purpose to hand; and,
2. Know the level of variability that can be expected between the actual and predicted tide.

4.1 Qualitative Assessment

The qualitative assessment is made at the end of each year when the non-tidal residuals calculated by subtracting the official predictions from the observations are produced. The assessment is based on expert experience and the known weather conditions experienced at the prediction port.
Diagrams 7, 9, 11 are the year 2004 non-tidal residuals for the selected ports. They are typical for a:-

1. Small range semi-diurnal tidal regime (Mooloolaba, about 2.1m range. Diagram 9)
2. Large range semi-diurnal tidal regime (Hay Point, about 7.1m range. Diagram 7)
3. Medium range diurnal tidal regime (Weipa, about 3.4m range. Diagram 11)

Note The examples are of tides in Queensland waters where, except for cyclones, the weather is usually benign and its impact on the tides is minor in comparison to its impact on the tides of Australia’s south west coast. See Diagram 2 Six Minute Residual Water Levels (m) – March 2005 for an example of the Australia wide non-tidal residuals.

4.2 Quantitative Assessment

The quantitative assessment is undertaken during the analysis stage of the preparation of the tidal predictions.

The non-tidal residuals of the tidal height at each hour of the day are summarised numerically. Diagrams 8, 10, 12 are the statistical and frequency table representations of the non-tidal residuals for the three ports referred to in Section 4.1.

The table provide numeric values for input to the tidal component of risk assessments for commercial shipping port operations where the under keel clearance is a minimum.

A significant number of port and other users need to be aware of the accuracy of the time and height at high and low water. Refer to Diagram 13 Mooloolaba High Tide Differences and Diagram 14 Mooloolaba Low Tide Differences for the relationship between the tidal predictions and the actual tide. The table is based on all available tidal recordings during the years 1985 to 2003.

The statistics and frequency table of the non-tidal residuals complemented by the tidal prediction continuity test express the level confidence that the tidal predictions represent the actual tide levels.

5 Conclusion

5.1 Discussion

Each user of tidal predictions must assess their individual “level of confidence”. They all have different needs regarding the precision of tide predictions and a different means of responding the variability in them.

The port operators, mariners, and the port hydrographic surveyors use tidal predictions as an input to the risk assessment component of their operations. They have a requirement for a high level of accuracy and confidence. However all uses need to know the accuracy of the tidal predictions that they use as an input to the risk assessment component of their individual operations. Based upon an objective measure

The quantum of the variability that can be accepted for particular purposes is addressed elsewhere. However in respect of hydrographic surveying and shipping operations in ports it is related to:-

1. The height error budget applicable to the reduction of soundings to chart datum; and,
2. The tidal error budget in the port’s under keel clearance allowance

The factors that contribute to dilution of the accuracy of tidal predictions may be summarised as follows:-

1. The tidal range;
2. The tidal form;
3. The availability and reliability of the observations upon which the tidal predictions are based;

4. Subtle and unnoticed changes to the tidal regime resulting from man-made or natural changes to the depth and widths waterways adjacent to the tidal stations;

5. The calculation method (and associated assumptions) used to determine the tidal constituent constants used to prepare the predictions; and,

6. The effect of the weather and climate on the sea level.

Because the contribution of each of these factors varies from place to place, the tides (including the accuracy of the predictions) are site specific.

It follows that the answer to the questions posed in the terms of reference depends on the circumstances of the tides and weather at each port. Accordingly, it is not possible to make a general statement about the accuracy of tidal predictions.

The following recommendations are made in relation to those tidal predictions that are a critical component of port operations.

5.2 Recommendations

It is recommended that:-

1. The anecdotal evidence concerning a temporal change in tidal range be investigated;

2. The tidal recording instruments are calibrated regularly and the tidal observations used as the basis of the predictions are checked frequently;

3. All possible steps are taken to ensure that the meteorological effects on tides used as the basis of the tidal predictions are typical of the tidal regime at the place;

4. Those of us responsible for tidal observation and prediction be watchful for changes to the environmental conditions that may change the tidal regime at the tidal station;

5. The number of tidal constituents used to prepare the predictions is the maximum that may be drawn reliably from the available observations and all critical constituents are included in the calculation of the predictions;

6. The methodology used to prepare the predictions includes a quantitative assessment of their accuracy; and,

7. A tidal recorder is operated rigorously at all places where tidal height is critical to safe and efficient maritime operations.

The Factors Contributing to the level of Confidence in the Tidal Predictions   Accuracy of Tidal Predictions

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The Factors Contributing to the level of Confidence in the Tidal Predictions   Accuracy of Tidal Predictions

Abbreviations

Abbreviation	Meaning
IHO	International Hydrographic Organisation
MSQ	Maritime Safety Queensland
ANTT	Australian National Tide Tables
ATT	Admiralty Tide Tables
TSTT	Torres Strait Tide tables
cpd, cph	Cycles per hour, cycles per day

The Factors Contributing to the level of Confidence in the Tidal Predictions   Accuracy of Tidal Predictions

Glossary

Term	Meaning
Standard Port	See Reference Station
Reference Station	A place where tide or tidal current constants have been determined from observations, and which is used as a standard for comparison of simultaneous observations at a subordinate station. It is also a place for which independent daily predictions are given in the tide or tidal current tables, from which corresponding predictions are obtained for other locations by means of differences or factors. Also called standard station and standard port (British terminology). IHO 1994
Secondary Port	See Subordinate Station
Subordinate Station	One of the places for which tide or tidal current predictions are determined by applying a correction to the predictions of a reference station. A tide or tidal current station at which a short series of observations was made and reduced by comparison with simultaneous observations at a reference station. Called secondary port in British terminology. IHO 1994
Harmonic analysis of tide	The mathematical process by which the observed tide at a place is analysed by breaking it down in to a number of constituent tides of simple periodic forces, each having a fixed period. In this process the sun and moon are replaced by a number of hypothetical tide-producing bodies which move in circular orbits around the earth in the plane of the equator. IHO 1994
harmonic constants	The amplitude and epochs of the harmonic constituent of the tide, or tidal current, at any place. IHO 1994. *In Australian practice, the term phase lag is used in place of epoch*
Harmonic constituent	One of the harmonic elements in a mathematical expression for the tide-producing force, and in corresponding formulae for the tide or tidal current. Each constituent represents a periodic change or variation in the relative position of the earth, sun, and moon. Also called tidal constituent or component. IHO 1994
Harmonic prediction	In tidal terminology, the method of predicting tides and tidal currents by combining the harmonic constituents into a single curve. The work was usually done mechanically by a machine designed for the purpose, called a tide predicting machine; nowadays the work is done by computers. IHO 1994
Non-tidal residual	The remainder after the expected (predicted) tidal component has been removed.
Form of the tide	All tides are composed of both semi-diurnal and diurnal components. The form of the tide is a qualitative description of the proportion of each component in the tide.
Tsunami	Japanese for *harbour wave*. A transient long-period wave typically caused by an underwater disturbance such as an earthquake, volcanic eruption or landslide. Tsunami can travel very long distances across the planet and effect remote coasts, often being amplified as it enters shallow waters and capable of significant inundation. Tsunami are sometimes incorrectly termed *tidal waves*. Harper 2000
Wave Setup	Quasi-steady superelevation of the water surface due to the onshore mass transport of water caused entirely by the action of breaking waves. *Wave setup* is sometimes included in calculations of *wave runup* . Harper 2000
Highest Astronomical Tide)	This is the highest level which can be predicted to occur under average meteorological conditions and any combination of astronomical conditions. These levels will not be reached every year; HAT generally occurring at any one location once every 18.6 years. Harper 2000
Inverse Barometer Effect	The proportional rise in water level due to the hydrostatic pressure deficit beneath a tropical cyclone. The pressure deficit is the difference between the MSL ambient pressure and the MSL pressure at the centre of the tropical cyclone. The local magnitude of the rise in elevation is approximately 10mm per 1hPa of pressure deficit Harper 2000

Storm Tide	The combined action of *Storm Surge* and *Astronomical Tide*. Harper 2000
Astronomical Tide	The periodic rising and falling of the oceans resulting from the gravitational attraction of the Moon, Sun and other astronomical bodies acting upon the rotating Earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the “tide”, it is preferable to designate the latter as the *Tidal Current*, reserving the name *Astronomical Tide* for the vertical movement. Harper 2000
Storm Surge	A rise above normal water level on the open coast due to the combined effects of surface wind stress and atmospheric pressure fluctuations caused by severe weather events, eg. *tropical cyclones*. Harper 2000
Wave Setup	A quasi-steady superelevation of the water surface due to the onshore mass transport of water caused entirely by the action of breaking waves. *Wave setup* is sometimes included in calculations of *wave runup* . Harper 1996
Spectral analysis	The process whereby a representation of the tidal time series in terms of frequency is calculated.
Rayleigh Criteria	Two constituents are accepted as being resolvable if the total change of relative phase of them equals or exceeds 1 cycle within the available duration of readings

The Factors Contributing to the level of Confidence in the Tidal Predictions   Accuracy of Tidal Predictions

Appendices

Appendix 1 The Harmonic Method.

The waters of the oceans and seas respond to the gravitational forces that maintain the sun, moon, and earth in their orbits. The relative positions of these bodies are precisely known and the variations in the forces can be used as a basis for predicting the tidal times and heights (stream vectors) known as the gravitational tide.

At this point the concept of harmonic method of tidal analysis is introduced. The method simply decomposes the observed tidal time series in the sum of a number of simple harmonic functions.(aCosb) called tidal constituents. The variations in the gravitational forces are periodic and well known. They provide the frequency for each constituent.

The list of constituents together with the associated frequency is referred to in this paper as the tidal model.

The mathematical model relating the tidal time series and constituent constants is:-

$$y(t^i) = \sum^n h^n \mathrm{Cos}(V^n - g^n) \qquad 1.$$

where $y(t^i)$ is the tidal height at the required instant of time t^i

h is the amplitude of the n^{th} constituent

V is the phase of the n^{th} constituent at time t^i $(V = n*(t^i - t^o))$

g is the phase lag of the n^{th} constituent at the time origin (t^o)

n is the frequency of the n^{th} constituent

The h and g values for the constituents are referred to as tidal constituent constants.

Commonly the least squares algorithm is used to fit equation 1 to the observed tidal heights to provide the tidal constituent constants h and g. Although the number of constituents that can be resolved is dependent on the length of the observation set available, typically between 70 and 120 may result from one year of recorded readings.

Clearly the set of equations to be solved is heavily over determined. As a consequence, the fit between the mathematical model and the observations will always result in some differences. Because we have accounted for as much of the theoretical tide as possible, we call the differences non-tidal residuals.

The non-tidal residuals contain three elements:-

1. A difference due to our inability to completely model the tide;

2. Errors in the tidal time/height measuring process; and,

3. Variations in the observed water level which are due to non-tidal causes (the effects of the weather on the water level).

It is necessary to rely on the skill of the analysist to minimize the first one and tidal observer to ensure that the errors in the measuring process are small and stochastic. One needs to be aware of the the effects of the weather on the tidal observations under analysis.

This said, it is not always true that differences due to our inability to completely model the tide can be over looked.

Tidal prediction (given the tidal constituent constants) is the converse of the analysis process.

Appendix 2 Extract from the Report "Determination of LAT datum from Short Term Tidal Analysis" (Peddersen 2001)

Introduction

One of the methods of establishing tidal datum is by tidal analysis. Ideally the longest tidal record available will be used to produce a tidal analysis for constituent constants that will be used to predict the Lowest Astronomical Tide (LAT) datum over a 19 year tidal epoch.

The purpose of this study is to establish the integrity of a LAT datum determination based on the analysis of data periods less than 365 days. The report is undertaken in the situation of a semidiurnal tide regime in which shallow water effects are minimal.

There is a need to investigate the situation of a semidiurnal tide regime in which shallow water effects are minimal.

Methodology

Tidal Analysis of data subsets of varying lengths

This method was used to determine the minimum period of observed data that can be used to give an acceptable determination of LAT.

Tidal data from the Gladstone Auckland Point gauge tidal records for period of 385 days (December 1998 to December 1999) was analysed for the entire period. Data period subsets of 6 months, 3 months, 2 months and 35 days were also analysed to determine which tidal constituents are deduced from the various data periods.

LAT predictions done for 1992-2010 epoch for each data period with Z00 set to zero.

LAT results tabulated to determine how the LAT to HAT range varies as analysis period is shortened.

Long term analysis and constituent subsets

This method was used to illustrate the theoretical differences in LAT predictions produced by varying only the number of constants used.

The latest NTF analysis (C052027A.99) for Gladstone is based on 15 year data period (1985 - 1999) with Sa and Ssa from long period analysis of 21 years (1978- 1999). The constituents from the NTF long term analysis were formed into subsets of constituents corresponding to the constituents that are derived from the shorter analysis periods

LAT predicted and results were tabulated to determine how the LAT to HAT range varies as subsets of constituents are reduced in number.

Rationale for using data subsets and constituent subsets

As the length of the analysis period increases constituents are deduced more precisely as more data redundancies are available.

As the length of the analysis period shortens, the analysis process can no longer separate clusters of adjacent frequencies. The number of constituents deduced is reduced and these constituents represent an approximation of the adjacent frequency clusters.

By using constituent subsets of a long term analysis you can examine the effects of reducing the number of constituents, while maintaining the long term integrity of the constituents used;

To compare LAT predictions produced by data subsets and constituent subsets, the long term Sa, Ssa as supplied by NTF was included. The long term mean sea level (Z00) was set to zero to remove any bias introduced by seasonal adjustment of mean sea level.

Comparisons of LAT/HAT calculations at Gladstone.

The initial calculations of LAT/HAT were referred to a mean sea level datum (Z00=0). The LAT/HAT values were then adjusted to LAT datum for the tables below. The Gladstone long term (21 year) values of Sa and Ssa supplied by NTF were used in all calculations.

Table 1 LAT calculations using analysis from observed data subsets

	12 month (69 constants) Appendix 2	6 month (52 constants) Appendix 3	3 month (40 constants) Appendix 4	2 month (40 constants) Appendix 5	35 day (38 constants) Appendix 6
HAT	4.78	4.80	4.80	4.88	4.90
Z00	2.31	2.31	2.32	2.35	2.36
LAT	0.00	0.00	0.00	0.00	0.00

Table 2 LAT calculations using constituent subsets from NTF long term analysis 1985--1999

	All available constants (15 years of data and 118 constants) Appendix 7	6 month (52 constants) Appendix 8	3 -2 month (40 constants) Appendix 9	35 day (38 constants) Appendix 10
HAT	4.75	4.82	4.84	4.86
Z00	2.30	2.32	2.34	2.35
LAT	0.00	0.00	0.00	0.00

Summary of Results

As the length of the analysis shortens the LAT- HAT range increases.

From 12 month down to 3 months the increase in LAT - HAT range is less than 2.0%

A 35 day analysis increases the LAT - HAT range by approximately 2.5%

Conclusion

The best determination of LAT datum is going to be derived from the longest term tidal analysis available.

However acceptable determinations of LAT datum can be obtained from data sets of 3 months or more provided a long term regional Sa and Ssa is available.

The shorter data periods require more inferencing of constants which is probably leading to biasing in the LAT calculations.

Caution is required when selecting the inferencing port to ensure that the form (shape and range) of the tide at the inference port and secondary port are similar.

Note:- The appendices referred to in this extract from the report are not included here.

Appendix 3 Calibration of Tidal Stations

There are a number of methodologies available to ensure the recorders of tidal are measuring the height of tide accurately.:-

The PCTMSL “Recommended Operating Procedures for Tide Gauges on the National Network”, “Tide Gauge Survey Instructions” and the “Manual on Sea Level Measurement and Interpretation”, Ainscow W. et al, 1985, provide appropriate processes, including setting the elevation of the station tide board relative to Chart Datum and the ongoing water level checks, to confirm and document the continued accuracy of the tidal recordings.

Refer to the PCTMSL “Tide Gauge Survey Instructions” for an appropriate method by which a tidal height station may be calibrated in-situ, Section 2.2 of the Calibration of Automatic Recorders.

Ainscow et al. also provides comprehensive information on the operation and ongoing testing (Van de Casteele test) of tidal recording equipment.

Provided that it is possible to synchronize the readings from the recorder and the water level checks accurately, it is possible is possible to monitor the ongoing calibration (span and zero setting) using the water level checks. Perform a linear regression using the tide board readings and the recorded readings. The slope should be 1.000 and the offset 0.000. (Broadbent 2004)

5.3 Appendix 4 The Effects of Storm Surges on Analysis

1. Introduction

A tidal analysis was required of 64 days of observations (02/03/93 to 04/05/93) from the tidal station Military Jetty - Pumicestone Passage. – 010011.

During the analysis period, Cyclone " Rodger " was responsible for a significant tidal surge (up to 0.50m). This study attempts to quantify what effect a tidal surge has on the analysis results.

2. Methodology

A tidal analysis was done with the complete observation set and then the analysis was repeated with the cyclonic surge period (13 -20 March) data removed.

The Mooloolaba storm surge gauge observations were used for the mean sea level seasonal adjustment as the influence of the cyclone " Rodger " was identical to that at Military Jetty. The Brisbane Bar tidal constants were used for inferencing and for the regional Sa and Ssa variation.

3. Analysis Results

Removing the cyclonic surge data before analysis reduced the sine and cosine errors and reduced the size of the mean residual and the spread of the residuals. However the tidal constants produced by both analysis methods were very similar and both constants sets produce almost identical predictions.

SUMMARY OF ANALYSES RESULTS

Analysis Statistic	Complete Data Set	Cyclonic Surge Removed
MSL from Analysis	0.614m	0.574m
MSL (Seas. Adj.)	0.632m	0.630m
Sine & Cos Error	0	0
Matrix Condition	0.72	0.29
Raw Mean Residual Std Deviation	0.114m ± 0.15m	0.080m ± 0.10m
Adj Mean Residual Std Deviation	0.139m ± 0.15m	0.125m ± 0.10m
O1 (Amp. & Phase)	0.102m 157.3®	0.099m 153.7®
K1 "	0.136m 196.3®	0.137m 193.7®
M2 "	0.197m 301.3®	0.195m 301.0®
S2 "	0.039m 321.4®	0.039m 321.7®
M4 "	0.028m 130.4®	0.029m 131.8®

4. Conclusions

This study showed that the cyclonic surge present in the analysis data set had minimal effect on the final constituents values.

The removal of cyclonic surge data improved the statistics of the analysis result slightly by removing outlying residuals (see Appendices 2 & 3 for analysis reports), however comparison of major tidal constants show that there is no practical improvement in precision of predictions (see Appendix 1 for comparisons of residuals).

The most significant surge from cyclone "Rodger" lasted for approximately 48 hours (17-18 March 93) and this amounts to 3% of the 64 day data period thus any "bias" introduced into the analysis by the cyclone would be minimal. Further study would be required to check the effects of 3 or 4 cyclonic surges in a data period of about 60 days.

In conclusion it would appear that the effects of a cyclonic surge can be ignored in tidal analysis provided that period of the surge is short compared to the data period.

Diagrams

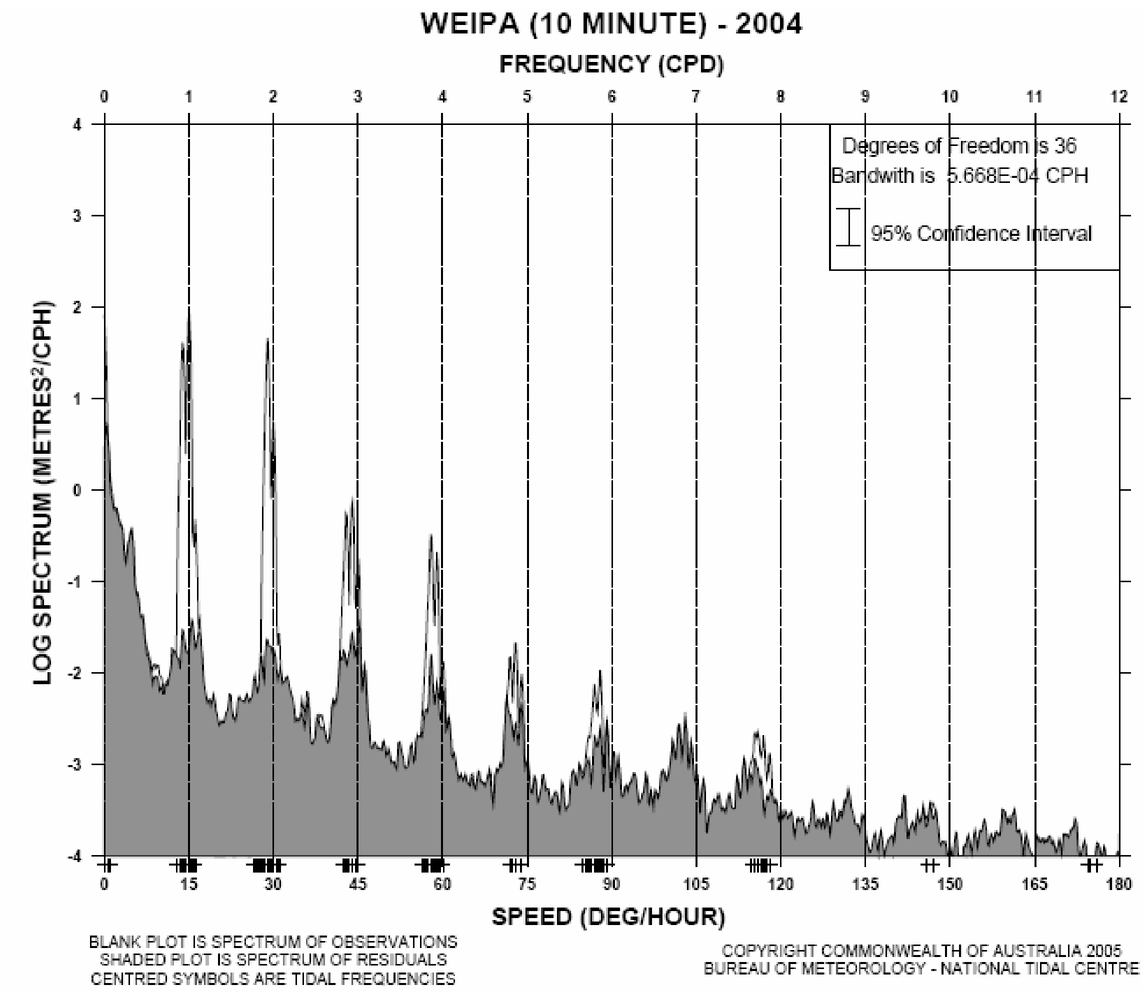

Diagram 1 Weipa Tidal Spectra

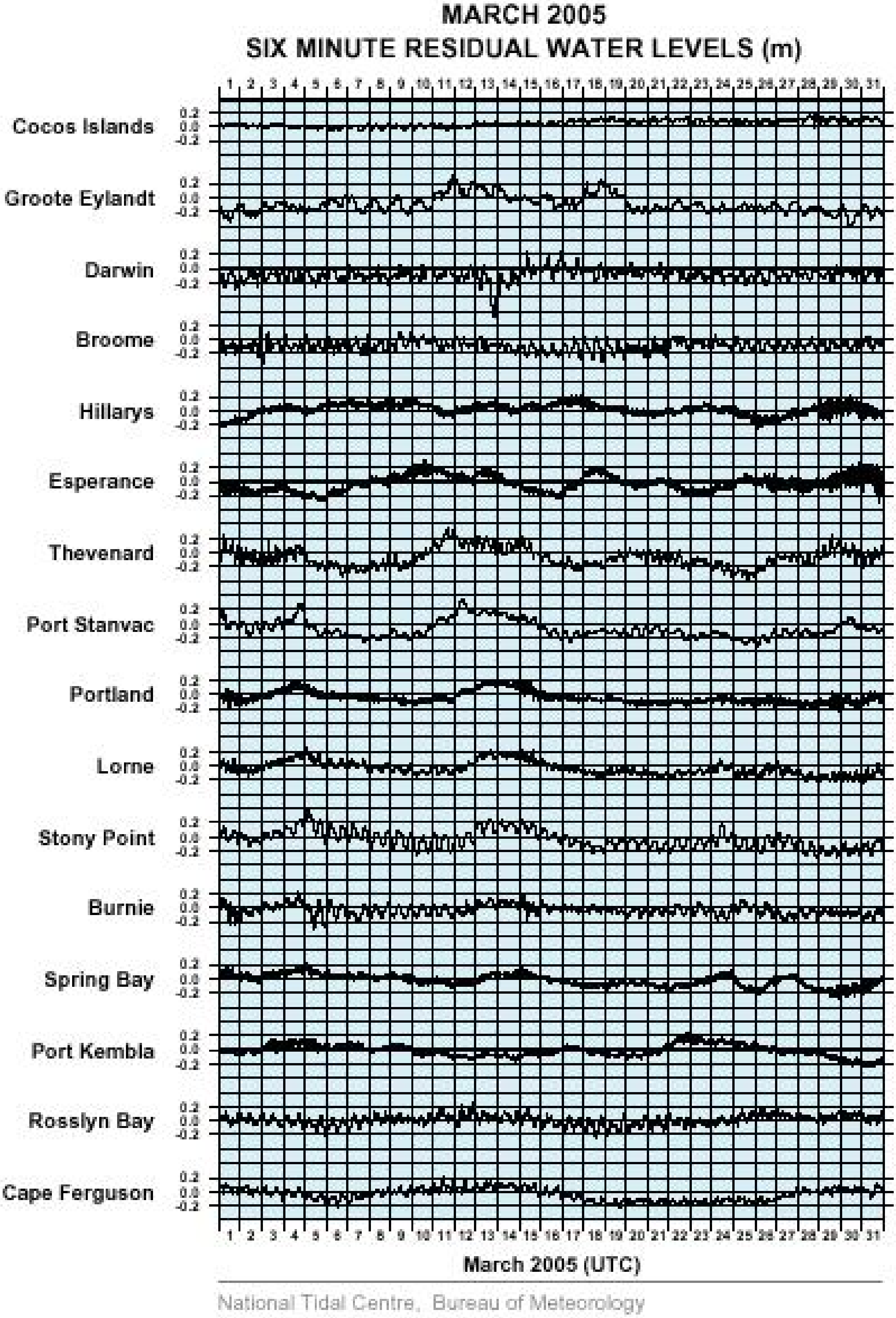

Diagram 2 Six Minute Residual Water Levels (m) – March 2005.

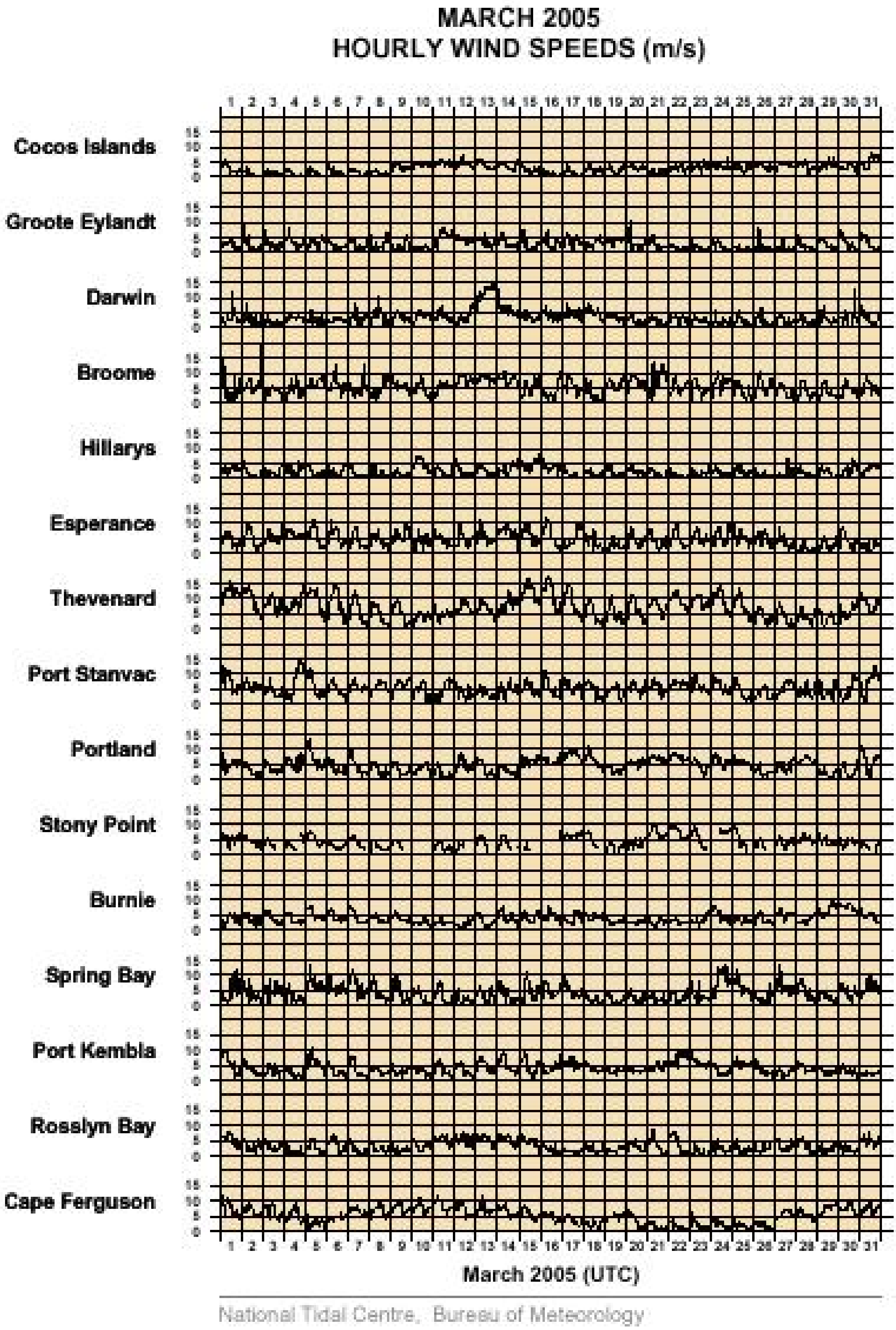

Diagram 3 Hourly Wind Speeds (m/s) – March 2005.

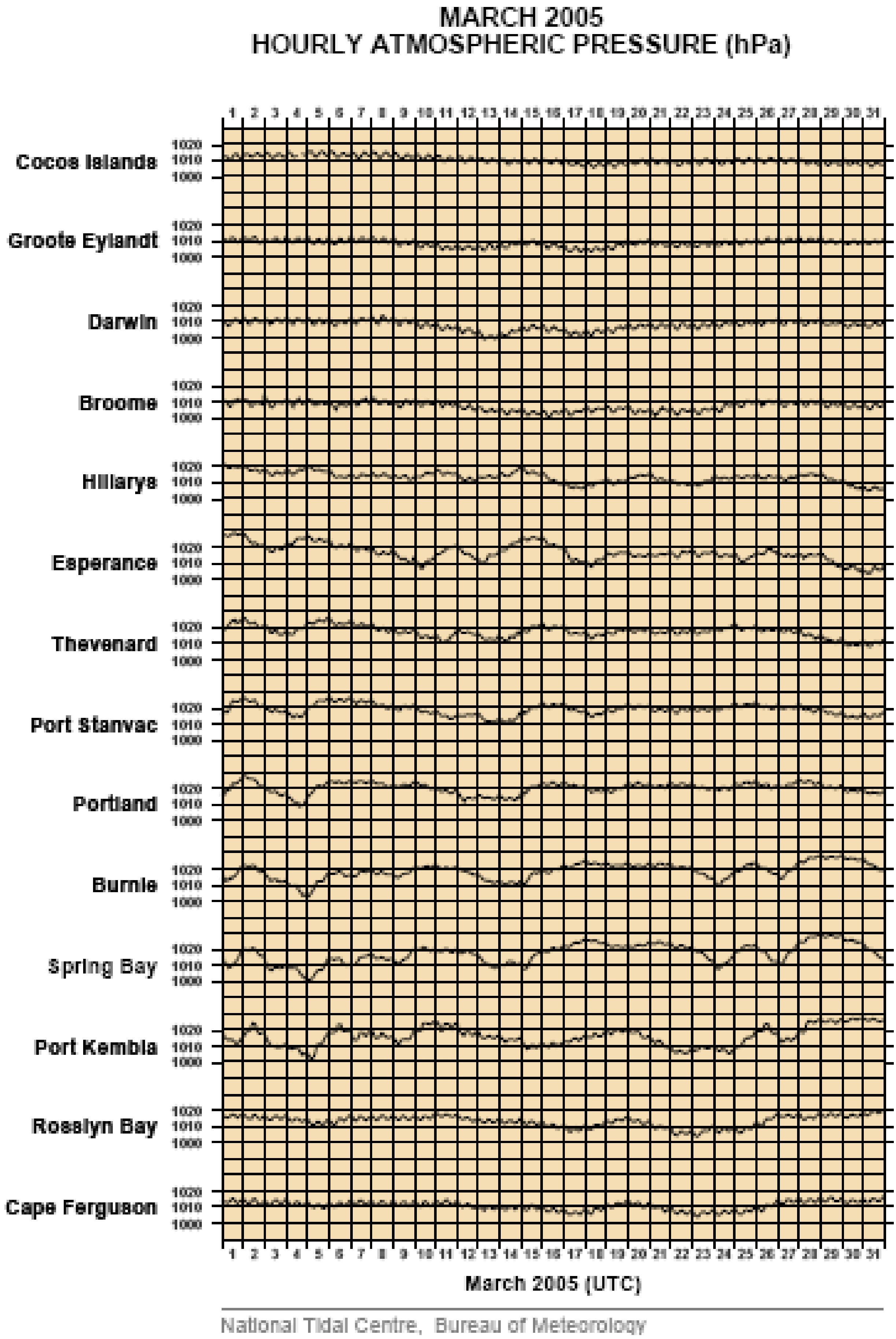

Diagram 4 Hourly Atmospheric Pressure (hPa) – March 2005.

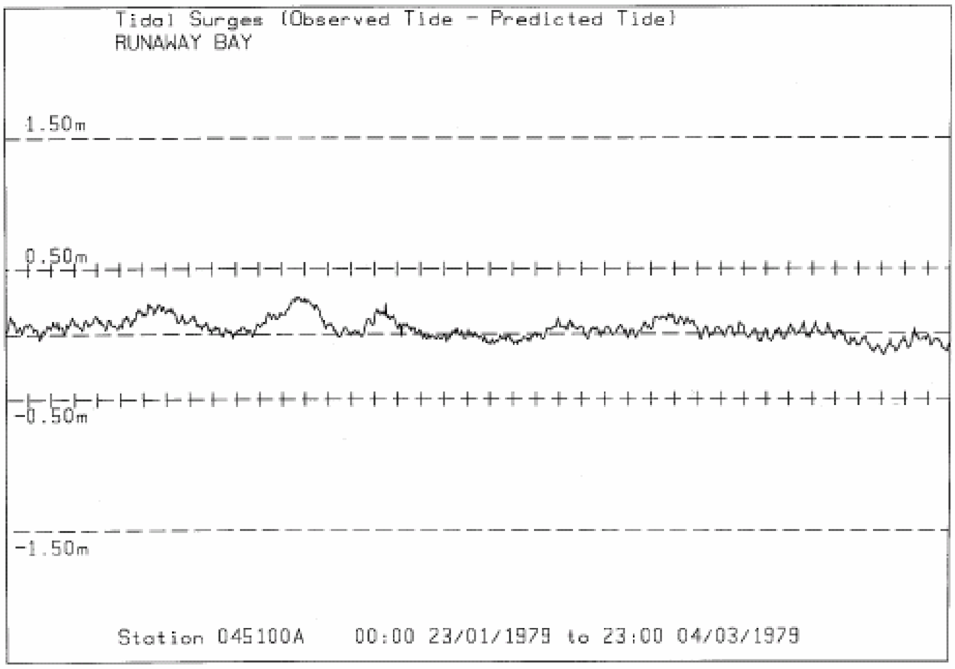

Diagram 5 Non-tidal residuals for 1979 at Runaway Bay (in the Broadwater) Predictions based on an analysis of the 1979 observations.

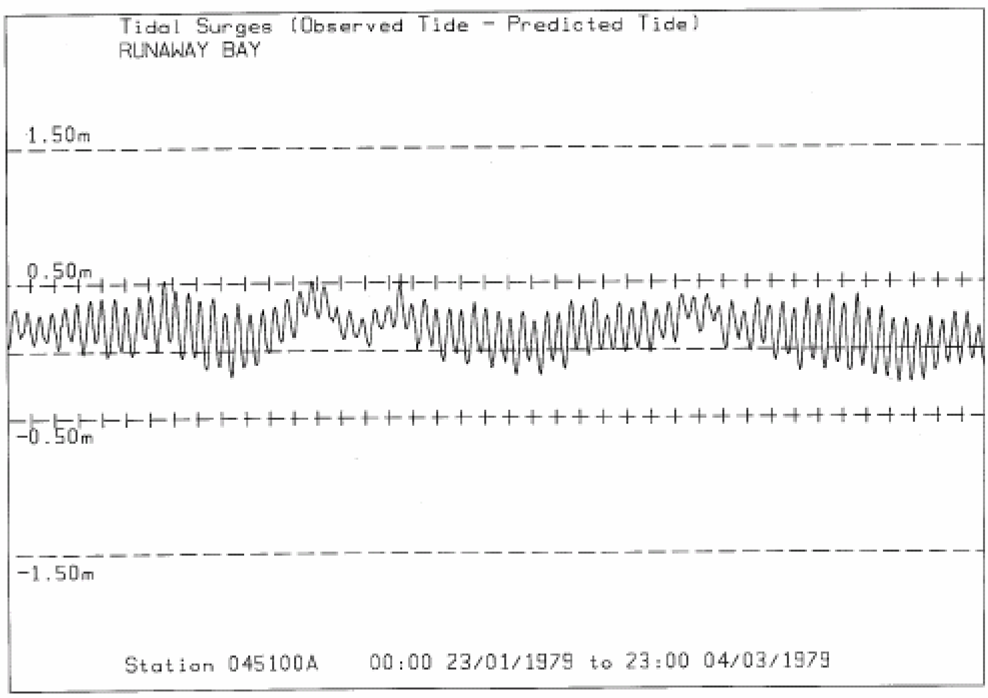

Diagram 6 Non-tidal residuals for 1979 at Runaway Bay (in the Broadwater) Predictions based on an analysis of recent observations.

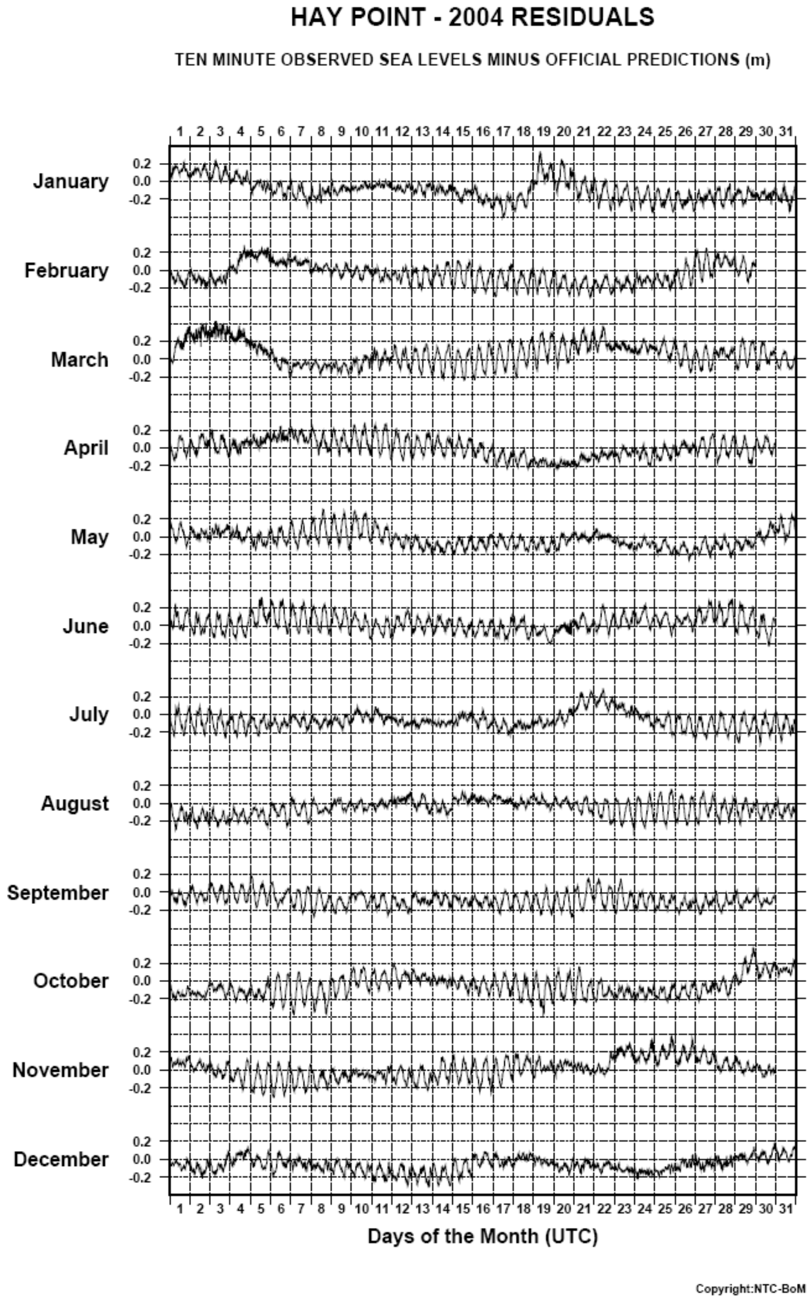

Diagram 7 Hay Point 2004 Residuals

HAY POINT - 2004 DATA USING AN ANALYSIS OF THE 2004 DATA

Mean	: residuals	0.000	observations	3.328
Mean of absolute value	: residuals	0.076	observations	3.328
Standard deviation	: residuals	0.097	observations	1.418

Distribution of residuals

From	To	Number	Percentage
-0.40	-0.30	3	0.01 %
-0.30	-0.20	518	0.98 %
-0.20	-0.10	6655	12.57 %
-0.10	0.00	21544	40.70 %
0.00	0.10	16481	31.14 %
0.10	0.20	5938	11.22 %
0.20	0.30	1526	2.88 %
0.30	0.40	244	0.46 %
0.40	0.50	23	0.04 %

Number of values = 52932, zeros = 239 and gaps = 0

Diagram 8 Hay Point 2004 Non-Tidal Residual Statistics

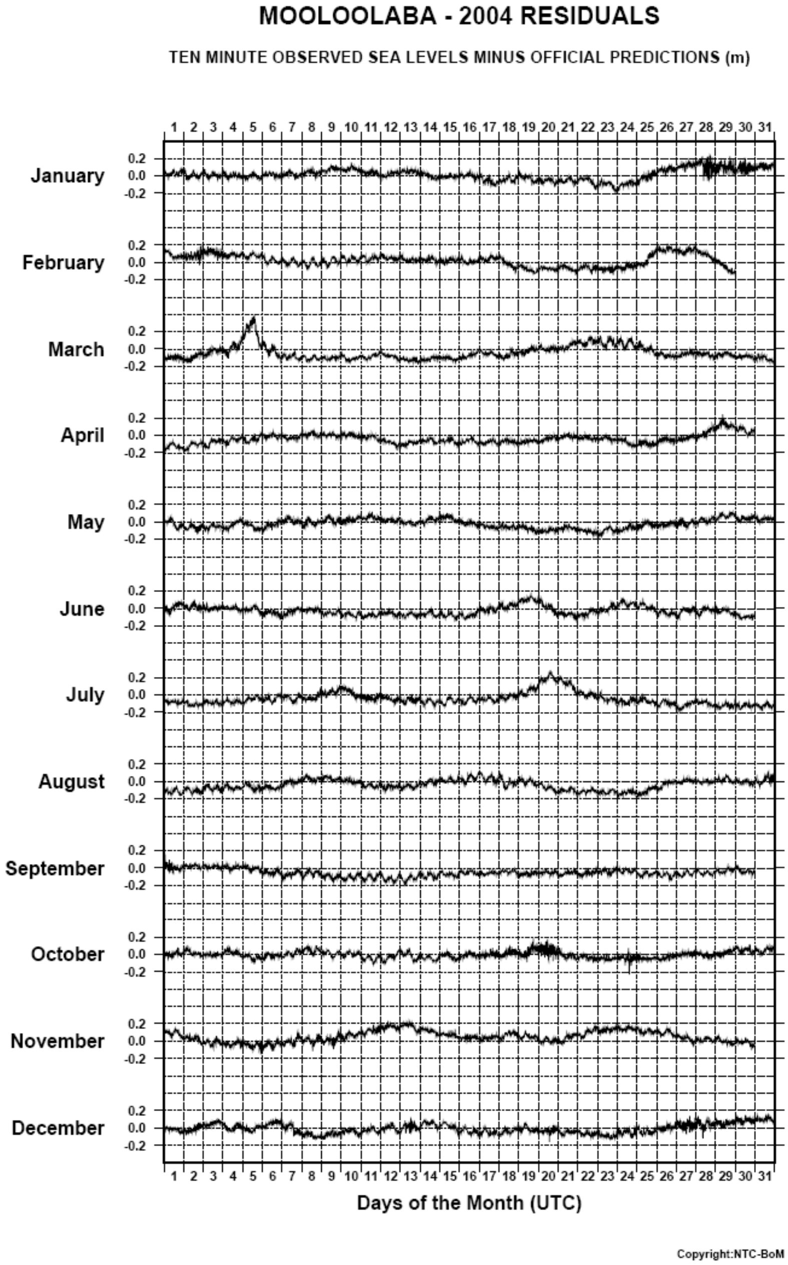

Diagram 9 Mooloolaba 2004 Residuals

MOOLOOLABA - 2004 DATA USING AN ANALYSIS OF THE 2004 DATA

Mean	: residuals	0.000	observations	0.934
Mean of absolute value	: residuals	0.048	observations	0.934
Standard deviation	: residuals	0.060	observations	0.440

Distribution of residuals

From	To	Number	Percentage
-0.30	-0.20	1	0.00 %
-0.20	-0.10	1288	2.43 %
-0.10	0.00	27714	52.36 %
0.00	0.10	20814	39.32 %
0.10	0.20	2924	5.52 %
0.20	0.30	149	0.28 %
0.30	0.40	42	0.08 %

Number of values = 52932, zeros = 313 and gaps = 0

Diagram 10 Mooloolaba 2004 Non-Tidal Residual Statistics

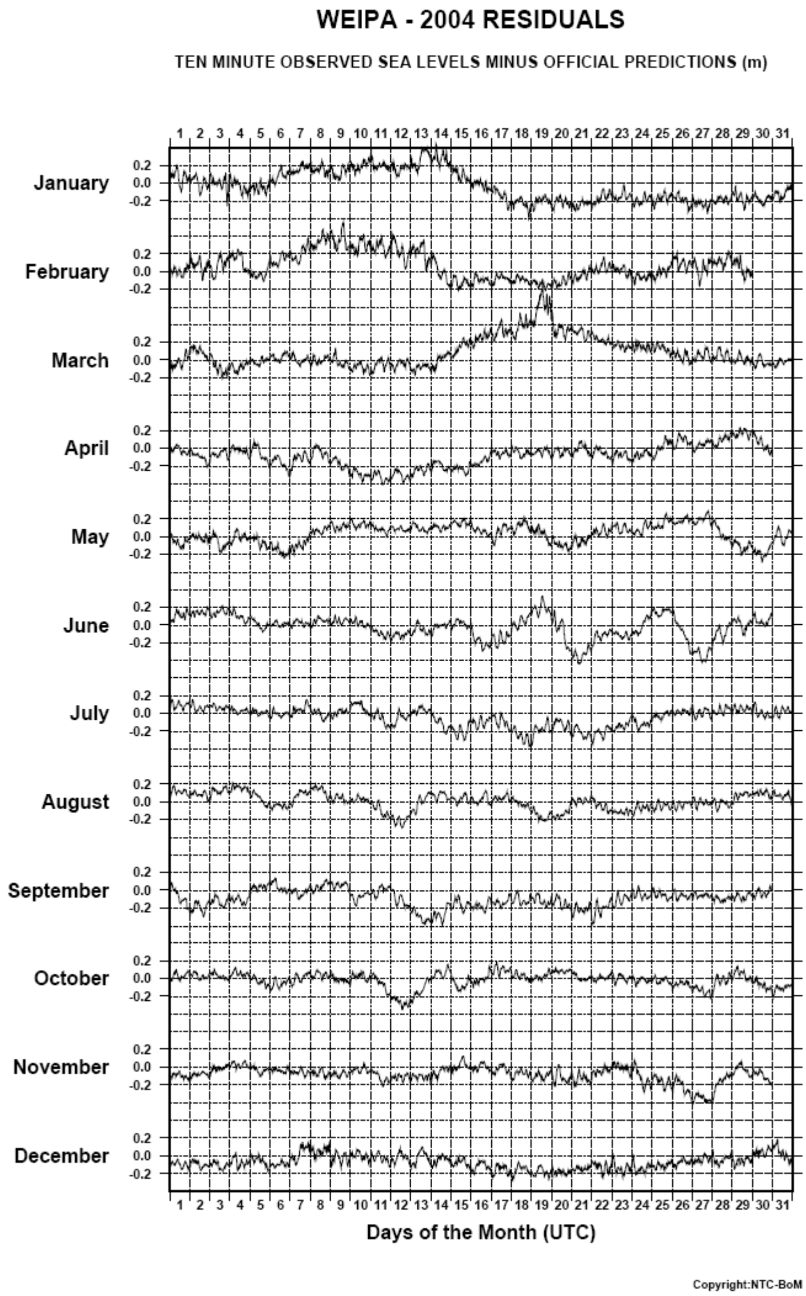

Diagram 11 Weipa 2004 Residuals

WEIPA - 2004 DATA USING AN ANALYSIS OF THE 2004 DATA

Mean	:	residuals	0.000	observations	1.803
Mean of absolute value	:	residuals	0.100	observations	1.803
Standard deviation	:	residuals	0.130	observations	0.585

Distribution of residuals

From	To	Number	Percentage
-0.50	-0.40	31	0.06 %
-0.40	-0.30	701	1.32 %
-0.30	-0.20	2483	4.69 %
-0.20	-0.10	7667	14.48 %
-0.10	0.00	15396	29.09 %
0.00	0.10	16105	30.43 %
0.10	0.20	8092	15.29 %
0.20	0.30	1578	2.98 %
0.30	0.40	661	1.25 %
0.40	0.50	114	0.22 %
0.50	0.60	47	0.09 %
0.60	0.70	41	0.08 %
0.70	0.80	11	0.02 %
0.80	0.90	5	0.01 %

Number of values = 52932, zeros = 169 and gaps = 0

Diagram 12 Weipa 2004 Non-Tidal Residual Statistics

Mooloolaba High Tide Differences

01/01/1985 to 31/12/2004

Time Class Minutes	Percentage	Height Class Centimetres	Percentage
OUT OF RANGE	0.0	-035 TO -031	0.0
-055 TO -051	0.0	-030 TO -026	0.1
-050 TO -046	0.0	-025 TO -021	0.3
-045 TO -041	0.1	-020 TO -016	2.1
-040 TO -036	0.1	-015 TO -011	8.2
-035 TO -031	0.3	-010 TO -006	15.5
-030 TO -026	0.5	-005 TO -001	24.1
-025 TO -021	1.0	000 TO 004	23.2
-020 TO -016	2.1	005 TO 009	15.1
-015 TO -011	5.1	010 TO 014	7.2
-010 TO -006	11.4	015 TO 019	2.6
-005 TO -001	23.3	020 TO 024	0.9
000 TO 004	27.2	025 TO 029	0.4
005 TO 009	16.7	030 TO 034	0.1
010 TO 014	6.8	035 TO 039	0.0
015 TO 019	2.9	040 TO 044	0.0
020 TO 024	1.2		
025 TO 029	0.6		
030 TO 034	0.3		
035 TO 039	0.1		
040 TO 044	0.1		
045 TO 049	0.1		
050 TO 054	0.0		
055 TO 059	0.0		

Diagram 13 Mooloolaba High Tide Differences

Mooloolaba Low Tide Differences

01/01/1985 to 31/12/2004

Time Class Minutes	Percentage	Height Class Centimetres	Percentage
OUT OF RANGE	0.0	-035 TO -031	0.0
-055 TO -051	0.0	-030 TO -026	0.1
-050 TO -046	0.0	-025 TO -021	0.6
-045 TO -041	0.1	-020 TO -016	2.7
-040 TO -036	0.1	-015 TO -011	9.0
-035 TO -031	0.2	-010 TO -006	17.1
-030 TO -026	0.5	-005 TO -001	23.7
-025 TO -021	1.2	000 TO 004	22.1
-020 TO -016	2.3	005 TO 009	14.2
-015 TO -011	5.7	010 TO 014	6.6
-010 TO -006	13.2	015 TO 019	2.4
-005 TO -001	24.1	020 TO 024	1.1
000 TO 004	25.6	025 TO 029	0.3
005 TO 009	15.1	030 TO 034	0.1
010 TO 014	6.4	035 TO 039	0.1
015 TO 019	2.7	040 TO 044	0.0
020 TO 024	1.4		
025 TO 029	0.6		
030 TO 034	0.3		
035 TO 039	0.2		
040 TO 044	0.1		
045 TO 049	0.0		
050 TO 054	0.0		
055 TO 059	0.0		
OUT OF RANGE	0.0		

Diagram 14 Mooloolaba Low Tide Differences

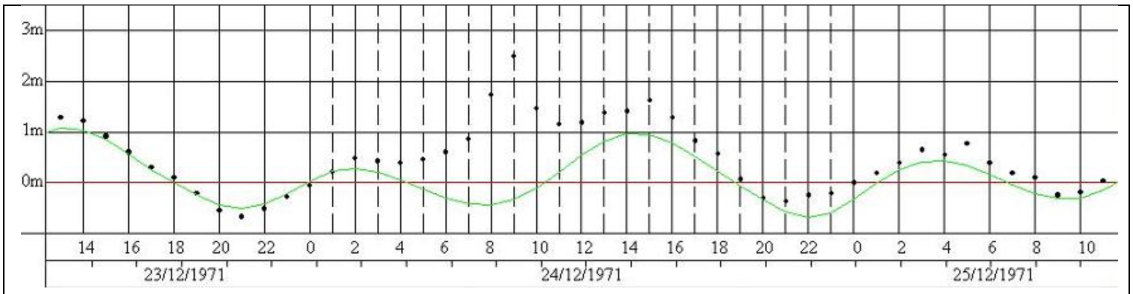

Diagram 15 Cyclone Althea – Townsville 24 December 1971
Dotted line – Recorded height   Full line Predicted height
Heights are referred to the Australian Height Datum.