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

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Assessment of BLUElink OceanMAPSv1.0b against coastal tide gauges

A.Taylor, G.B. Brassington and J. Nader

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[Photo Stamy Criticos]

Enquiries should be addressed to:
Andy Taylor
Centre for Australian Weather and Climate Research
GPO Box 1289 Melbourne
Victoria 3001, Australia

a.taylor@bom.gov.au

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ABSLMP	Australian Baseline Sea Level Monitoring Project
ACCESS	NWP system expected to be operational at Bureau of Meteorology mid-2010
ALSOS	ATWS Sea Level Observation System
ATWS	Australian Tsunami Warning System
BLUElink / Bluelink	Joint research project to develop operational ocean forecasting systems for Australia. Bureau of Meteorology, CSIRO and the Royal Australian Navy.
BODAS	Bluelink Ocean Data Assimilation System
BRAN	Bluelink Re-Analysis Project
CSIRO	Commonwealth Scientific and Industry Research Organisation
GASP	NWP system operational at Bureau of Meteorology across the study period
HAT	Highest Astronomical Tide
IB	(Local) Inverse Barometer
LAT	Lowest Astronomical Tide
MSLP	Mean Sea Level Atmospheric Pressure
NRMSE	Normalised Root Mean Square Error
NWP	Numerical Weather Prediction
Obs	Observations
OceanMAPS	Ocean Modelling, Analysis and Prediction System: version 1.0b
OGCM	Oceanic General Circulation Model
PSD	Power Spectral Density
RMSE	Root Mean Square Error
S(t)	Tidal residual ('Surge')
SEAFRAME	Tide gauge type:Sea Level Fine Resolution Acoustic Measuring Equipment
SLA	Sea Level Anomaly
SLP	Sea Level Atmospheric Pressure
SST	Sea Surface Temperature
T(t)	Tidal sea level signal
TC	Tropical Cyclone
T_Tide	Software tool for harmonic tide methods within Matlab
X(t)	Total sea level signal
$Z_0(t)$	Mean Sea Level or Zeroth harmonic component
σ	Standard Deviation

1. ABSTRACT

This report documents the first systematic comparison of OceanMAPS with the national tide gauge network to assess the level of skill for predictions of coastal sea level. This report also serves to benchmark the performance for future system upgrades. OceanMAPSv1.0b (Brassington et al. 2007) produces a non-tidal coastal sea level that responds to atmospheric surface forcing and changes to the ocean state but does not include effects of tides, barometric pressure or wave setup. Statistical comparisons are made between OceanMAPS daily mean sea level anomaly and processed tide gauge observations. The results indicate that OceanMAPS is skilful over the majority of mainland and Tasmanian tide gauges when the full range of frequencies is considered. However, when long-period variations (> 2 months) are removed from the comparison, the resulting skill of the system remains high only in the mid-latitudes and particularly the Great Australian Bight.

1.1 Document Overview

Section 2 contextualises the investigation and defines key terminology.

Section 3 provides an overview of the Bluelink OceanMAPS operational ocean prediction system and its general performance.

Section 4 provides an overview of the real time tide gauge observation network in question, a discussion of specific data quality issues and pre-processing steps employed to derive quantities directly comparable to the OceanMAPS output.

Section 5 describes the methods employed to compare the gridded product with insitu observations; including use of the nearest grid point, the limitation to daily averages, the subtraction of respective sample means and the definition of a skill score.

Section 6 presents results for the comparison of OceanMAPS *analysis* SLA with the observation derived SLA. *Analysis* values are considered the best operational estimate of the ocean state.

Section 7 extends the comparison in Section 6 to the consideration of the OceanMAPS *forecast*s. The results of this comparison are a measure of how the forecast skill typically evolves over each forecast period.

Section 8 provides a discussion of the results from various perspectives. It includes a discussion of the issues associated with deriving SLA from observations and the nature of OceanMAPS within the coastal zone. Finally, comments are made concerning the operational goal of producing forecasts of the total sea level.

The appendices include further specifics and details of statistical results, time series and observation locations.

2. INTRODUCTION

2.1 Motivation for this work

2.1.1 Motivating question

In essence, the question that motivates the present report is as follows:

"Could Bluelink-OceanMAPS be employed to produce useful forecasts of coastal non-tidal sea level in the Australian region?"

The question is approached by means of a systematic statistical comparison between daily mean sea level anomaly data products and observations from the national tide gauge network.

2.1.2 This is a preliminary report

This is a preliminary study of non-tidal sea level for the following reasons:

- It represents the **first stage** of a planned wider study effort;
- Observational data have been limited to a sparse **subset of the tide gauge network**;
- All data has been limited to relatively **short timeseries of daily means**;
- The pre-processing and comparison methods employed are considered naïve yet pragmatic.

2.1.3 Performance benchmark

A secondary motivation for this work is to establish a performance benchmark to facilitate objective evaluation of the coastal sea level performance of the OceanMAPS in real-time and future system upgrades. Future changes to the observing system, analysis and model will impact performance for which this benchmark will help quantify any improvement.

2.2 Historical context

2.2.1 Insitu Tide predictions

Variations in sea level have long been of practical importance to coastal communities and marine operations. It is common to refer to any visible changes in sea level across periods ranging from hours though to seasons as *tidal*. In the present context of quantitative sea level prediction a more nuanced vocabulary is required and this document approaches with some care familiar terms such as tide and tidal.

Predicting the sea level at the coast has a rich historical legacy. And this history is witness to both remarkable successes and ongoing elusive challenges (Cartwright 1999). Despite the apparently regular fluctuations of sea level at most coastal locations, 'tide predictions' to this day are rarely provided with error bars and by definition do not predict non-periodic events. The fact that tide predictions do not forecast the total sea level is illustrated by the frequency of sea level maxima well above *highest astronomical tide*. See for example Mitchell (2008, Fig. 2).

The first truly successful quantitative predictions of sea level exploited the apparent relationship between sea level patterns and the relative positions of the Earth, Moon and Sun. The Newtonian physics that provided accurate predictions of these celestial motions also founded a method of modelling sea level variations. This was achieved by means of a fitting a finite set of sinusoidal functions at predefined astronomical frequencies to observations. The success of this 'harmonic analysis' approach represents a triumph of linear mathematics. For any one location, a long series of historical observations can be used to provide remarkably accurate predictions of the cyclical portion of sea level fluctuations for several years into the future. Variations of the harmonic analysis method have been employed to produce tide predictions for over 100 years and are enormously important to the present day. But by definition these well-established sea level forecast products surrender what can be a large fraction of the total sea level signal. It is important to note that harmonic tide predictions neither account solely for the astronomically driven variations nor attempt to predict the 'total sea level'. Traditional tide predictions in principle provide no warning regarding the influence of geophysical turbulence – most notably sea level changes associated with 'weather effects' (Pugh 1996).

2.2.2 NWP, storm surge and waves

Over recent decades, the development of atmospheric Numerical Weather Prediction (NWP) has provided new insights into meteorological forces acting on the ocean. The availability of good estimates of wind patterns over the ocean extend the predictable portion of the sea level variability to include coastal 'storm surge'. Storm surge is the most significant source of non-tidal coastal sea level and operational *event based* forecasting has become relatively mature. Such systems can give relatively skilful forecasts out to more than 3 days into the future - comparable to the timescales of NWP. It is noted however that the skill of NWP can be considerably less for extreme storms as well as for the representation at or near to the land-sea boundary. In the Australian context the prediction of surges associated with tropical cyclones (TC) has received the most attention and effort. And this attention is indeed warranted by the extreme nature of TC surges. A variety of approaches to TC surge prediction are implemented operationally across the regional offices of the Australian Bureau of Meteorology, the skill of which are all fundamentally limited by the skill of the atmospheric forcing (e.g. Davidson et al . 2005).

Such predictions are however only performed event-wise in the course of forecasting the impact of identified extreme storms.

Another result of the improved estimates of wind patterns provided by NWP is the ongoing development of deep-water wave forecasting systems. The availability of skilful wave forecasts renders the wave setup contribution to coastal sea level potentially predictable. However, this potential is yet to be exploited operationally (due to the complications involving the numerical treatment of shallow-water wave processes) and is a relatively recent research topic not further discussed here.

2.2.3 Extension of ocean prediction systems

The advent of ocean prediction systems founded on numerical *ocean* general circulation models (OGCMs) and data assimilation is a relatively new development. Such systems represent an oceanic analogue to NWP which amongst other things offer additional insights into forecasting sea level fluctuations (e.g. Smith 2006). Furthermore, the broad spatial domain and regular schedule of the new operational systems can be contrasted to existing event-based local sea level prediction tools.

The introduction of OGCM based prediction systems to operational centres extends the practically predictable part of coastal sea level to include a broader spectrum of ocean processes and driving forces than was previously possible. In effect, claiming as "signal" a greater portion of the observational record. Ocean forecasts of coastal sea level variability produced by the new class of system notably include contributions of several physical processes across the range of time and space scales, such as:

- coastally trapped waves;
- baroclinic phenomena;
- coastally impinging of boundary currents and eddies;
- seasonal and interannual variations of heat and salinity.

Often each of these individual effects can represent a relatively small contribution to the total sea level variability, as typically the tidal signal is dominant. In fact the success of conventional tide prediction is based on the ability to estimate an ongoing periodic signal amongst this 'noise'.

But even relatively small amplitude phenomena can be significant.

The most direct example of this significance is the case of extreme sea level events. Any additional contributions to coastal sea level may be of great practical importance when the sea level is already close to some critical threshold – for example in the context of coastal flooding or shipping related 'under keel clearance'.

This broad category of physical phenomena can also be significant in a less direct manner via the method by which the *tidal* prediction is derived. The presence of such signals in the observational record can have a corrupting effect upon the results of tidal harmonic analysis. With regard to this impact, the following characteristics of these non-tidal ocean dynamics are highlighted:

- Are often associated with turbulence and are not strictly periodic;
- Can represent spectral power at tidal frequencies;
- Can persist for long periods and impact the apparent mean sea level.

The dynamics of such phenomena are numerically represented in 3 spatial dimensions within the OGCM component of an ocean prediction system. The relatively recent implementation of the OceanMAPS system at the Australian Bureau of Meteorology (Brassington et al. 2007) now offers the possibility of routinely predicting the associated non-tidal sea level variations and subsequently providing improved forecasts of coastal sea level.

It is asserted that for certain contexts, the accurate prediction of sea level extrema some days in advance may in fact be of more value than long term predictions that neglect intermittent peaks. In this respect improved routine sea level predictions could be formed by augmenting traditional tide predictions with the new non-tidal predictions.

Given the varied nature of the superposing phenomena that contribute to coastal sea level, the likelihood of coincidence resulting in an extreme sea level event at any particular time and place is relatively low. However, the likelihood of such superposition resulting in significant events at least somewhere along the vast Australian coastline is not negligible. For instance the simultaneous occurrence of an astronomical spring tide high water with the passing of a remotely generated coastally trapped wave and strong onshore winds. Examples include flood events at the Derwent River (TAS) in August 2007 and suburban Adelaide (SA) in April 2009. The potential value of routine 'total sea level' forecast products of this nature forms the backdrop against which the present work has been developed and is discussed further in Section 8.9.

2.3 Definition of Non-Tidal Sea level and Sea Level Anomaly (SLA)

2.3.1 Sea level, sea surface height and datums

'Sea' and 'ocean' here refer only to the large contiguous body of water commonly identified as the global ocean. Other large bodies of water, enclosed seas and lakes are excluded from the model under consideration.

This report proceeds on the basis that the concept of a measurable sea level is not problematic. The direct effects of phenomena such as breaking waves are not explicitly relevant to this study, though they are implicit in the observations and OceanMAPS. The vertical height of the sea surface can be quantified relative to a reference surface, of which several are in common use. Examples of such references in use include the Australian Height Datum and geocentric reference ellipsoids, IGSM (2009). Essentially arbitrary offsets are also included in the various data sources for the sake of instrument or model convenience. The variety of reference datums in use mean that direct comparison of absolute insitu sea level quantities from different sources is not always straightforward. However, it is asserted that the subtraction of the respective sample means from any pair of insitu time series renders them meaningfully comparable, so long as the time period is equivalent.

Any effects due to terrestrial dynamics, such as solid body earth tidal motions and secular crustal trends are not explicitly treated here. Whilst the effects of the solid-earth and load-tides cannot typically be neglected for numerical tidal modelling (Ray 1998), the present work compares only insitu land-referenced observations and the non-tidal OceanMAPS which assimilates SLA pre-corrected for such effects.

Finally, it is noted that although the choice of terminology can sometimes be taken to imply a disciplinary bias, the terms 'sea level', 'sea level height', 'sea surface height' and 'recorded tide' are taken as equivalent.

2.3.2 Traditional tidal decomposition of total sea level

Traditional *in situ* tide prediction practice has focussed attention on best identifying a periodic signal within the observational record. The present work directs its attention to phenomena that generally contribute to the 'tidal residual', but that may overlap into the tidal scope depending on the details of the signal decomposition.

This report intentionally proceeds from the established conceptual framework of *in situ* tide prediction practices, due to it's ongoing importance in the area of coastal sea level . However, the common definitions and terminology can at times be a little ambiguous and historical developments have contributed to this situation. Practices that developed prior to the satellite age generally consider *any* apparently periodic fluctuations as the subject of tidal analysis – including seasonal effects and 'radiational tides'. However more recent and globally focussed tidal literature has tended to treat strictly the gravitational forcing alone as tidal, whist still using much of the legacy terminology, see for example Lyard et al. (2006).

Whilst acknowledging the above reservations regarding signal decomposition, the established conceptual framework for *in situ* analysis is considered appropriate to repeat here. Thus, the observed sea level at a point, X(t) can be separated into three components (Pugh 1996 pp17; Pugh 2004 130):

$$X(t) = Z_0\ (t) + T(t) + S(t) \qquad (1)$$

where, Z_0(t) is the slowly varying 'mean' sea-level (e.g. redistribution of mass), T(t) is the predicted tide and S(t) is whatever signal remains unaccounted for or 'the residual'.

S(t) is also frequently termed the 'meteorological surge', hence the letter 'S', due to the dominance of this a-periodic contribution although this terminology can be misleading. In particular, the word 'surge' unnecessarily emphasises specific time scales and physical characteristics and additionally can leave ambiguous the distinction between prediction error and physical causation. This definition of S(t) is directly tied to the quantification of the other terms, which in practice amounts to a dependence on the particular tide analysis method in use.

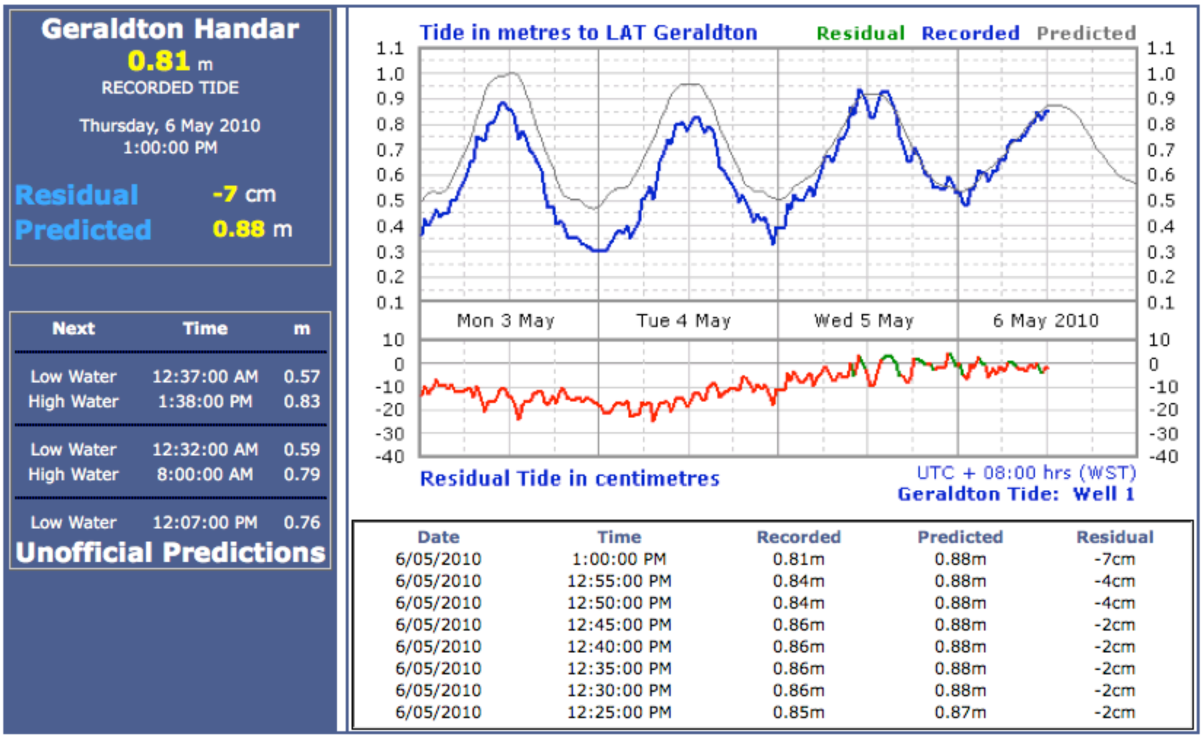

Fig. 1 Example of typical tide prediction and observations information from a public website.

[Ref Geraldton Port Authority public website]

In this *tidal* context, there is also an implicit bandwidth restriction with regard to the signals in question, including S(t). At the high frequency end variations beyond about 1 cycle per hour are not typically considered relevant (Schahinger 1985), excepting the special applications to phenomena such as tsunamis. Tide gauge instruments typically incorporate either physical or onboard electronic measures to smooth high frequency variability. At the low frequency end, the variations in S(t) are not commonly considered at periods far beyond the annual cycle. The definition of T(t) does generally incorporate the effects of some select periodic variations beyond 1 cycle per year – that is, the lunar and solar perigees and lunar nodal regression (whilst the 'pole tide' or Chandler wobble is often neglected). Longer period changes not occurring at these known tidal frequencies are likely to be treated as a secular trend in $Z_0(t)$ rather than a contribution to S(t).

Fig. 1 is included for illustration only and shows a typical example of observed coastal sea level being broken down into tidal prediction ($T+Z_0$) and residual (S). The residual in this case is seen to contain multi-day and sub-inertial frequencies.

2.3.3 Definitions of the tidal signal

The traditional decomposition of the total sea level into tidal and non-tidal components brings into question exactly what should define the tidal signal. The definition is especially relevant in the present context, as the tidal signal needs to be removed from the observational data to facilitate comparison with the non-tidal output of OceanMAPS. See Section 2.3.6.

Common to any definition of the tidal signal is an association with the relative positions of the Sun, Earth and Moon. All definitions are also founded on the recognition that the signal represents complex dynamical fluid adjustments strongly influenced by bathymetry. The astronomical tide generating forces at the Earth's surface can be mathematically described as a scalar potential field dependant on the relative positions of Sun, Earth and Moon. These 'astronomical ephemerides' display regular cycles and are forecast to such great precision so as to be taken for granted from an ocean prediction perspective. Modern catalogues of the tidal potential have extended to include the gravitational effects of other planets (Hartmann 1995), but the Earth-Moon-Sun system alone is considered sufficient for ocean studies and founds the conceptual legacy of tide analysis. The ocean tidal potential is often expressed in units of height as the 'equilibrium tide' (Marchuk and Kagan 1989:7).

The 'response method' of tidal analysis (Munk and Cartwright 1966) defines the tidal signal as a linear response of the ocean to an input time series. The input is primarily the gravitational potential but can be extended to include for example the solar 'radiation potential'. With this method the equilibrium tide is decomposed into a series of spatial spherical harmonics but *not* temporal harmonics. The forcing input time series is calculated via these spatial harmonics and tabulated ephemerides. Whilst this approach has the advantage of an explicit physical basis, it is not in widespread usage.

In contrast, the conventional harmonic analysis method broadly defines the tidal signal as *any* periodic variations occurring at a set of special predefined frequencies. These frequencies are the result of a *temporal* harmonic decomposition of the equilibrium tide. Amplitudes of signals occurring at these special frequencies are assigned traditional names and called tidal constituents.

In general only the frequencies from the equilibrium tide decomposition are important for harmonic analysis methods. However, the relative amplitudes are also commonly employed to account for the modulation effects of the three longest tidal periods via so called 'satellite' or 'nodal' corrections (Pugh 1997).

Harmonic analysis methods are in common usage by authorities around the world, including the Australian Bureau of Meteorology. However, the method is sensitive to conventions and details such as length of historical record, inclusion of constituent terms and non-tidal ‘noise’. The present report does not utilise any ‘official’ tide predictions.

For the purposes of this study two different methods for ‘de-tiding’ were employed, neither of which can be said to represent the true physical tide, but which illustrate the range of practical approaches. Different methods of defining the tidal signal could have ramifications for future developments and this topic is further discussed in Section 8.3.

2.3.4 Spectral contamination of tidal predictions and the attribution of errors

Tidal analysis results are impacted by non-gravitational contributions and variations that are a-periodic (Pugh 1987:184,308). In general this negative impact can be described as an issue of signal to noise ratios, as per Marchuk and Kagan (1989:10). The ‘noise’ in a tide gauge record from the perspective of tidal analysis would typically include storm surge and variations attributable to large-scale meteorological patterns.

Consider for example seasonal changes to sea level associated with fluxes across the ocean air-sea interface or ‘side wall’ fluxes from river runoff and sea-ice melt. The ensuing ocean dynamics represent mixed barotropic-baroclinic responses that are distinguishable on a physical basis from the gravitational tides (and furthermore can be represented by OGCMs). Although the sea level signal associated with such dynamics may at times appear to be periodic, such phenomena are in fact connected with geostrophic turbulence and are subject to significant a-periodic changes.

A-periodic contributions to sea level should be considered as ‘noise’ when applying harmonic analysis with the goal of producing tidal predictions. However, the method cannot distinguish quasi-periodic noise from true signal and energy is inappropriately aliased onto the tidal harmonics, ultimately compromising the tidal predictions.

Tide predictions thus inherently contain statistical errors associated with non-tidal contamination that amounts to a form of ‘modelling error’. Whilst statistical methods can be employed to estimate the error bands for analysed constituent amplitudes, in practice tide predictions are rarely (if ever) promulgated with quantified confidence intervals. Any misfit between predictions and observations is bundled into the residual S(t).

Tidal authorities attempt to minimise modelling error by performing the harmonic analysis on a long historical record of high quality observations. Where possible a record spanning the approximately 19-year period of the regression of the lunar ascending node is utilised so as to directly fit all of the practical tidal constituents (the 20,000 year cycle of solar perigee is far too long). In practice the ideal time series is not always available.

To highlight the issue of the spectral contamination that can lead to harmonic modelling errors Fig. 2 and Fig. 3 are included for illustration. These show overlayed power spectral density (PSD) plots estimated from the hourly observations and matching tide predictions at two Australian tide gauges, using the data of Mitchell 2008. The intention of these plots is to illustrate the broad-band spectral spread of sea level variations from which the harmonic analysis method determines weights to attribute to the tidal constituents. Note that the tidal PSD does not appear as a pure line spectrum as it has been estimated from a finite length hourly time series using exactly the same methodology used for the observational time series. Comparison of the two plots also highlights that the tidal signal to noise ratios are highly location dependant. The mid-latitude location (Thevenard) shows a powerful ‘weather band’ bulge not nearly as apparent at the tropical station (Darwin).

The above discussion highlights some limitations arising from the traditional approach to decomposing sea level observations into tidal and non-tidal components. In particular, the issue of assigning respective error characteristics to decomposed signals would render the use of such datastreams problematic in context of data assimilation.

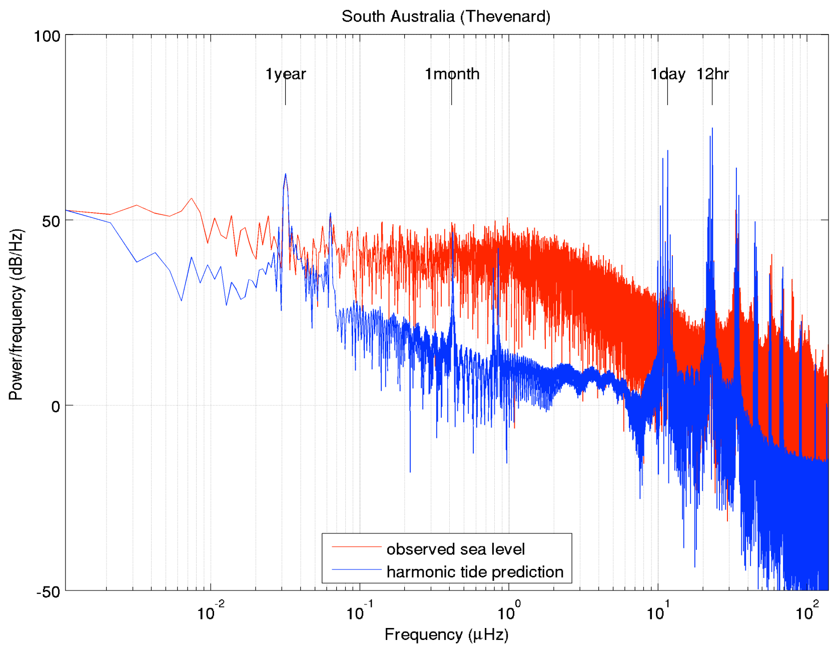

Fig. 2 Illustrative PSD for observed sea level variations in Southern Australia (Hourly samples).

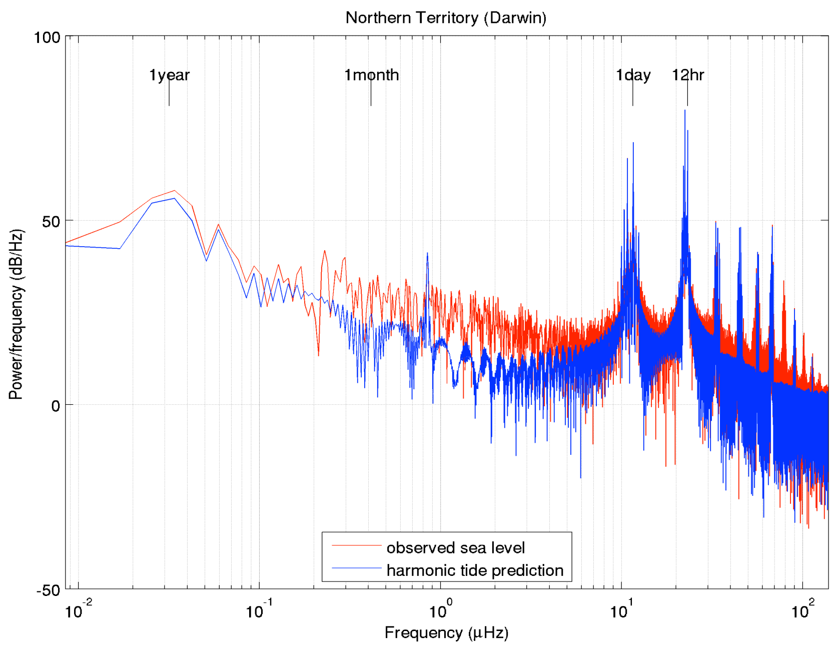

Fig. 3 Illustrative PSD plot for observed sea level variations in Northern Australia (Hourly samples).

Note that the frequency axis limits are not equal in Fig. 2 and Fig. 3

2.3.5 Sea Level Anomaly in OceanMAPS

The OceanMAPS system includes neither the forcing due to the tidal potential nor assimilation of tidal observations, and in that respect is a non-tidal model. In addition OceanMAPS v1.0b does not include the forcing due to atmospheric sea level pressure (SLP) nor does it assimilate any SLP associated observations. Thus OceanMAPS does not attempt to estimate the total sea level but rather a subset quantity that can be termed the 'atmospheric pressure adjusted SLA', hereafter simply referred to as SLA.

The absolute value of the SLA quantity within OceanMAPS is made up of a static component and varying component. The static component is the models representation of the ocean mean dynamic topography (MDT), which accounts for the mean distribution of mass in response to the atmospheric winds. In geocentric coordinates, the MDT is the difference between the mean sea surface height and the geoid. A long period integration using reanalysed atmospheric surface forcing can be used to estimate the models effective approximation of MDT. For the present report each of the individual time series was pre-processed by removing the respective sample means, such that the OceanMAPS SLA signal under investigation is only that relative to the MDT. Refer to Section 3.3 for further comments.

In summary:

- SLA is quantified in length units (metres) measured vertically up;
- SLA does not include motions due to forcing by the tidal potential;
- SLA as used in this report does not include motions due to atmospheric pressure forcing (inverse barometer);
- Absolute values of SLA include an essentially arbitrary offset.

2.3.6 SLA cannot be directly observed

SLA cannot be directly observed - it is a derived quantity. Subsequently the observational data from tide gauges needed to be pre-processed to facilitate comparison with the OceanMAPS output.

As explained in section 2.3.1 the sample mean sea level for each data series under investigation was removed for the purposes of comparison. Thus removing any need for consideration of arbitrary offsets contained within absolute values.

In short, to render the observational data from the tide gauges comparable with the OceanMAPS output, the observations were de-trended, de-tided and adjusted for the effect of atmospheric pressure by a local inverse-barometer approximation.

The order and details of this pre-processing is described in Section 4.3.

3. OCEANMAPS: AN OPERATIONAL OCEAN PREDICTION SYSTEM

3.1.1 General System Description

The Bureau of Meteorology's first general ocean circulation prediction system went ‘operational’ in August 2007 (Operations Bulletin APOB69), meaning that the system is run and maintained as a public service by the Bureau alongside its various other regularly scheduled operations. The Ocean Model Analysis and Prediction System (OceanMAPSv1.0b; Brassington et al. 2007) was developed by the BLUElink project and is based on several major components:

- OFAM: the BLUELink Ocean Forecast Australia model (Schiller et al. 2008);
- BODAS: the BLUElink Ocean Data Assimilation System (Oke et al. 2008);
- Input surface fluxes from the GASP NWP system (Seaman et al. 1995);
- Real-time quality control for the global ocean observing system and other features for real-time forecasting (Brassington et al. 2007).

3.1.2 The OGCM component

The OFAM is an ocean general circulation model based on MOM4p0d (Griffies et al. 2004). It contains a 3D gridded representation of the global ocean. The spatial grid is fixed in time and has been configured to have a varying spatial resolution. Within the Australasia region, defined to span 90E-180E and 65S-16N, the grid has a horizontal resolution of 0.1° and this is considered sufficient to be mesoscale ‘eddy-resolving’. The remainder of the global ocean has lower horizontal resolution. In the vertical dimension, the upper 200 m of the ocean grid has regular 10m cell thicknesses. The vertical resolution becomes increasingly coarse from the 200 m depth down to the maximum of 5500 m. The bathymetry in the Australian region is based on a Geoscience Australia product.

The Australian coastline and continental shelf are resolved at the models maximum resolution. However, for numerical stability the minimum column depth must contain two vertical cells, which is equivalent to a minimum depth of 20 m. For water columns deeper than 20 m the depth is more accurately represented by "shaved cells". Furthermore any section of ocean bounded horizontally such as a bay and strait must be resolved by a minimum two "t-cells" width or ~20 km. It follows that the model can only represent bathymetry down to the lower size limits of mean depth 20m and mean width of 20km. In some specific regions where this leads to closure of narrow straits that are known to be locations of important throughflow, an artificial widening or deepening has been undertaken so as to better represent the real physics within the bounds of the model resolution.

The ocean model is forced by time averaged atmospheric surface fluxes of heat, mass and momentum (but not SLP in the present version) taken from the Bureaus’ operational global prediction system at a temporal resolution of 3hrs. The atmospheric fluxes need to be re-gridded prior to application to the ocean model grid. In the Australian region these fluxes are first resolved to a regular grid at 0.75° from a Gaussian grid. Atmospheric surface fluxes are in general not continuous across adjacent cells of land and sea and in particular surface wind stress contains a discontinuity due to the surface roughness. All values over land cells are discarded and "filled" using a Laplacian solver. A one-dimensional spline interpolation is applied successively to each dimension to de-alias grid discontinuities transitioning from the source grid to the target grid.

3.1.3 The data assimilation system

The BLUElink ocean data assimilation system (BODAS; Oke et al. 2008) is a multi-variate ensemble optimal interpolation scheme which uses a stationary ensemble of model monthly anomalies to represent the background error covariance. A total of 72 ensemble members are derived from a forced "spinup" model integration for the five prognostic variables. Specifically these variables are SLA, temperature, salinity, and horizontal velocity components. OceanMAPS v1.0b assimilates observational information via satellite-derived sea level anomaly data (Jason1 and Envisat; GFO is not used); satellite SST (AMSR-E) and in situ temperature and salinity (Argo, XBT and TOGA-TAO).

3.1.3.1 SLA from satellite

SLA is a derived quantity from satellite altimetry observations, which is dependant on a series of corrections. Firstly the sea surface height (SSH) above the geocentric reference ellipsoid is calculated from the raw range signal by accounting for the instrument altitude and applying corrections for moist atmosphere, dry atmosphere, ionosphere and the effect of wind waves in the ocean (‘sea state bias’). SLA is subsequently derived from the SSH by subtracting estimates of several geophysical phenomena:

- Mean dynamic topography - itself relative to a geocentric geoid estimate;
- Geocentric ocean tide model (combined ocean and load tides - excluding long period constituents);
- Long period ocean tides modelled by the equilibrium tide;
- Solid earth tide;
- Pole tide;
- Atmospheric pressure effect model;
- Sea state.

Further details can be found in Picot (2003).Due to the reduced signal to noise over the continental shelf, the lower accuracy of corrections and the land contamination of some of the instrumentation involved, SLA observations are not assimilated within the 200m isobath – see also Section 8.8.

Satellite-derived SLA is obtained from narrow-swaths that orbit the earth in ascending and descending tracks. One complete orbit takes ~9.9 days for Jason1 and ~35 days for Envisat. It has been found that the ocean analysis performs best when a minimum of one complete orbit of Jason 1 is available. SLA derived from Jason1 becomes available to OceanMAPS 3-days behind real-time.

The availability of a complete orbit was influential in the design of the OceanMAPS operational schedule, and this is discussed further below.

3.1.3.2 Tide gauge observations not assimilated

It is important to note that observational data from tide gauges is **not** assimilated into OceanMAPS.

3.1.3.3 Other data

SST and Argo observational data are both available for use in OceanMAPS close to real-time and are also included in the two multi-variate analyses. SST is observed using wide-swath which provide global coverage in 24 hrs. An observation window of +/-1 day is applied.

3.1.4 Operational cycle

The operational schedule design is directly influenced, *inter alia*, by the availability of SLA data products. In particular, an initial behind-real-time symmetric analysis is performed 8 days behind the base date using an observation window of +/-5days for SLA. An asymmetric analysis is then performed closer to real-time at 5 days behind the base date with an observation window or -5days to +2days. During the hindcast portion of each cycle, each 24 hours of surface fluxes is made up of a composite of the respective four 6hrly NWP analyses. During the ocean forecast portion of the cycle forecast atmospheric surface fluxes are applied.

The operational cycle of OceanMAPS v1.0b repeats every Monday and Thursday. A schematic of the schedule is illustrated in

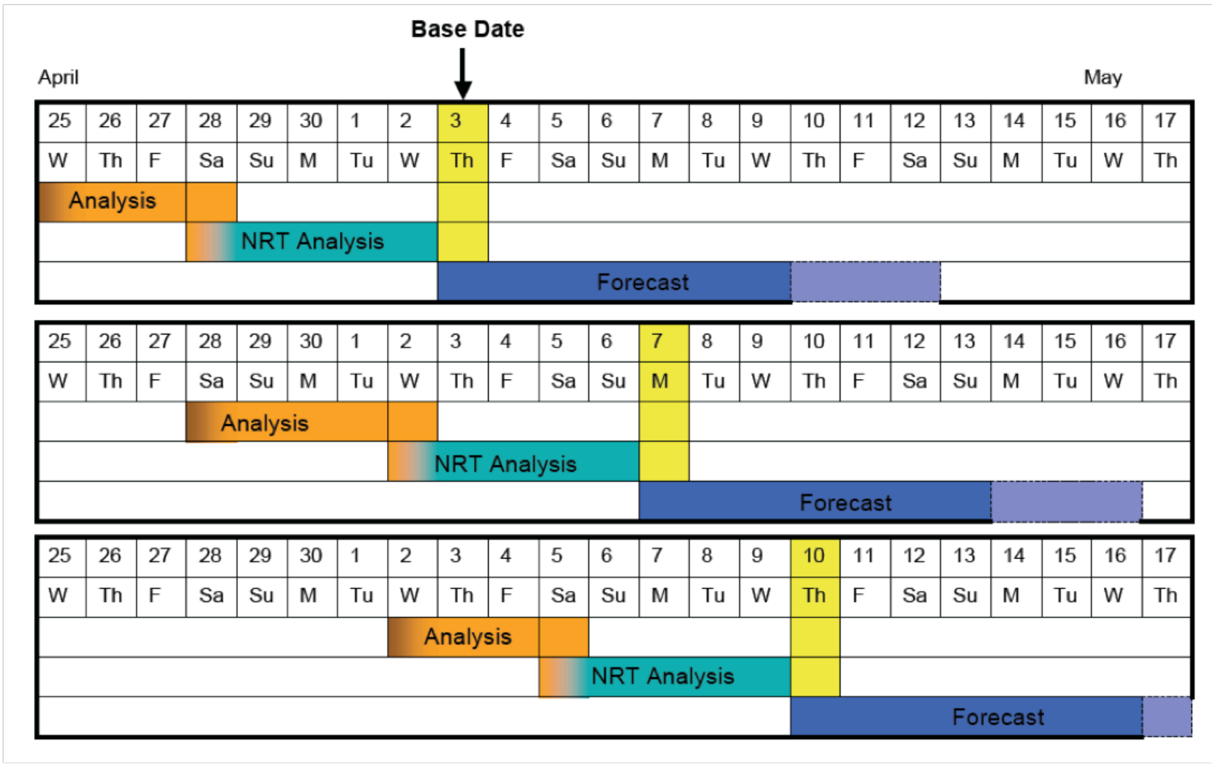

Fig. 4.

Fig. 4 Illustration of OceanMAPS operational cycles for 3 successive base dates.

3.1.5 General output

A range of graphical and data products for public end-users of OceanMAPS are routinely produced from the forecast daily average model output. Figure 2 is an example of the sea level anomaly in the Australian region. For the ongoing operational forecast products refer to the following public website: http://www.bom.gov.au/oceanography/forecasts/

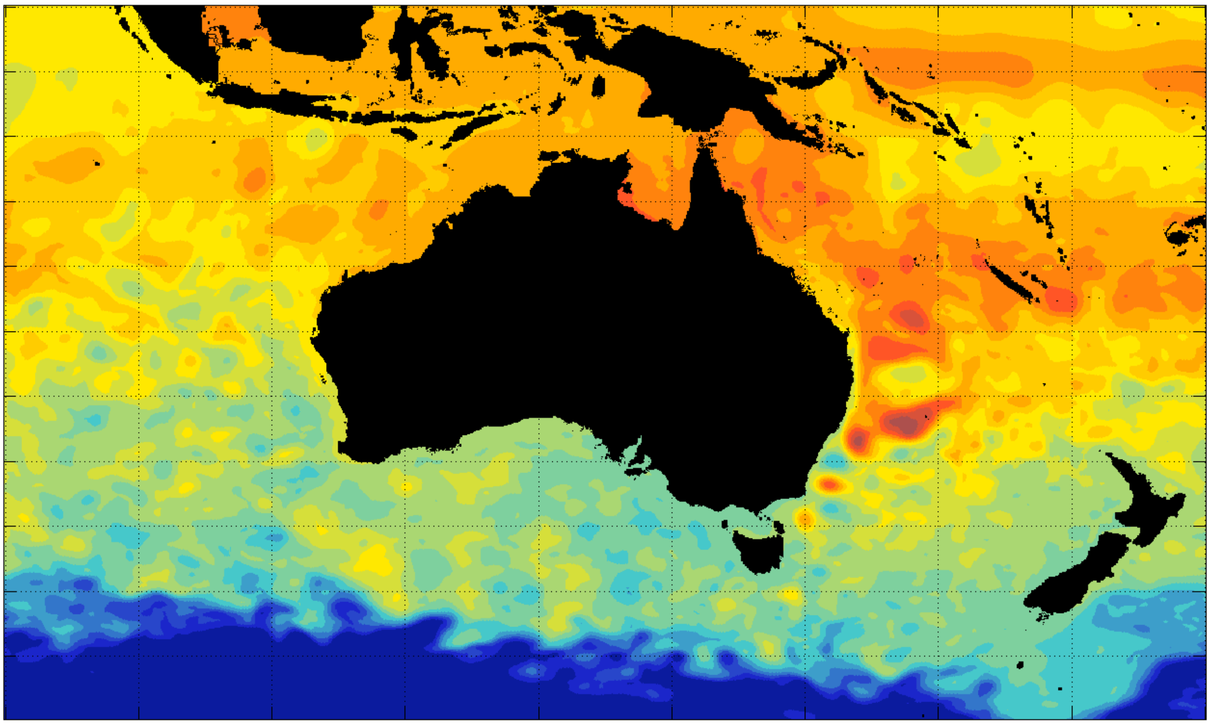

Fig. 5 Example visualisation of OceanMAPS SLA across the high resolution Australia region.

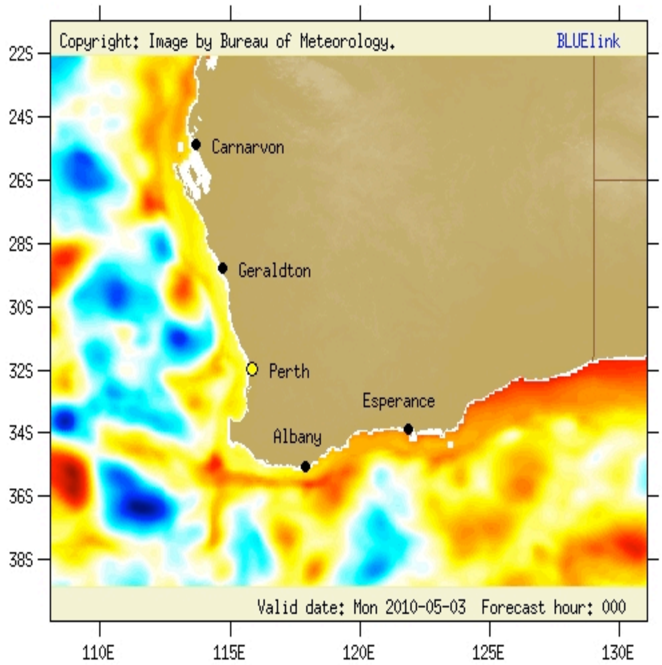

Fig. 6 Example of SLA forecast corrected for the mean dynamic topography as provided on the public website for the South WA region.

3.2 General System Performance

The general performance of the Bureau's ocean prediction system has been evaluated through statistical performance, specific event based analysis and intercomparisons with equivalent operational ocean prediction systems from other international centres (Hernandez et al. 2009).

On the basis of such assessment results Bluelink OceanMAPS is considered to perform quite well over the *open ocean*, within the region of high resolution and it's representation of the general circulation can be treated with some confidence. However, no international intercomparison is available that evaluates performance in the *coastal zone* for these systems. Such a study would be of value and may be undertaken in the future as an extension of the present report.

As an example of the comparative performance assessment, Fig. 7 shows the root mean square error, standard deviation and correlation relative to SLA over the South East Indian Ocean between Feb-Apr 2008 in the form of a Taylor diagram (Taylor, 2001). Each diagram shows in a geometrically compact manner the results for the following operational datasets:

- [Australia] OceanMAPSv1.0b analysis - *labelled "OMAPS(an)"*;
- [Australia] OceanMAPSv1.0b 3-day forecast - *labelled "OMAPS(fc)"*;
- [France] Mercator analysis (Brasseur et al. 2005);
- [UK] UK Met Office analysis (Martin et al. 2007);
- [USA] NRL HYCOM-NCODA 5-day forecasts (Cummings 2005).

Within these diagrams both OceanMAPS and NRL HYCOM-NCODA, which are *eddy-resolving* models in the regions of interest, show comparable variability to the observed. The OceanMAPS analysis shows the best performance in the evaluated region among all the analyses for this period. The OceanMAPS 3-day forecasts shows the expected decay in performance compared to the analysis and is comparable to the performance of the 5-day forecasts from NRL, HYCOM-NCODA system. OceanMAPS performs comparably for SLA, SST and T/S sub-surface profiles to other operational systems in the Australian region.

Comparison of Fig. 7 and Fig. 8 also illustrates the regional variability in performance of the different prediction systems. It is emphasised that these diagrams have been included only as an indication of broader performance evaluation. The choice to show results for the Indian Ocean, rather than any other regions, was one of convenience only.

The Taylor diagram (Taylor 2001) summarises quite a lot of statistical information in a compact form. A very simple way of interpreting the diagrams in this context is to consider how close each point plotted is to the point representing the observations. Closer is better.

South-east Indian Ocean 01-Feb-2008 - 30-Apr-2008
Sea Level Anomaly
Observations(#obs): JASON/ENVISAT (42356)

System	HYC	MER	UKM	OM(an)	OM(fc)
Bias (m)	-0.05	-0.18	0.01	0.01	0.01

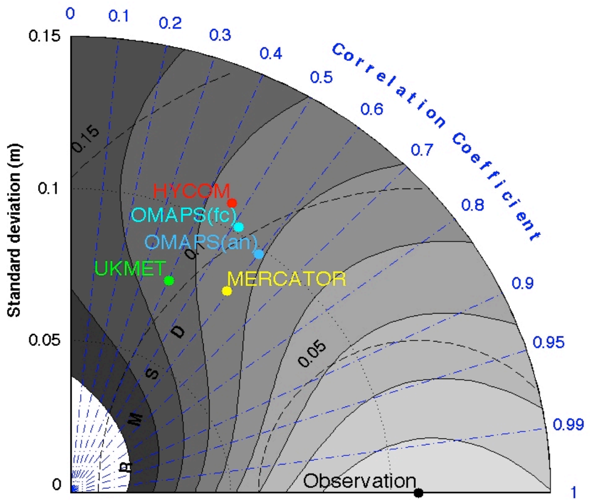

Fig. 7 Taylor plot showing relative performance of various ocean prediction systems for SLA in the South East Indian Ocean.

Darker shading indicates increasing values of the skill score as defined in Section ***5.4.1***

Tropical east Indian Ocean 01-Feb-2008 - 30-Apr-2008
Sea Level Anomaly
Observations(#obs): JASON/ENVISAT (27759)

System	HYC	MER	UKM	OM(an)	OM(fc)
Bias (m)	-0.13	-0.19	0	0	0

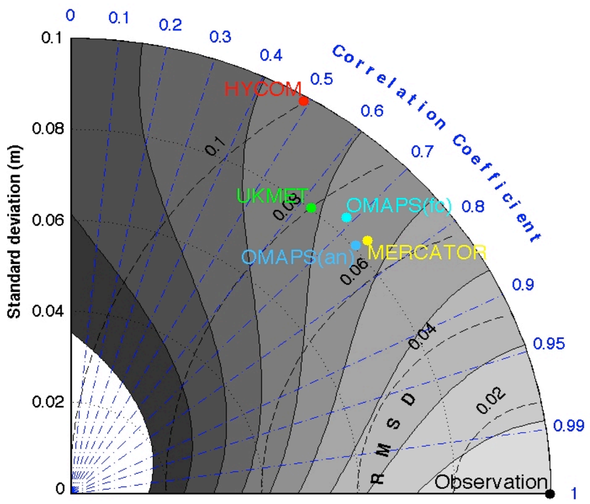

Fig. 8 Taylor plot showing relative performance of various ocean prediction systems for SLA in the Tropical East Indian Ocean.

3.3 Further details regarding SLA output

It is emphasised that OceanMAPS does not model the ocean tides. There is no astronomical forcing applied. Whilst the assimilated SLA satellite data products have been corrected for tides (see Section 3.1.1) it is acknowledged as a possibility that differences between the 'true' tide and the estimated tide could result in leakage of open ocean tidal signals into OceanMAPS. This possibility has not been explicitly considered in the present report. However, the known deviations of the shortest of the long period tides from the equilibrium approximation (Wuncsh et al. 1997, Egbert and Ray 2003) may direct future investigations in this regard to periods of approximately 8 days, 2 weeks and 1 month.

The representation of sea level variations in OceanMAPS is limited by the grid resolution where wavelengths less than 2 grid spaces (i.e. 0.2°) are damped and poorly resolved. The ocean model does not explicitly model short period wind waves and swell but instead parameterises the wind energy total kinetic energy into potential energy in the form of overturning (mixing) the vertical stratification and momentum transfer over the surface layer. Wind driven effects related to the large scale and near inertial advection of mass in the form of Ekman transport are modelled. The model therefore represents, storm surge (or related upwelling) at the coast as well as basin and gyre scale Sverdrup dynamics.

Sea level air pressure (SLP) forcing was not applied within the operational system during the period of the present study (OceanMAPSv1.0b). Similarly, the assimilated SLA observations are corrected for related effects, see Section 3.1.1. In principle it would be straightforward to apply this additional force to the existing ocean model, as the required code exists in MOM4 and the forecast fields are available from NWP systems. However, this has implications for the data assimilation system where errors in SLP could reduce the constraint on the mesoscale.

Similarly, for pragmatic operational reasons SLA output from OceanMAPS v1.0b has been archived as daily averages only. Higher frequency data is in fact internally calculated but not output and stored. The daily frequency of output was defined on the basis that the mesoscale ocean dynamics at periods greater than the inertial period, along with reducing disk storage.

In summary, it is considered appropriate to compare the archived OceanMAPS SLA output to the observed tidal residual adjusted for air pressure and averaged for each calendar day.

4. OBSERVATIONS AND PRE-PROCESSING

4.1 Real-time coastal tide gauges

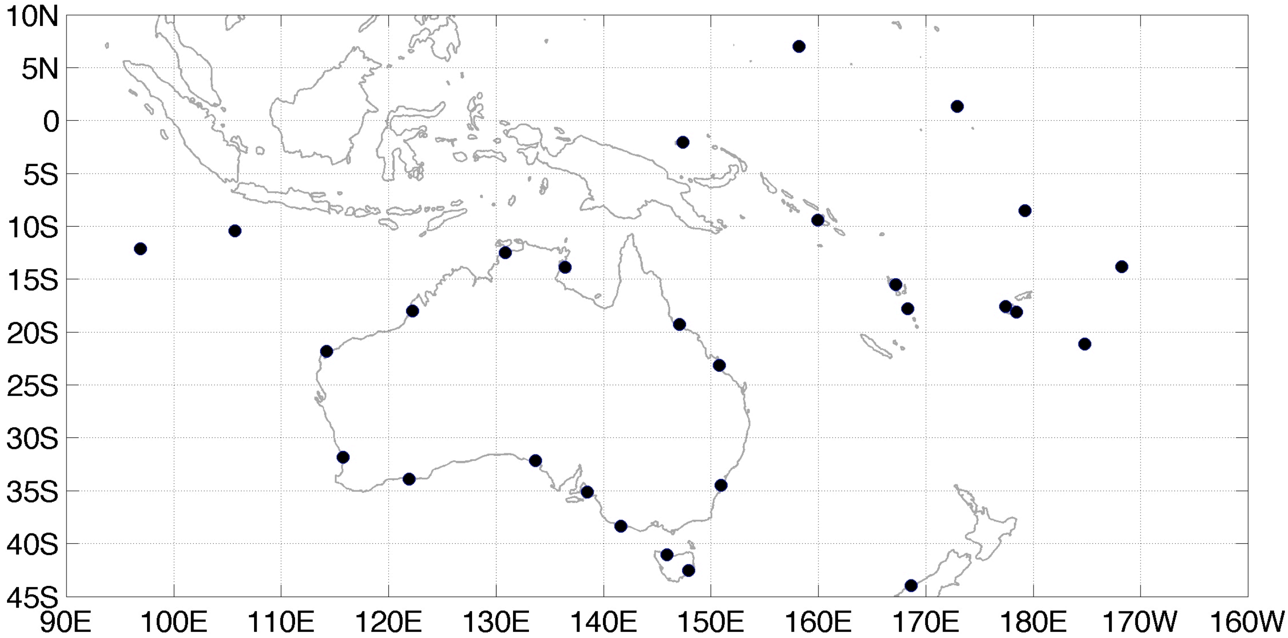

Fig. 9 Location of real-time reporting tide gauges referenced in this study.

4.1.1 Independence from OceanMAPS

No observational data derived from coastal tide gauges are assimilated into OceanMAPS. Thus the tide gauge data is asserted to be independent of the model and the prediction system and can justifiably be compared as such. The observations used in the assimilation system are discussed in Section 4.1.2. Context of the wide tide gauge network.

4.1.2 Context of the wider tide gauge network.

Routine observations of coastal sea level are made with a class of instruments referred to as 'tide gauges'. A variety of tide gauge instrument types are installed throughout the Australian region – all with the common characteristics of being land mounted in a fixed location very close to the coast.

The tide gauge network routinely retrieved by the Australian Bureau of Meteorology was developed via a range of funding and ownership arrangements, with a central role played by the Bureau's National Tidal Centre in particular collection and archive. The technical design of the system components has been influenced by the priorities of contributing projects. The initial configuration of the gauges referenced here is attributed to projects focussed on long-term sea level changes – such as the *Australian Baseline Sea Level Monitoring Project* and the *South Pacific Sea Level and Climate Monitoring Project*. More recent communications system upgrades that facilitate the routine availability of real time data streams are largely due to the requirements of the *Australian Tsunami Warning System Sea Level Observation System*.

It is understood that ongoing observation network developments are underway with respect to sensor types, data stream handling and more general logging equipment upgrades. These developments are expected to increase the availability of coastal sea level observations suitable for future studies and potential assimilation into operational systems.

The temporal data requirements of the Bluelink ocean prediction system fall in between the extremes of climate studies (delayed mode lower frequency) and tsunami monitoring (real time high frequency).

4.1.3 Selection for inclusion

A selection of 28 tide gauges provided the observational reference for this preliminary assessment of ocean prediction system skill. These tide gauges are situated around Australia, in the Pacific Ocean and in the Indian Ocean as indicated in Fig. 9. More detail for each location is included in the Appendices.

Selection of the locations for inclusion in the study was determined primarily by what data streams were known to be available at the time of writing. In particular, this constituted routine real time 1 min data appearing within a particular real time database in the Australian Bureau of Meteorology head office [viz. the 'sea_lvl' sequence in the Neons system].

The selection represents a relatively homogeneous set of instruments employing either an acoustic sensor (25 gauges) or a downward looking radar sensor (3 gauges). Many of the installations in fact feature multiple redundant sensors. Due to availability at the time of writing, only data from the primary sensor at each location was utilised in the present study.

4.1.4 Exposure to open ocean

Overall, the selected tide gauges are at locations that are relatively exposed to open ocean sea level signals; as opposed to highly sheltered estuaries perhaps more typical of tide gauges in general. This is deduced from the historical developments that lead to the establishment of the real time reporting regime. And the requirements of the Australian Tsunami Warning system in particular are noted in this regard.

The fact that these tide gauges are relatively exposed to the open ocean is considered to be favourable for the comparison with OceanMAPS.

OceanMAPS currently has 10km horizontal resolution (related future regional systems may extend this to 1km) and is not designed to accurately represent circulation within estuaries and semi-enclosed bays. More sheltered tide gauges are not expected to compare as favourably with OceanMAPS as exposed stations. Subsequently any expansion of the real-time tide gauge network to include sheltered stations is likely to impact the mutual relevance of the network to OceanMAPS as a whole. Methods to explicitly account for sub-grid scale coastal dynamics may become particularly relevant with the use of sheltered locations, but treatment of this important consideration is beyond the scope of the present report.

Fig. 10 Real-time tide gauge station at Portland, VIC.

[photo: National Tidal Centre]

4.2 Data Quality

4.2.1 Instruments and the expected quality of observations

The tide gauges referenced in this report are relatively modern and are expected to provide useful observational data.

Fundamentally, the raw observations were made by downward looking, noncontact sensors installed on land-based structures. The majority of these tide gauges, 25 in total, were SEAFRAME type installations. The primary sensor quantifies the sea level by means of a timed acoustic pulse reflected from the water surface. Further description of the SEAFRAME device network and related information is given in Mitchell (2008). The remaining three gauges are broadly similar installations that differ in that a timed radar pulse, rather than an acoustic pulse, is employed to quantify the sea level.

It is asserted that this selection of tide gauges can be treated as a homogenous set of instruments and that the variations in instrument error characteristics can be neglected. This is justified on the basis that all time series were reduced to relatively long period variations in the form of daily averages. Similarly, the datum levels are assumed to be unchanging over the period of study and any constant bias can be neglected as only the fluctuations relative to each observed mean is treated.

4.2.2 Choice to utilise archived raw real-time data

It was chosen to base the present study on raw real-time data, rather than the more complete delayed mode quality controlled archives maintained at the Bureau's National Tidal Centre. This was considered an important exercise and secondary objective for this study in the context of developing the operational ocean forecast system. It is acknowledged however that future studies will benefit from the inclusion of both the real-time data and the complete delayed-mode historical record. In particular, this would enable quantification of the differences between real-time and delayed mode data and the subsequent impact on skill evaluation.

As a result of this choice, several specific data quality issues had to be addressed prior to use in the present comparison process and these are highlighted in the following section.

‘Raw data’ here refers to the 1 minute averages as transferred to head office database. These are calculated onboard each instrument from sensor samples taken at 1 Hz.

4.2.3 Quality issues with real-time data

Although accessed from historical archives, the data employed in this study was effectively raw instrument output that had not been subject to prior quality control or verification.

Any future efforts to utilise tide gauge data in an operational system will require improved ability to apply quality control measures in real time. For instance, this may be facilitated by the routine availability of quality flags and additional sensor data. It is understood that some such improvements are underway at the time of writing.

Additional relevant data is generated at many of these installations but was not made available in real time by the telecommunications system at the time of writing. Most notable among the missing real time data was atmospheric pressure. This discrepancy is believed to be a result of both instrument communications hardware limitations as well as transmission message design. Consequently for this study station status information and *in situ* barometer data were not available. Barometer observations from the closest alternative station where substituted to enable application of the local inverse barometer correction.

Rectification of data stream availability would be considered a significant improvement with regard to future employment in an operational system. It is understood that some of these improvements are underway at the time of writing.

4.2.3.1 Quality Issue 1 - Gaps

Missing values of durations ranging up to several months appear in the observational time series. These gaps may have been the result of communications drop-outs or instrument failure. It is noted that the data used in the present report were archived real-time data streams, such that communications drop-outs remain as gaps regardless of the possibility of delayed mode recovery from *in situ* data loggers.

4.2.3.2 Quality Issue 2 - Noise

In some instances the raw data was found to be abnormally noisy, in the sense that the expected smoothness of the data was compromised. It is speculated that this may arise as a result of exposure of the instrument to large short period waves or internal instrument issues.

4.2.3.3 Quality Issue 3 / Gauges Faulting

Occasional non-physical values appear in the raw datastreams. In instances when such non-physical values are recurrent or exhibit certain characteristic patterns, the corrupted data is considered to be a result of ‘instrument faulting’. Any cases of faulting that did not result in noticeable non-physical values or patterns remained undetected within the quality controlled dataset and thus contribute to instrument error.

4.2.3.4 Quality Issue 4 / Low value data clipping

The absolute observed sea level value is measured relative to some arbitrary datum for each station. In principal, it is expected that these settings be such that the absolute sea level values are always positive in sign. However upon inspection of the data it was found that several stations exhibited data clipping below the positive value range. This issue was later found to be the result of a bug within the Bureau’s data base configurations rather than any issues with the instruments or transmissions. Rectification of this issue is believed to underway at the time of writing.

4.2.4 Quality control: manual inspection and rejection

Data used in this study was subject to manual quality control processes that relied primarily upon visual inspection and subjective judgement. An inspection and rejection process was applied using semi-automated interactive software. This process was systematically applied to:

- sea level observations;
- barometric pressure observations;
- SLA derived from sea level observations.

It is emphasised that the nature of the quality issues was found to be non-uniform, even within each time series. Subsequently a fully automated objective process was not applied here. This situation highlights the need for a comprehensive quality control system for real time tide gauge observations in the future. Table 3 summarises the rejection rates.

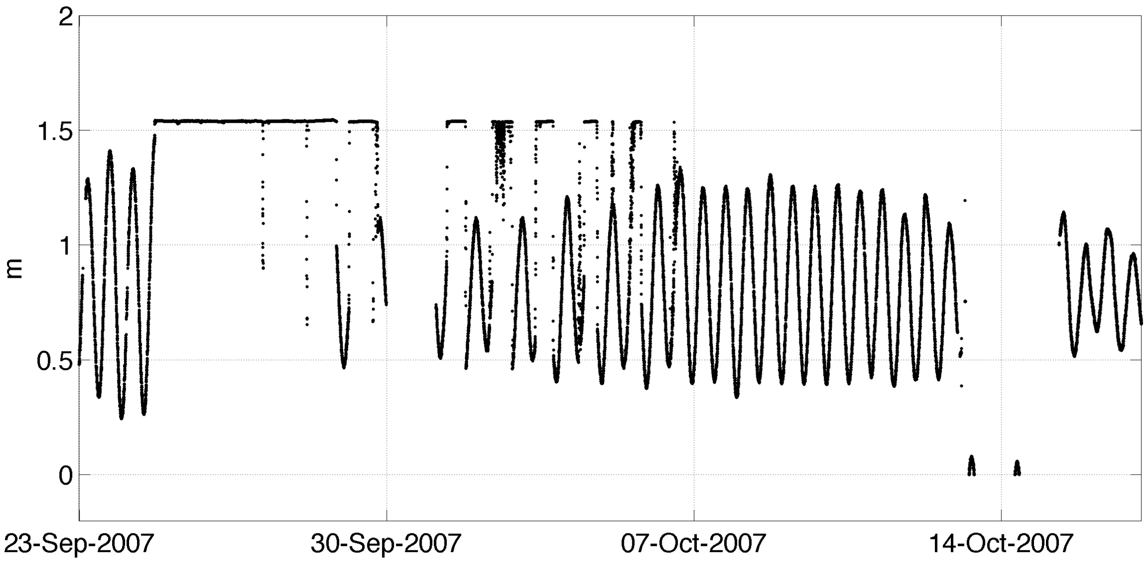

Fig. 11 Example of compromised real time data.

[Location: Apia (Samoa)]

4.3 Derivation of comparable SLA signal from observational data

Sea Level Anomaly (SLA) is not a directly observed quantity; it is derived from the total sea surface height via a number of assumptions and signal estimates. For further details see Section 3.1.1.

4.3.1 Linear decomposition assumption

The concept of SLA assumes that the observed sea level at a point location is linearly separable into contributing component signals, Following on from the conventional (though problematic) tidal notation introduced in Section 2.3.2, the tidal residual S is here further decomposed into an inverse barometer and SLA component, $S_{IB}$and S_{SLA} respectively.

$$X(t) = Z_0\ (t) + T(t) + \{S(t)_{IB} + S(t)_{SLA}\} \qquad (2)$$

This formulation ignores any non-linear effects that would be present should the component signals actually be physically superimposed. Whilst non-linear interactions are typically relevant for describing coastal ocean dynamics, this formulation may not be as blunt as it first appears. This decomposition can still account for non-linear interactions *within* the respective component signals - just not *between* them. In some instances non-linear effects can project onto the linear components (e.g. errors in the tidal harmonic amplitudes). Ultimately non-linear effects that are not represented remain within the residual time series.

In the related case of 'shallow water' surge models it has been shown that linear addition of independent tide and surge forecasts can generally be expected to *overestimate* the total sea level (Tang et al. 1996). However, the error characteristics of a total sea level forecast based on the present operational OceanMAPS are yet to be determined. The effect of different spatial grids and the simple inverse barometer approximation are highlighted as complications in this regard.

4.3.2 Method for estimating direct atmospheric pressure loading

Barometer instruments were in place at most of the tide gauge stations referenced in this study. Unfortunately the data was not available due to limitations within the information system, as described in Section 4.2.1. Substitute data was sourced from the closest available barometer within the Australian Bureau of Meteorology automatic weather station network. The identification of the closest station was performed manually and each station identification number is recorded in the Appendices. This substitute barometer data was interpolated temporally to match the time stamping of the sea level observations.

The sea level signal attributed to the atmospheric pressure was calculated by applying the traditional local inverse barometer calculation (Gill 1982:337).

$$S(t)_{IB} = \frac{(p_0 - p_{local})}{\rho\, g} \qquad (3)$$

Where $S(t)_{IB}$ is the sea level signal attributed to the inverse barometer effect and $p_{local}$is the local observed SLP. The remaining terms are assumed constant values as follows: p_0 is MSLP over the wider ocean 101325 Pa, we assume $\rho=\rho_0$ is sea water density 1025 kg/m^{3}and g is vertical gravitational acceleration 9.81 m/s^2.

Fig. 12 illustrates how the calculated *local* inverse barometer signal is defined to correspond directly to the changes in local barometric pressure. A higher pressure in the upper axis results in a depression in sea level seen in the lower axis – likewise a lower barometric pressure results in an elevation in sea level.

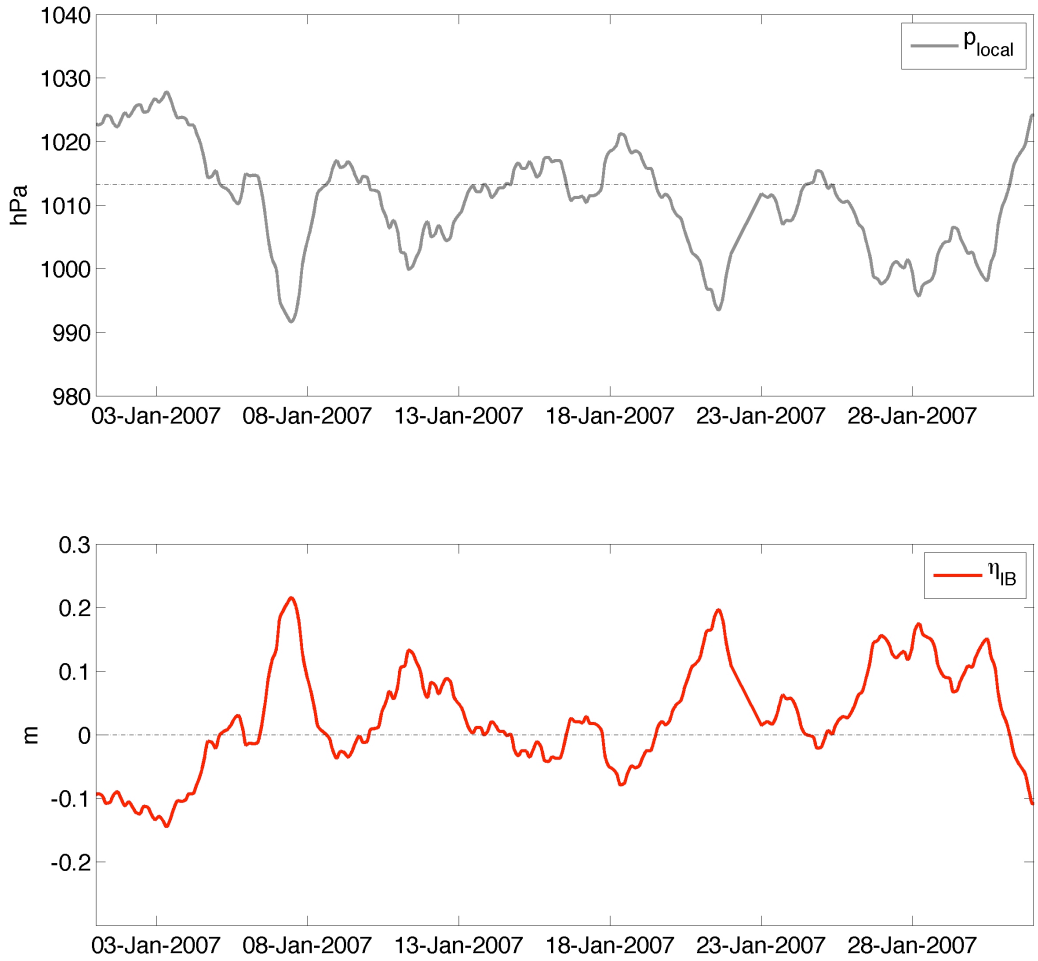

Fig. 12 Example of derived Inverse Barometer signal. [Location: Spring Bay, Tasmania].

It is emphasised that the amplitude of the inverse barometer signal can be of comparable variance (power) to the derived SLA itself in some locations. Given the significant role of the atmospheric pressure forcing in the derivation of SLA, the simplistic conventional calculation described above could be further improved. The impacts of inaccuracies associated with the 'inverse barometer' approximation have been discussed in the literature from a variety of perspectives (Wunch and Stammer 1997; Mathers and Woodworth 2001, Carrere and Lyard 2003). Whilst particular errors have been noted within the mesoscale range of frequencies, it is still considered a pragmatic choice in the present context. Future versions of the OceanMAPS prediction system will trial the inclusion of SLP forcing directly and potentially remove the need to apply a post-processing adjustment.

4.3.3 Methods to determine and remove the tidal signal (de-tiding)

In the present report, two separate de-tiding approaches were taken and applied naively. The application was considered naive in the sense that the de-tiding methods were applied without detailed consideration of a range of factors that may become relevant in future work. These methods were as follows:

- Subtraction of a harmonic analysis derived from the observations;
- Application of a simple low pass filter.

Note that the harmonic tide derived from observations is unlikely to exactly match the officially promulgated predictions from the Bureau's National Tidal Centre (NTC), as per the discussion in Section 2.3.3.

The choice of these methods and the details of application were chosen primarily for convenience but with recognition of the broad context of working towards real time operational systems.

Method 1: Subtraction of a harmonic tide signal using 't_tide'

For this method, the steps performed to derive SLA from each observational time series was as follows:

- Pre-processing to remove the inverse barometer signal and the sample mean;
- Application of harmonic analysis to estimate tidal signal;
- Subtraction of estimated tidal signal.

The harmonic analysis was performed utilizing the default settings of the freely available software toolbox named 't_tide' (Pawlowicz et al. 2002). This toolbox is founded on the original code and method as described in Foreman (1977). Important points regarding this implementation of the harmonic analysis method are as follows:

- Constituent selection algorithm based on time series length and signal estimated signal to noise ratios;
- Least squares fit to sinusoids at the selected tidal frequencies;
- Classical nodal corrections to account for long period modulations.

As this method of de-tiding selectively removes signal at a pre-defined list of special frequencies, the spectrum of the derived SLA retains some power over the full range of frequencies of the original time series. Thus this method does not involve 'filtering' per se, but rather the subtraction of estimated component timeseries from the original.

Method 2: Application of a digital low-pass filter

For this alternative method, the steps performed to derive SLA from each observational time series was as follows:

- Pre-processing to remove the inverse barometer signal and the sample mean;
- Application of low pass filter to attenuate frequencies > ~ 0.5 cycles per day.

Whilst this is a somewhat 'blunt' tool, it is very simple to apply in real time and attractive from an operational point of view. The premise of this filtering concept is that the tidal signal can be approximated by any observed high frequency variations - those at diurnal, semi-diurnal and higher frequencies. This effectively partitions the observed spectrum into the categories of tidal and non-tidal on the basis of frequency alone. An implication of this simple method is that the astromical tidal forcing at long periods is negligable.

The time series segements overlaid in Fig. 13 are intended to illustrate the different natures of the alternative de-tiding methods. Of particular note is the different treatment of high frequency variations, which are removed entirely by the low-pass filter. The reader is reminded that all datasets were subsequently reduced to daily averages.

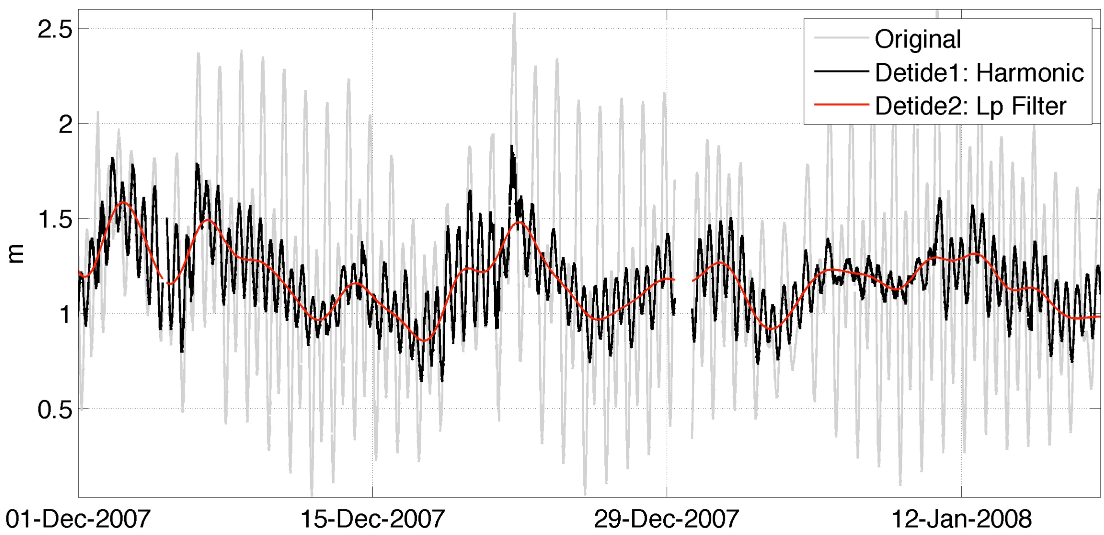

Fig. 13 Illustrative comparison of the effect of the two de-tiding methods.

Note that this plot shows high frequency data prior to reduction to daily averages [Location: Portland Victoria].

5. COMPARISON METHODOLOGY

5.1 Closest OceanMAPS grid point

The output of the OceanMAPS model consisted of gridded data at approximately 10km spacing within the Australia region. These grid locations in general did not exactly match the geographic locations of the tide gauges. As a result, some methodology was required to extract model output that could be compared to the observational time series in a meaningful manner. The method chosen was to find a single grid point (t-cell) with minimal great arc distance from each tide gauge. This identification was carried out using an automatic script and visually verified.

5.2 Daily means

All data used in the assessments was reduced to daily means prior to comparison. The existing data archiving settings of OceanMAPS effectively dictated this temporal sampling rate; see also Section 3.1.1.

Whilst the existing output settings of OceanMAPS are limited to daily means, these settings could feasibly be modified without any change to the model itself. In particular, the barotropic time step is already much shorter than 1 day and it is the frequency at which the model is sampled that is under discussion here. Coastal sea level applications of OceanMAPS may well benefit from changing these output settings so as to extract data at periods shorter than 1 day. This is especially the case given that semi-diurnal tides are often the dominant source of sea level variability. Accurate prediction of the relative timing of peak non-tidal and tidal sea levels will be critical to the quality of any future total sea level forecasts and extreme sea level warnings.

It is recommended that the OceanMAPS output schedule be modified so as to archive relevant data at higher sample frequencies than the present daily means. Ideally this should comprise hourly values for SLA for the entire Australiasia region (a 2D field). At a minimum the set of locations corresponding to quality tide gauges should be included in the higher frequency dataset. The computational expense of such a measure is expected to be modest.

5.3 Removal of sample mean

The present report treats only variations in sea level. The effect of datum choice or any other mean offset to values was removed from each respective dataset. See Section 2.3.5.

Future work towards ‘total sea level’ products would likely need to contend with this conceptually simple yet potentially messy aspect of measuring absolute sea level. Pragmatic approaches to resolve such complications may involve either calibrations to the output in real-time or alternatively restricting forecasts to representing anomaly quantities. The most likely pragmatic choice will be to develop total sea level anomalies with respect to a regional estimate of mean sea level.

5.4 Calculation of comparative statistics

Statistics quantifying the degree of similarity between OceanMAPS and tide gauge observations time series were treated 'pairwise'. That is, any days with data gaps in the observational data were excluded from the calculations.

The statistical values calculated using standard definitions were as follows:

- Correlation coefficient;
- Root-mean-squared-error (RMSE);
- Standard deviation;
- Root-mean-squared-error normalised with observations standard deviation (NRMSE);
- An example skill score – See Section 5.4.1.

5.4.1 Skill score definition

It is convenient to present a single numerical representation of the overall level of skill in each comparison.

Whilst there is a wide variety of valid skill score definitions that could be applied, the one chosen here is based on correlation and standard deviations. It imposes a relatively greater penalty for poor correlation (Taylor 2001).

$$SkillScore = \frac{4(1+R)^4}{(\hat{\sigma}+\frac{1}{\hat{\sigma}})^2(1+R_0)^4} \tag{4}$$

where R is correlation coefficient and R_0 is its theoretical maximum, here taken as 1, σ is the standard deviation of the model normalised by the standard deviation of the observations. With this definition a value of 1 indicates perfect skill and a value of 0 indicates no skill, although it is noted that other limits of skill such climatology or persistence may offer better reference levels for skill.

5.4.2 Confidence intervals

Statistical confidence intervals were not quantified for this report.

It is however asserted that the results associated with especially short time series should be regarded as relatively less significant.

Several of the time series included in this report were noticeably short in comparison to the other data sets. These locations are included for completeness but have been highlighted in both the plots and appendices to alert the reader to this deficiency.

6. OCEANMAPS ‘ANALYSIS’ RESULTS

6.1 Description of pre-processing variations

As described in Section 2.3.6, the observational data was pre-processed to facilitate direct comparison with OceanMAPS. Three types of such corrections were applied in a variety of combinations. The correction types were as follows:

- Removal of tides;
- Removal of atmospheric pressure effects (inverse barometer approximation);
- Removal of long period or ‘seasonal’ variations (2 month high pass filter).

The motivation for performing variations on data pre-processing was to allow some differentiation of what processes contribute to variation of skill across the locations under consideration.

Table 2 (Note) that each Assessment was carried out using both of the tide removal methods.

	Tide signal *Remove using 2different methods*	**Seasonal signal** *Remove with 2-month highpass filter*		**SLP signal** *Remove with ‘local inverse barometer’*
	[Obs]	**[Obs]**	**[OceanMAPS]**	**[Obs]**
Assessment 1 Naïve comparison	✓	✗	✗	✓
Assessment 2 Mesoscale comparison	✓	✓	✓	✓
Assessment 3 Sensitivity to SLP	✓	✓	✓	✗

Table 2: **Pre-processing combinations applied prior to each assessment.**

6.1.1 Assessment 1: Naïve comparison

Assessment 1 represents a naïve comparison, in the sense that the observations data has been minimally pre-processed with no account made for the contextual focus on OceanMAPS forecasts.

The fact the variations over seasonal timescales are represented by OceanMAPS can contribute significantly to the skill scores but be misleading in respect to that attributable to mesoscale phenomena – especially where a relatively large fraction of the signal power is found at such longer frequencies.

The pre-processing steps were applied prior to comparison in the following order:

- Quality control rejection of suspect data;
- Subtract the calculated 'inverse barometer' sea level signal;
- Remove the tidal signal using the two methods.

6.1.2 Assessment 2: Mesoscale comparison

Assessment 2 represents a mesocale comparison in the sense that it is restricted to shorter space and time scale variations via subtraction of any long period signal. Skill at the mesoscale is considered directly relevant to the present operational forecast cycle. Viewed from a slightly different perspective, the comparison represents a sensitivity test to diagnose the amount of skill being attributed to season length variations in Assessment 1. This rough scale separation is useful but is not strictly valid. It assumes that the seasonal signal is cleanly separable from the mesoscale - which is not always possible. For instance, the seasonal transport of heat content into the Tasman Sea by the East Australian Current is a mesoscale geostrophically turbulent process.

The pre-processing of the observations data was as per Assessment 1 with the additional final step of applying a digital high pass filter to all datasets. Specifically;

- Quality control rejection of suspect data;
- Subtract the calculated 'inverse barometer' sea level signal;
- Remove the tidal signal using the two methods;
- Apply seasonal high pass filter to both observations and OceanMAPS.

The design of the 'seasonal' filter was such that the component of the signal with periods longer than two months would be removed. The net result of the pre-processing for this assessment was then in effect a type of mesoscale band pass filter; the seasonal filter attenuating the low frequencies and the daily averaging and de-tiding removing the high frequencies.

6.1.3 Assessment 3: Sensitivity to atmospheric pressure

Assessment 3 represents a test of sensitivity to the application of the local inverse barometer correction.

As discussed in Section 4.3 the effect of atmospheric pressure is removed from the observations to render them comparable to the model output, as SLP forcing is not included in the present version of OceanMAPS. Thus any loss of skill compared to Assessment 2 diagnoses the relative significance of this pre-processing operation for each site.

The pre-processing steps were as per Assessment 2, but without the initial subtraction of the calculated inverse barometer signal. Specifically;

- Quality control rejection of suspect data;
- (none)
- Remove the tidal signal using the two methods;
- Apply seasonal high pass filter to both observations and OceanMAPS.

Note: a compromised sensitivity test

It is noted here that observed barometric pressure signals can contain significant spectral power at tidal frequencies – across both the short and long period constituents (Pugh 1996). It follows that some degree of the inverse barometer signal will inevitably be removed by steps 3 and 4 above, despite the fact that step 2 was not carried out. Furthermore the pattern of spectral overlap differs between the two tide removal methods.

Thus while Assessment 3 tests the impact of not including an explicit subtraction of direct atmospheric pressure effects it is inevitably a somewhat compromised test which in turn further highlights the non-trivial issue of properly decomposing the total sea level signal.

6.2 Results in graphical form

Given the relatively large number of stations under investigation, the results of the statistical comparisons are presented in a compact graphical form.

The intention of the diagrams is to facilitate interpretation of variations of skill across geographic location and pre-processing steps.

6.2.1 Geographic distribution of correlation coefficient

The series of maps on the following pages summarise the correlation coefficient results across all of the tide gauge locations.

Each page shows two maps – reflecting results for each of the de-tiding methods respectively. For simplicity, coloured symbols were assigned to categories summarising arbitrary ranges of correlation coefficient. Note that the correlation coefficients are *not* squared. All values are rounded down to the nearest single significant figure with a catchall lower category for correlation coefficients lower than 0.6. This lower limit was arbitrarily chosen to distinguish between 'good' and 'poor' correlation.

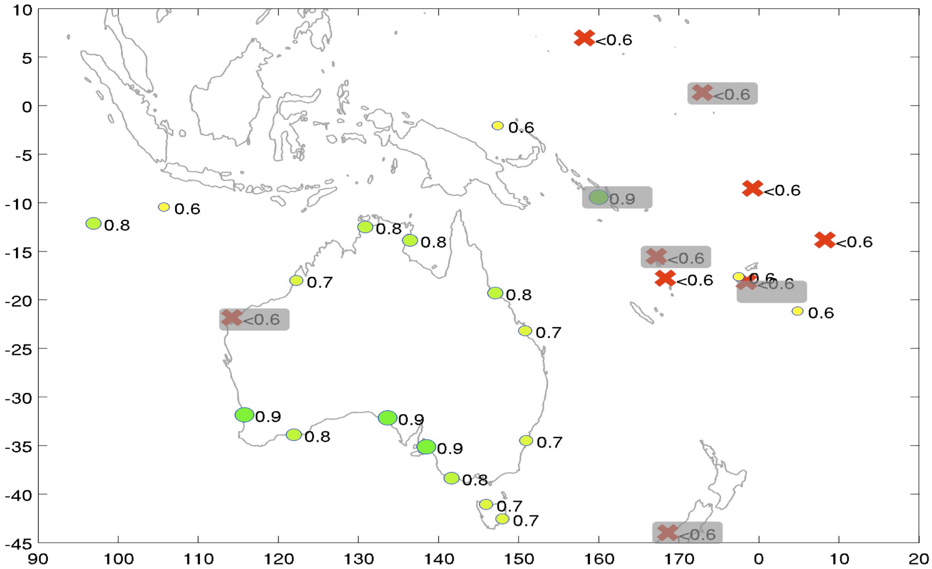

Fig. 14 Correlation Coefficient Assessment 1 (Naïve) – Tide method: harmonic.

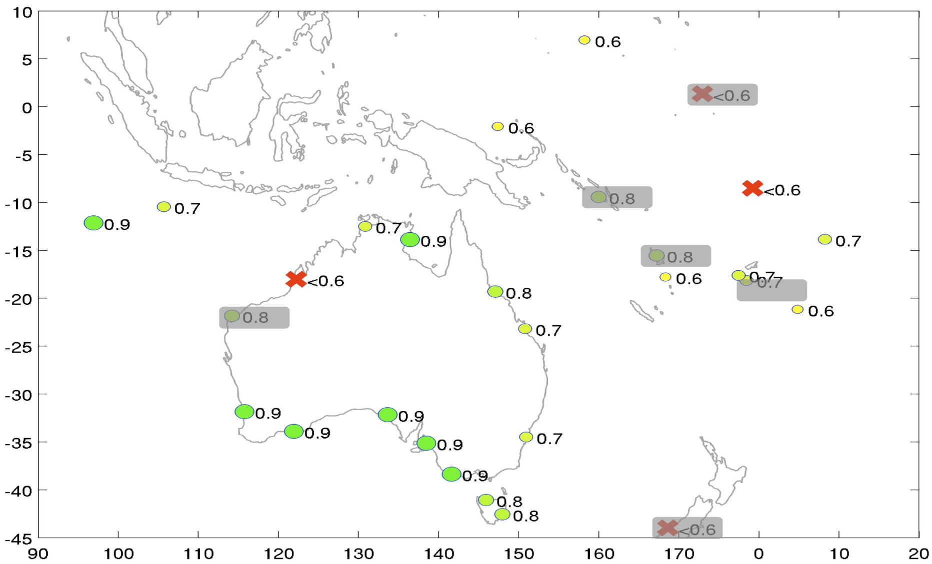

Fig. 15 Correlation Coefficient Assessment 1 (Naïve) – Tide method: lowpass filter.

Shaded items correspond to abnormally short data sets.

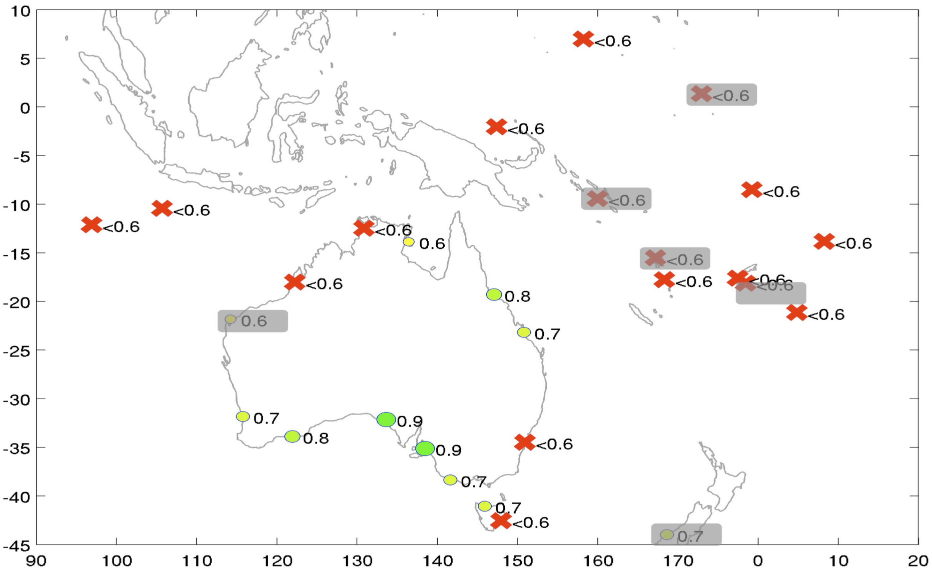

Fig. 16 Correlation Coefficient Assessment 2 (Mesoscale) – Tide method: harmonic.

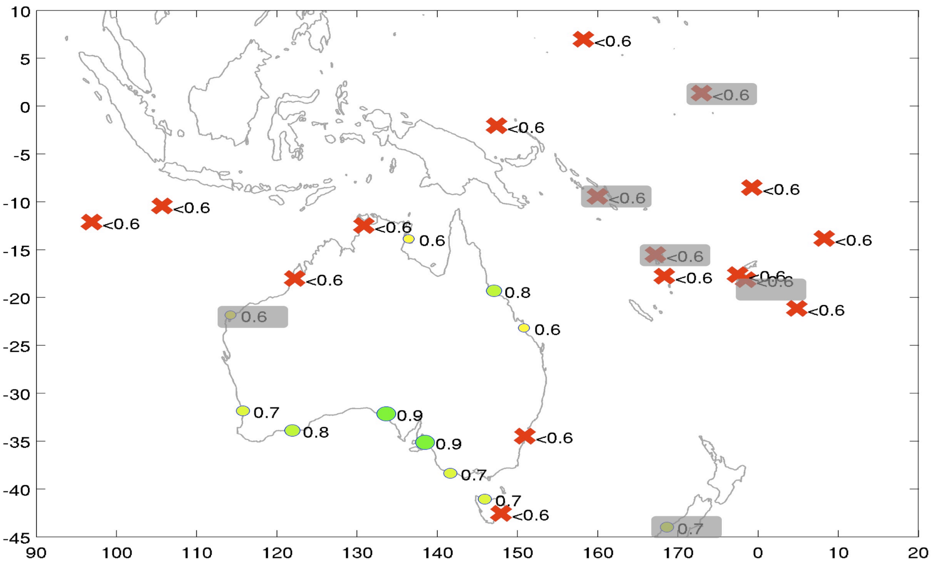

Fig. 17 Correlation Coefficient Assessment 2 (Mesoscale) – Tide method: lowpass filter.

Shaded items correspond to abnormally short data sets.

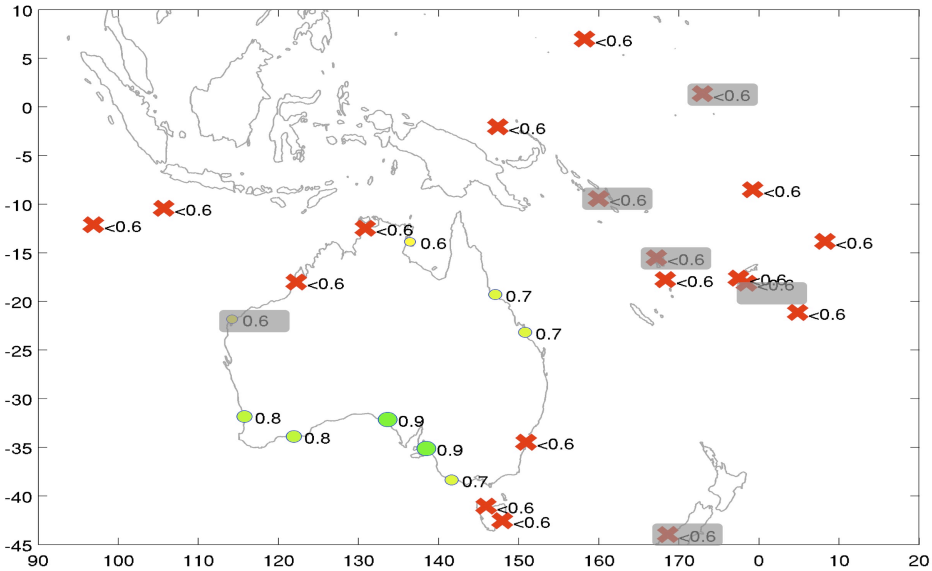

Fig. 18   Correlation Coefficient Assessment 3 (SLP sensitivity) – Tide method: harmonic.

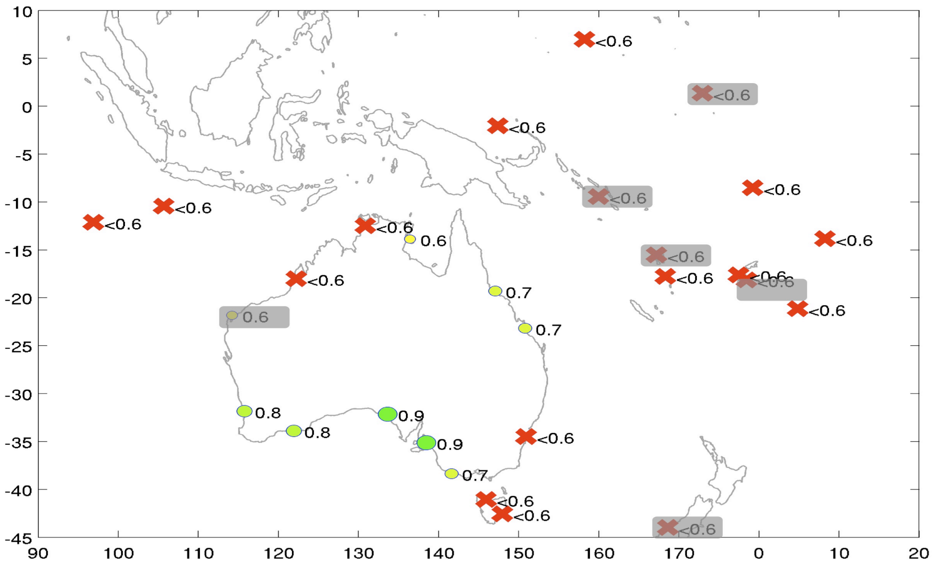

Fig. 19   Correlation Coefficient Assessment 3 (SLP sensitivity) – Tide method: lowpass filter.

Shaded items correspond to abnormally short data sets.

6.2.2 Variation of pre-processing with skill score

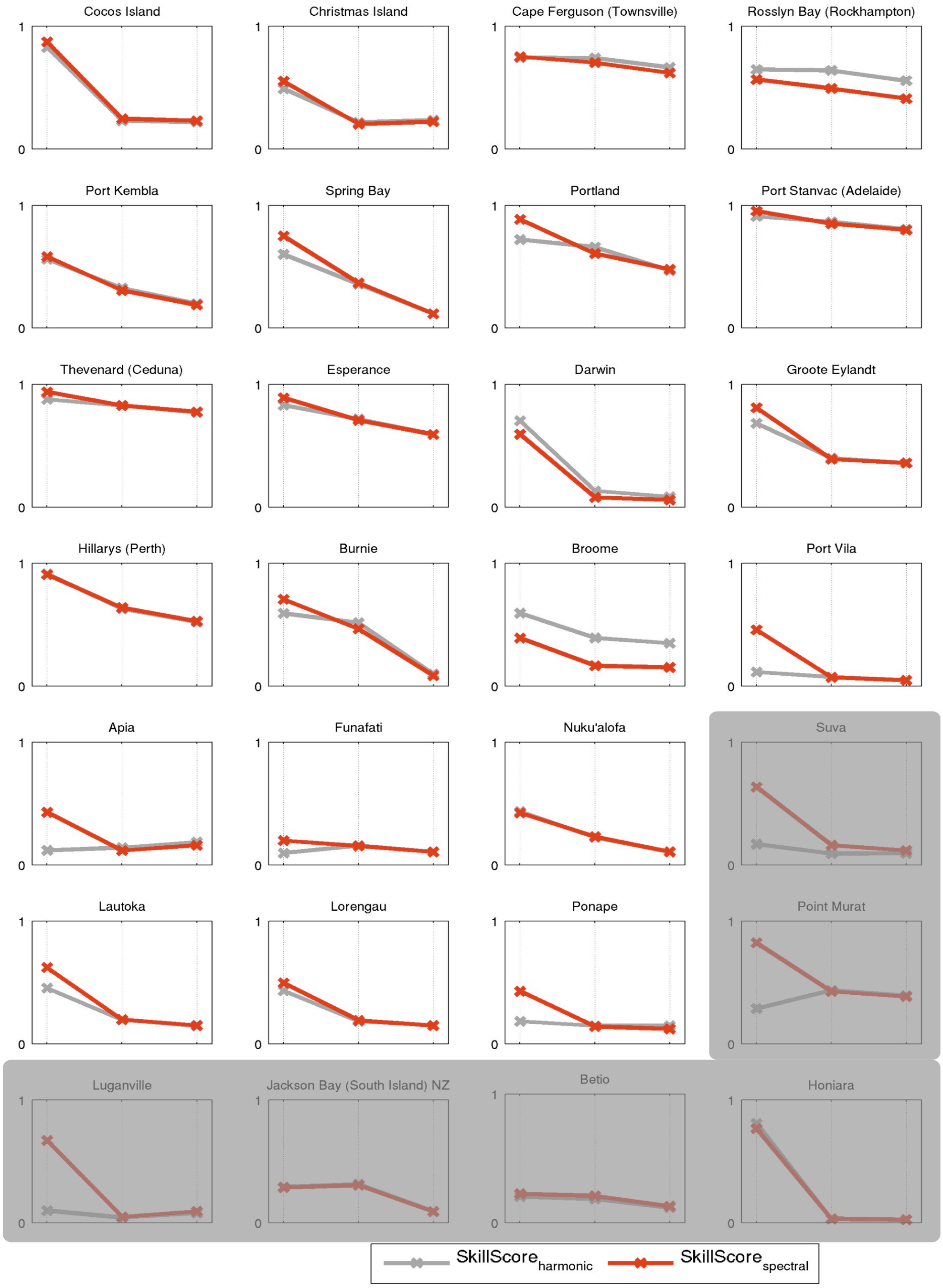

Fig. 20 Skill score for both de-tide methods across the 3 assessment variations.

Red: Spectral lowpass de-tide method. Grey: Harmonic de-tide method.

Perfect skill = 1, No Skill = 0. Shaded axes correspond to abnormally short data sets.

7. OceanMAPS 'FORECASTS'

7.1 Description of pre-processing variations

This section of the report considers the *forecast*, as opposed to *analysis*, data from OceanMAPS.

All details for each of the three *forecast* assessments are identical to those employed in the *analysis* assessments as described in Section 6.1. For emphasis it is noted that the distinguishing feature when considering *forecasts* (as opposed to *analyses*) is a focus on the evolution of skill across the forecast period for each pre-processing variation.

Whereas a separate *analysis* is generated for each calendar day, only two 7-day forecasts are produced each week. Subsequently the following results rely on relatively small sample populations for calculation of the assessments statistics. The details of the operational cycle are outlined in Section 3.1.1.

7.2 Evolution of skill scores across forecast period

The multiple axes shown in Fig. 21, Fig. 22 and Fig. 23 summarise the evolution of skill score at each location across each forecast period - for Assessments 1, 2 and 3 respectively.

With regard to interpreting these plots note the following:

- The abscissa in each axes for these diagrams refers to the forecast day relative to the base date: ranging from day-0 through to day-6;
- Skill score is defined in Section 5.4.1;
- The results for the two de-tiding method are overlaid;
- As a qualitative indication of relative confidence intervals, results associated with an especially small number of data points are shaded.

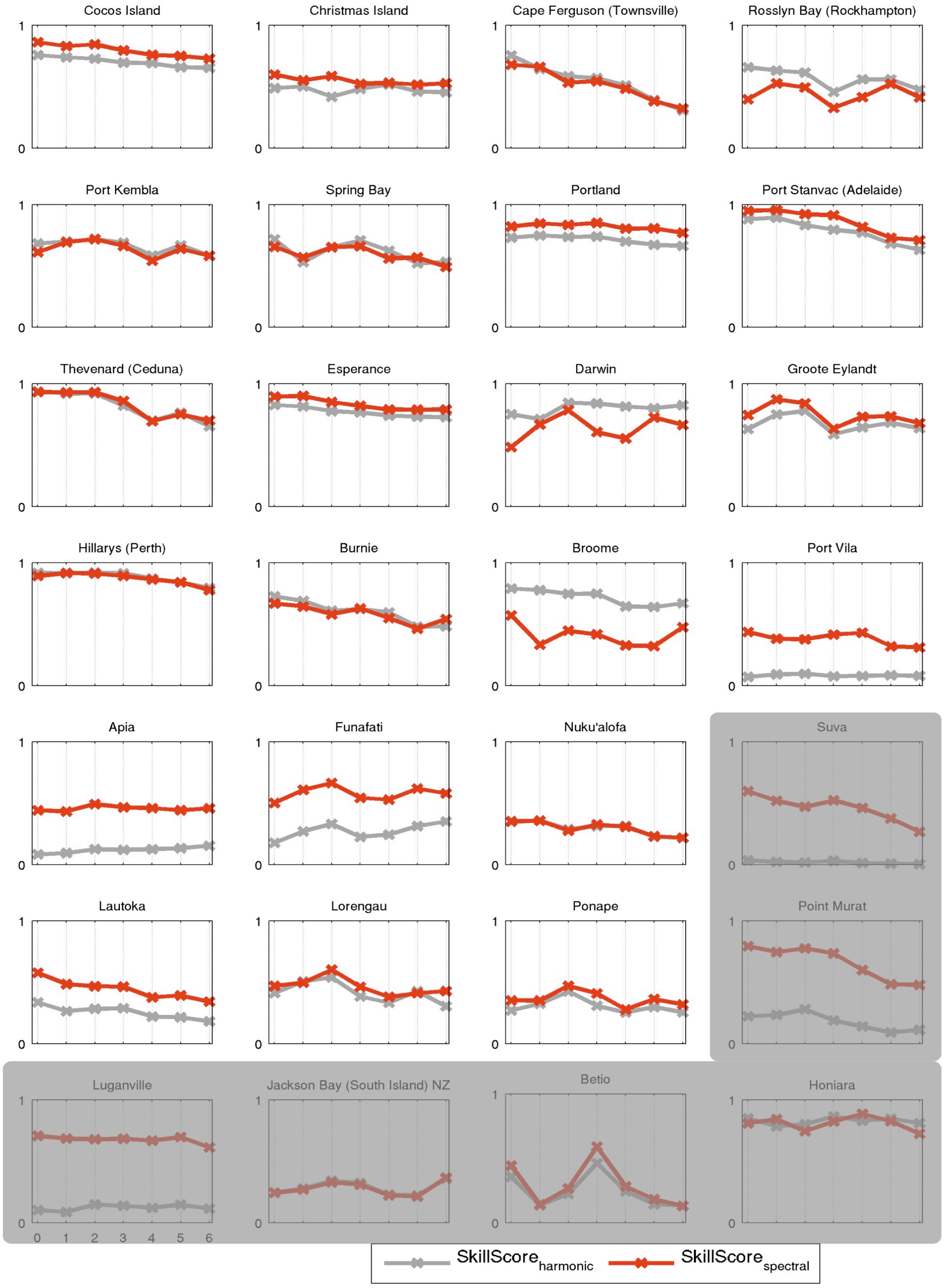

Fig. 21 Assessment 1 (Naïve):Skill score evolution with forecast length - both de-tide methods.

Red: Spectral lowpass de-tide method. Grey: Harmonic de-tide method.

Perfect skill = 1. No Skill = 0. Shaded axes correspond to abnormally short data sets.

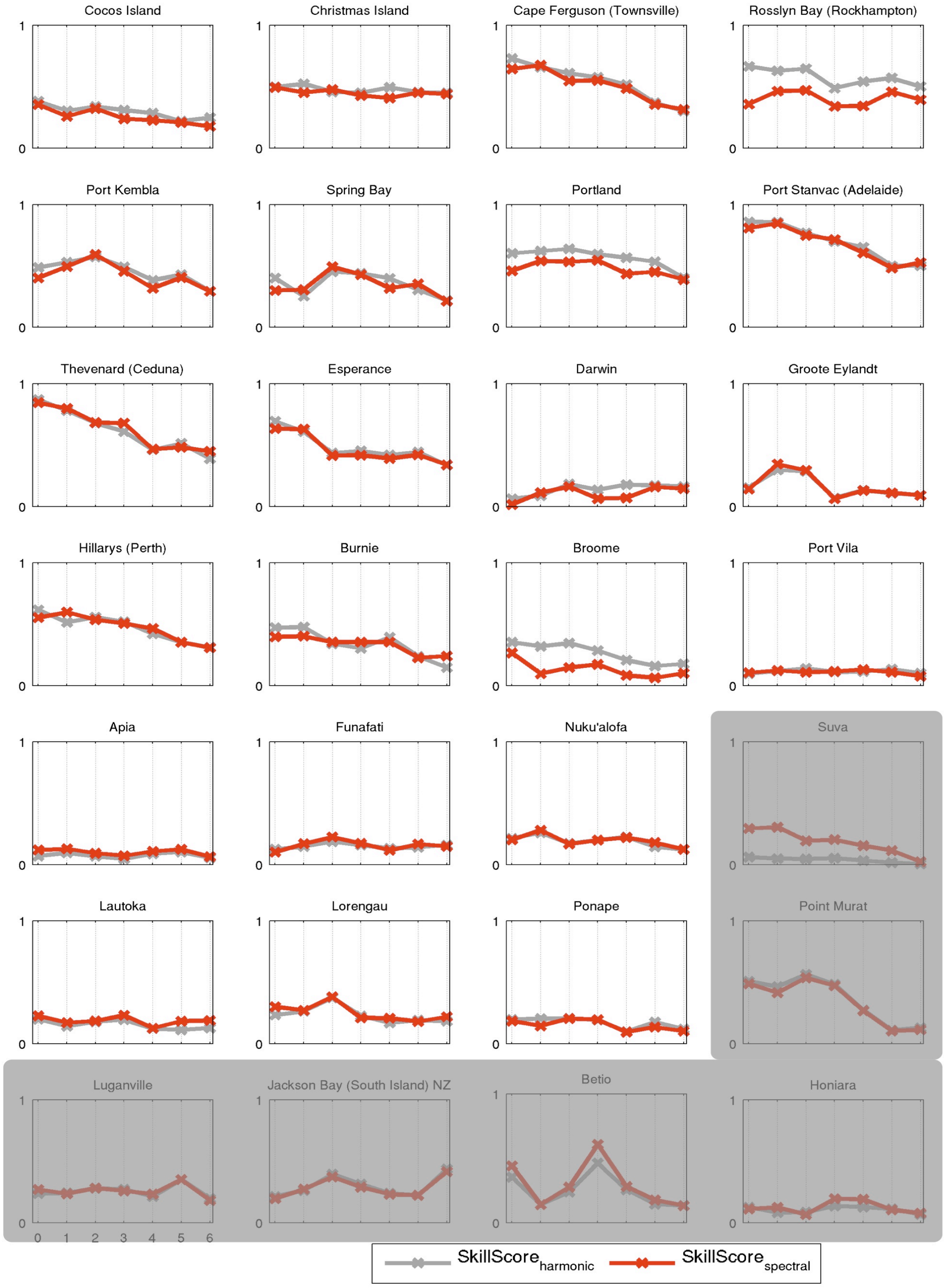

Fig. 22 Assessment 2 (Mesoscale): Skill score evolution with forecast length - both de-tide methods.

Red: Spectral lowpass de-tide method. Grey: Harmonic de-tide method.

Perfect skill = 1. No Skill = 0. Shaded axes correspond to abnormally short data sets.

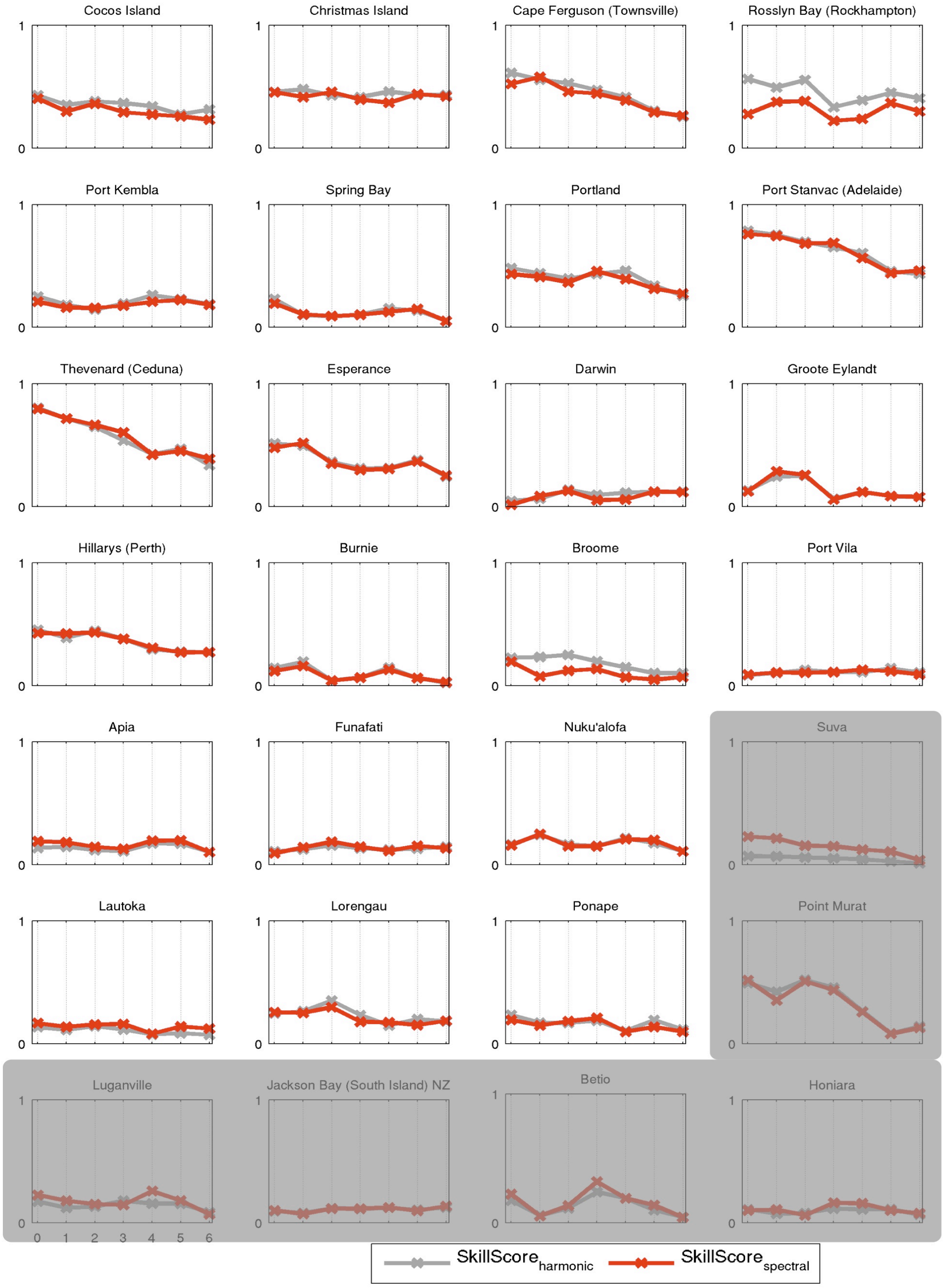

Fig. 23 Assessment 3 (SLP sensitivity):Skill score evolution with forecast length - both de-tide methods.

Red: Spectral lowpass de-tide method. Grey: Harmonic de-tide method.

Perfect skill = 1. No Skill = 0. Shaded axes correspond to abnormally short data sets.

8. DISCUSSION

8.1 Results overview

The answer to the motivating question posed in Section 2.1.1 is a qualified 'yes'. Despite the fact that OceanMAPS v1.0b was not specifically configured to forecast coastal sea level, the results presented in this report indicate a considerable amount of skill for SLA at certain locations. On the other hand there are several locations and regions where there is apparently no skill.

SLA is not a directly observed quantity. The pre-processing steps required to derive SLA from observed sea level inevitably have an impact on the subsequently calculated skill assessments. However in each instance we have elected to test the sensitivity of these choices or make conservative conclusions.

By testing variations on pre-processing steps, this report made some preliminary differentiations of the factors that apparently impact skill. Thus providing some insight into what OceanMAPS is good at, and what it is not, despite the naïve application of the methods.

For emphasis, one reason that the present report is considered a preliminary assessment is the fact that the naïve application of these pre-processing methods does not differentiate the contributing factors cleanly. An unquantified degree of spectral overlap exists between the nominally separate pre-processing steps that subsequently limit what can be inferred from the difference between results across the variations.

8.2 Does OceanMAPS provide skilful signal?

8.2.1 Location dependant skill

OceanMAPS does provide skilful coastal sea level signal, but to a degree dependant on geographic location.

The South Australian coast for example appears to score remarkably well across the board. This skill is interpreted as being the result of to the relatively large amount of spectral power attributable to phenomena well represented by OceanMAPS.This spectral range has been referred to as the 'weather band' and in this region is particularly associated with coastally trapped disturbances initiated by wind driven surge.

In contrast,the Pacific Islands in general rated poorly when the seasonal length variations were removed.This pattern is again interpreted as a reflection of the amount of power at mesoscale frequencies relative to that attributed to tidal, seasonal and inverse barometer signals. Where this effective 'signal to noise' ratio is low, the skill assessment is increasing susceptible to inaccuracies in the removal of the correction signals.

Exceptions to this broad location dependant pattern appear in the results for Broome, Port Kembla, Spring Bay and Darwin. Detailed explanations are not presented here, but the following contributing factors are highlighted as possible contributors to the relatively poor skill results:

- model ‘spin-up’ disturbances occurring close to the start of the OceanMAPS operational record (visible in some time series plots included in the Appendices);
- local bathymetry effects manifesting in sea level observations at non-tidal frequencies with periods close to 2 days;
- poor representation of sea level variations driven by barometric pressure.

A corollary of the skill results for the Pacific Islands is that OceanMAPS in general provides a skilful representation of the seasonal length variations. However, such estimates are likely obtainable from much simpler forecast systems or coarser resolution models and are not the focus of this study.

8.2.2 Expectations for extreme events

Although not evaluated in the present study, the skill for non-tidal coastal sea level may be expected to have higher skill for certain extreme events where mesoscale signals become especially dominant.

For instance consider the case of extra-tropical storm surge related events. Storm surge is primarily dependent on atmospheric surface winds and bathymetry. The atmospheric winds are known to high precision at the analysis time. Skill steadily decays throughout the forecast with high skill scores persisting for up to 3 days. Coastally trapped waves (CTW) are prominent phenomena closely related to storm surges. CTW representation is dependent on the accuracy of the initial disturbance and the model representation of their propagation and dissipation. Forecasts of the abnormal sea levels due to the arrival of remote generated CTWs are expected to benefit from the fact that the initial disturbances are more accurately represented by short range forecasts or analysis winds. The accuracy of the propagation and dissipation of CTW's has not been investigated in detail at this stage. However, there is anecdotal evidence that over the southern regions of Australia the CTW's are realistically propagated (Taylor 2009). On the other hand preliminary evidence indicates that there is insufficient dissipation of the CTWs occurs over the Great Barrier Reef in North Eastern Australia. In Australia's tropical region the continental shelf is significantly wider compared with lower latitudes. The mass flux of CTW's is frequently blocked or deflected by the many reef systems that occur in the region.

The accuracy of boundary current and eddies impinging onto the shelf is unknown, however the skill of the system to represent these features over the deep water is sufficient for impinging to occur at the right location.

The case of tropical storm surge events is expected to be less favourable due to the inadequate representation of the winds in the global NWP systems applied to OceanMAPS. Tropical storms (e.g. tropical cyclones) typically involve localised and steep physical gradients that require finer resolution to resolve. As the SLA signal in OceanMAPS is constrained by the NWP and its own model resolution, tropical storm surges are expected to be analogously ‘smoothed’ and thus less skilfully forecast.

8.3 Alternate de-tiding methods

Two alternate methods were employed to remove the tidal signal from the observations for this report. It is emphasised that alternate implementations of these same methods are possible which may be adopted for future analyses. A very notable example is with regard to the details of the harmonic analysis. As discussed in Section 2.3.3 the method is in general sensitive to details such as the time span of the observational record and the selection of analysed constituent frequencies. For instance, the role of the long-period tidal species is open to quite different treatment that may be of particular significance in the present context. The following approaches to long-period species in harmonic analysis each have draw-backs and would require consideration prior to incorporation into any operational system:

- Direct least squares fitting of all the long-period tides requires approximately 19 years of data – which is not typically available;

- Nodal correction methods (Pugh 1996) - used within the t-tide software and by the Australian National Tidal Centre -are based on the equilibrium tide approximation to the long-period tides. And this approximation has known deficiencies (Egbert and Ray, 2002);

- Total neglect of the long-period forcing asserts the insignificance of the tides in a broad frequency band and may render the remaining analysis incomparable to third party analyses.

Both the harmonic and the spectral methods tested remove the spectrally powerful diurnal and semidiurnal components of the tidal variations, but are fundamentally different with regard to the spectral range of the tidal signal calculated.

On the whole, skill scores achieved generally did not strongly depend on the de-tiding method, though noticeable differences are apparent for a few locations. For those cases where a marked difference was apparent, the distinction is interpreted as spectral in nature. In particular, most examples of such differentiation seen in *Assessment 1* show that the distinction is diminished with subsequent application of the seasonal filter. This illustrates a dominance of skill attributable to correlation of long-period changes. The harmonic de-tiding only removes select long period signals (depending on the constituent selection algorithm) whereas the low-pass filter allows all long periods to remain. The application of the high-pass seasonal filter in *Assessment 2* eliminates all long periods from the comparison and thus brings the two de-tiding methods into closer spectral equivalence and typically results in a lower but matching skill score. These patterns are illustrated by the overall similarity and occasional differences between the red and grey lines in Fig. 20.

The different geographic distribution of correlation coefficients seen between Fig. 14, Fig. 15 and Fig. 16 provides another perspective into the difference between de-tiding methods. A weak overall pattern of distinction may be seen between the mainland and the tropical islands. In particular, correlation at the topical islands appears dependant on the de-tiding method, with worse scores for the harmonic approach.

8.4 Impact of the seasonal filter

As expected, comparisons at most sites showed reduced skill score upon application of the seasonal high-pass filter. This is taken to indicate the relative importance of long-period variations for sea level at frequencies not fitted by the harmonic analysis software.

Thus it is suggested that OceanMAPS is quite accurately accounting for the timing and magnitude of long-period steric height changes typically associated with water temperature and salinity changes. Furthermore, this long-period part of the SLA signal may spectrally be the dominant non-tidal physical phenomena in those locations where the drop in skill score is greatest, such as Honiara and Luganville. The accuracy of seasonal effects is an advantage for total sea level calculations into the future.

The pattern of reduced skill upon application of the seasonal high-pass filtering was not universal and the spectral power in the seasonal signal tends to reduce with higher latitudes. In particular those regions not influenced by seasonally varying boundary currents. For example the South Australian sites at Thevenard and Port Stanvac showed very little drop from initially high skill scores.

8.5 Impact of adjustments for SLP

The removal of sea level signals attributed to sea level pressure (SLP) effects is considered to be an important pre-processing step to derive SLA from the observations. It is asserted that the skill impact of not first removing this component is indicated by any reduction in skill score seen between *Assessment 2* and *Assessment 3* - the impact can be visualised by the gradient of the last line segment in each panel of Fig. 20.

A pattern relative to latitude is apparent in the results. A substantial drop in skill between *Assessment 2* and *Assessment 3* is typical in higher latitude locations such as Burnie and Spring Bay in Tasmania and Jackson bay in New Zealand. This reflects the relative portion of the total variability attributable to SLP. This also reflects the climatological expectation of more dramatic atmospheric pressure systems at higher latitudes. The converse reasoning in part explains why the very low latitude locations such as Apia and Christmas Island show negligible change.

Important caveats regarding this interpretation were already stated in 6.1.3 - particularly due the fact that SLP effects are not cleanly separable from either tidal or seasonal signals. More generally, known issues with the simple approximation employed were addressed in Section 4.3.2, as was the possible future inclusion of SLP forcing directly into OceanMAPS.

8.6 Quantification of skill

This report presented the results of the skill assessment in terms of simple overall statistical measures that combined the RMSE, correlation coefficient and statistical variance. The particular score employed is one proposed by (Taylor 2001). Comparison of performance across the various locations is facilitated by the use of such a skill score, as it serves to condense three statistical parameters into a single value.

Alternate measures of skill may well be more relevant as routine diagnostic tool going forward, in particular with regard to the relative weighting of penalties imposed for different types of error. For example, an alternate score may assign greater importance to skill with regard to the phase timing of specific event categories. In addition, it may be relevant to evaluate derived quantities that emphasize performance with regard to sea level extrema such as ‘skew surge’ (Horsburgh et al. 2007).

8.7 Evolution of skill across the forecast

In general, if a numerical model forecast has skill, the skill score will decline monotonically across the forecast period before it asymptotes to a limiting value. The rate of skill decline reflects the amount of information contained in the preceding model forecasts as well as the rate of error growth both in phase and amplitude.

The evolutions illustrated in Fig. 22 can be broadly divided into those that do indeed decrease as expected and those that are relatively flat or already at the limiting value. Note that as there are far less forecast cycles than analysis dates within each time span, the statistical significance of the results associated with short time series are asserted to be relatively poor. Although included for completeness, the reader is cautioned not to place much value on the highlighted stations.

The South Australian coast again performs particularly well and conversely the tropical islands show no forecast skill (once the seasonal signal is removed). As per the discussion of the *Analysis* results, this is interpreted as a reflection of the amount of spectral power occurring within the range of interest. Or in other words, the southern coasts display especially strong signals within the weather band of frequencies (Middleton and Bye 2007).

At some of the tide gauge locations, there is an apparent increase in skill over the first one to two days. This anomalous result is likely a statistical anomaly. Such anomalies may be exaggerated at locations that are 24 to 48 hrs downstream from CTW source regions. In these locations the fact that the accuracy of the source winds remains relatively constant perhaps increases the sensitivity to statistical noise across changing forecast lengths.

An alternative factor that may contribute to apparent skill growth is the impact of numerical shock associated with data assimilation due to the 3/4 day cycle. However, as the observations assimilated are largely confined to the open ocean the impact is expected to be relatively limited on the coastal sea level.

Further investigation of forecast skill is reserved for future reports.

8.8 OceanMAPS in coastal areas

OceanMAPS includes a data assimilating component that systematically modifies the numerical ocean model in response to routine remote and *in situ* ocean observations. The data assimilation system was introduced in Section 3.1.1. For the period investigated in this report, the assimilated observations were restricted to the open ocean and no coastal ocean observations were assimilated.

It is emphasised that no tide gauge observations were assimilated by OceanMAPS for the period assessed. Whilst ocean observations from tide gauge stations could feasibly be incorporated into the assimilation system, implementation would be dependant on the resolution of a number of issues already outlined in this report. In particular the requirement for real time data quality control and methods for signal decomposition and error characterisation.

Assimilation of other coastal observations are actively being developed at the time of writing. Remote sea surface temperature (SST) observations where assimilated from AMSR-E instruments across the period reported here. These measurements are not available within 50km of the coastline. Subsequent upgrades have added SST observations from the AVHRR instruments to the operational system. These measurements are made at higher spatial resolution and available to within around 1km of the coast. The infrared sensors cannot observe SST through cloud, therefore multiple satellite are required to provide adequate coverage. It is noteworthy that significant wind events are frequently associated with cloud, limiting the observational impact at the time of an event. The value of these observations will be in estimating the ocean state prior to any such wind event.

Estimates of fresh water river discharge are also not included in the system to date. It is recognised that the volume of discharge from Australian rivers is generally quite low apart from seasonal and event based discharges in some tropical locations. Ongoing developments in the Bureau's operational forecasting of river flows are expected to facilitate future inclusion into OceanMAPS.

The satellite altimeter measurements discussed in Section 3.1.3.1 are an important constraint assimilated by OceanMAPS in waters beyond the 200m isobath. The restriction to deeper water is based on difficulties regarding the quality of corrections required to derive SLA over the continental shelf and near land-sea boundaries – effectively an issue of low signal to noise in shelf waters. Interpreting altimeter measurements in coastal waters is an active area of scientific research (COASTALT http://www.coastalt.eu/ and the CNES project PISTACH), but is not at present considered directly applicable to OceanMAPS.

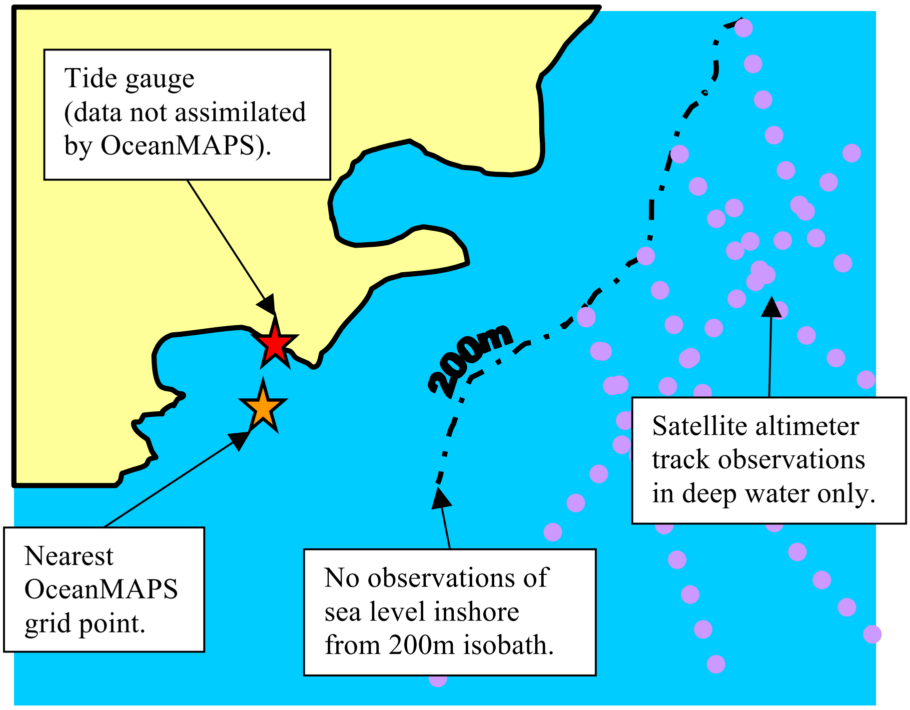

Fig. 24 Schematic illustrating coastal zone locations and deep water data assimilation.

The effect of data assimilation is to routinely constrain the OGCM component of OceanMAPS to observations. Thus, the absence of coastal zone observations means that these regions in the model are less constrained than the deep ocean and in principal may be subject to the development of larger errors. Regions where the continental shelf is narrow such as the South-East and South-West coasts will be constrained to some extent by exchange with the nearby deep ocean. Conversely, shallow water regions with wide continental shelves such as the Great Barrier Reef, North West-Shelf, Great Australian Bight and Bass Strait will be subject to relatively less constraint influence from deep water observations.

Hence the SLA forecast at the coast represents a projection from the constrained regions of the model and the NWP fields over the ocean; via the coastal dynamics resolved by the OGCM component. In light of the lack of observational constraint near the coast, the finding of significant skill in certain coastal locations effectively validates the contributing model physics. The representation of coastally trapped waves along the southern coast is highlighted in this regard (Taylor 2009).

In Northern Australia, the Gulf of Carpentaria is noted as being a region especially subject to a lack of observations as it represents a large area of shallow water. The poor mesoscale performance of OceanMAPS against the Groote Island tide gauge is attributable to this lack of observational constraint. It is suggested - but not here investigated in detail - that an apparently realistic signal is in fact propagated by OceanMAPS into the Gulf, but that this signal is subject to a distinct phase error. No time-lag correlations have been investigated here.

8.9 Towards 'total sea level' forecast products

An opportunity to extend the range of public ocean forecast services forms the backdrop to the present work. The recent extension of operational ocean prediction systems represented by OceanMAPS offers a new capability with regard to forecasting variations in sea level that are not traditionally estimated - that is, variations unrelated to tides and local storms. These phenomena include processes that are a-periodic and not forecasted by either linear methods or local shallow water models. This preliminary report is intended to formalise the first steps in ongoing work towards appropriately exploiting the new information as a public service – likely in the form of 'total sea level' or 'total sea level anomaly' forecasts.

'Total sea level' may be here considered as an extension to the familiar tidal prediction products.

Given that tide predictions have long period skill and NWP forecasts are skilful over the short-range, the fact that OceanMAPS displays skill in forecasting non-tidal portion of sea level renders the concept of total sea level forecast products feasible. Such forecasts are expected to be most applicable to regions where sea level extrema are of immediate concern. However, the target audience and specific format that such products could take is an open question under active consideration.

An important consideration in this regard is that the type of 'total sea level' products suggested here would essentially combine the outputs of systems that are already *operational* within the Bureau. Or in other words, this concept represents an attempt to capitalise on existing systems.

For example, a total sea level product may take the form of routine guidance for forecasting staff. Such a product may graphically summarise a likely range of daily extreme sea levels for the short-range of an NWP forecast or determine regions at risk over longer lead times subject to different magnitude weather events taking place. Such guidance products would be limited to regions where OceanMAPS has demonstrated skill for the phenomena contributing to any one event. This report provides a gross level of guidance on where such a product might be relied upon. However, more detailed analysis to essential to identify specific processes and their error characteristics to increase the level of confidence for use in specific events. At the other extreme of possibility, total sea level forecast products could take the form of augmented tide charts. The potential to make any such forecasts publically availability should be subject to careful consideration with regard to possible legal implications, especially concerning navigation.

8.10 Complementing existing tools

On a final note, the reader is reminded that OceanMAPS is not the only operational forecast system providing estimates of non-tidal sea level. 'Storm-surge' predictions are currently produced from geographically local models primarily driven by forecast wind fields. Most notably in the Australia region are those implemented in association with tropical cyclone forecasts (Davidson et al. 2005). Internationally, a well studied mid-latitude example is that implemented by the UK Storm Tide Forecasting Service (Horsburgh 2007).

Addressing the question of comparative performance is beyond the scope of the present report. But in general, the relatively mature localised tools are expected to outperform a broad scope system like OceanMAPS – especially when forecasting the extreme events they have been designed and tuned for.

Sea level forecasts based on OceanMAPS however represent a new opportunity to complement the existing local event-based tools with products exhibiting some contrasting characteristics:

- Routine scheduled forecasts;
- Equal coverage of the entire Australian region and coastline;
- Inclusion of remote forcing and baroclinic phenomena.

In conclusion, OceanMAPS presents practical opportunities to provide a new range of routine coastal sea level forecast products that would complement the existing tools for special classes of extreme event.

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APPENDIX A TABULATED STATISTICS

Table 3 **Observation Data Population Counts.**

	Final number of daily averages	**Percentage of raw real-time data not rejected**
Cocos Island	333	65%
Christmas Island	375	73%
Cape Ferguson, Qld	391	77%
Rosslyn Bay, Qld	356	70%
Port Kembla, NSW	384	74%
Spring Bay, SW Tas	362	71%
Portland, Vic	394	76%
Port Stanvac (Adelaide), SA	387	76%
Thevenard (Ceduna), SA	367	76%
Esperance, WA	381	74%
Darwin, NT	386	76%
Groote Eylandt, NT	390	75%
Hillarys (Perth), WA	390	77%
Burnie, Tas	378	77%
Broome, WA	339	69%
Port Vila, Vanuatu	378	73%
Apia, Samoa	288	66%
Funafati, Tuvalu	315	65%
Nuku'alofa, Tonga	345	76%
Suva, Fiji	**194**	38%
Lautoka, Fiji	331	69%
Lombrum, Manus Island, PNG	273	62%
Ponape, Micronesia	325	75%
Point Murat, (Exmouth), WA	**151**	79%
Luganville, Vanuatu	**140**	75%
Jackson Bay (South Island) NZ	**138**	81%
Betio, Tarawa, Kiribati	**69**	51%
Honiara, Solomon Islands	**62**	84%

Table 4 ***Analysis* Correlation Coefficients.**

	Assessment 1		**Assessment 2**		**Assessment 3**	
	HA	**LP**	**HA**	**LP**	**HA**	**LP**
Cocos Island	0.90	0.92	0.39	0.42	0.37	0.39
Christmas Island	0.68	0.74	0.42	0.39	0.44	0.41
Cape Ferguson, Qld	0.85	0.85	0.85	0.82	0.80	0.77
Rosslyn Bay, Qld	0.78	0.73	0.79	0.68	0.72	0.59
Port Kembla, NSW	0.72	0.74	0.50	0.48	0.33	0.31
Spring Bay, SW Tas	0.76	0.85	0.55	0.55	0.39	0.39
Portland, Vic	0.86	0.94	0.79	0.76	0.74	0.73
Port Stanvac (Adelaide), SA	0.94	0.97	0.92	0.91	0.91	0.91
Thevenard (Ceduna), SA	0.93	0.96	0.91	0.91	0.91	0.91
Esperance, WA	0.90	0.93	0.83	0.83	0.80	0.80
Darwin, NT	0.83	0.78	0.32	0.23	0.24	0.19
Groote Eylandt, NT	0.83	0.94	0.64	0.63	0.64	0.63
Hillarys (Perth), WA	0.94	0.94	0.80	0.80	0.80	0.80
Burnie, Tas	0.75	0.84	0.76	0.70	0.21	0.16
Broome, WA	0.75	0.58	0.58	0.36	0.53	0.34
Port Vila, Vanuatu	0.27	0.66	0.04	0.03	-0.07	-0.07
Apia, Samoa	0.34	0.71	0.27	0.20	0.32	0.27
Funafati, Tuvalu	0.20	0.37	0.28	0.28	0.16	0.16
Nuku'alofa, Tonga	0.65	0.65	0.37	0.38	0.16	0.16
Suva, Fiji	0.28	0.78	0.21	0.30	0.29	0.31
Lautoka, Fiji	0.64	0.77	0.32	0.33	0.24	0.26
Lombrum, Manus Island, PNG	0.62	0.67	0.36	0.37	0.34	0.31
Ponape, Micronesia	0.31	0.61	0.25	0.24	0.25	0.20
Point Murat, (Exmouth), WA	0.49	0.89	0.69	0.68	0.62	0.62
Luganville, Vanuatu	0.14	0.82	0.03	0.07	0.08	0.13
Jackson Bay (South Island) NZ	0.59	0.58	0.74	0.72	0.43	0.42
Betio, Tarawa, Kiribati	0.34	0.37	0.36	0.38	0.21	0.22
Honiara, Solomon Islands	0.90	0.87	0.12	0.13	0.13	0.14

HA = Harmonic tide method, **LP** = Lowpass filter tide method

Table 5 ***Analysis* Standard Deviations.**

	Assessment 1			Assessment 2			Assessment 3		
	O	HA	LP	O	HA	LP	O	HA	LP
Cocos Island	0.13	0.13	0.13	0.05	0.06	0.06	0.05	0.06	0.06
Christmas Island	0.10	0.12	0.13	0.05	0.08	0.08	0.05	0.07	0.07
Cape Ferguson, Qld	0.12	0.11	0.11	0.10	0.10	0.09	0.10	0.09	0.09
Rosslyn Bay, Qld	0.10	0.09	0.10	0.07	0.08	0.09	0.07	0.07	0.08
Port Kembla, NSW	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.07	0.07
Spring Bay, SW Tas	0.07	0.06	0.07	0.04	0.05	0.04	0.04	0.10	0.10
Portland, Vic	0.12	0.09	0.11	0.06	0.06	0.06	0.06	0.10	0.10
Port Stanvac, SA	0.19	0.18	0.18	0.13	0.14	0.14	0.13	0.17	0.17
Thevenard, SA	0.17	0.17	0.18	0.12	0.15	0.14	0.12	0.17	0.17
Esperance, WA	0.13	0.13	0.13	0.08	0.09	0.09	0.08	0.12	0.12
Darwin, NT	0.08	0.09	0.10	0.03	0.05	0.06	0.03	0.06	0.07
Groote Eylandt, NT	0.14	0.17	0.20	0.08	0.11	0.11	0.08	0.13	0.12
Hillarys, WA	0.14	0.14	0.14	0.07	0.09	0.08	0.07	0.12	0.11
Burnie, Tas	0.07	0.08	0.08	0.04	0.06	0.06	0.04	0.08	0.08
Broome, WA	0.10	0.09	0.12	0.06	0.06	0.10	0.06	0.06	0.10
Port Vila, Vanuatu	0.06	0.03	0.05	0.03	0.02	0.03	0.03	0.03	0.03
Apia, Samoa	0.09	0.04	0.05	0.04	0.02	0.03	0.04	0.03	0.03
Funafati, Tuvalu	0.08	0.04	0.05	0.04	0.03	0.03	0.04	0.03	0.03
Nuku'alofa, Tonga	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Suva, Fiji	0.05	0.04	0.04	0.02	0.04	0.03	0.02	0.04	0.04
Lautoka, Fiji	0.05	0.04	0.05	0.02	0.03	0.03	0.02	0.03	0.03
Lombrum, Manus Island, PNG	0.04	0.04	0.05	0.02	0.03	0.03	0.02	0.04	0.04
Ponape, Micronesia	0.04	0.03	0.04	0.02	0.03	0.03	0.02	0.03	0.03
Point Murat, WA	0.10	0.08	0.10	0.04	0.06	0.06	0.04	0.06	0.06
Luganville, Vanuatu	0.06	0.05	0.08	0.02	0.04	0.05	0.02	0.03	0.03
Jackson Bay, NZ	0.05	0.09	0.09	0.04	0.08	0.08	0.04	0.11	0.11
Betio, Tarawa, Kiribati	0.03	0.03	0.03	0.02	0.03	0.03	0.02	0.03	0.03
Honiara, Solomon Islands	0.05	0.06	0.06	0.02	0.06	0.06	0.02	0.07	0.07

O= Oceanamaps, **HA** = Harmonic tide method, **LP** = Lowpass filter tide method

Table 6 ***Analysis* RMSE Normalised with Observations Standard Deviation (NRMSE).**

	Assessment 1		**Assessment 2**		**Assessment 3**	
	HA	**LP**	**HA**	**LP**	**HA**	**LP**
Cocos Island	0.46	0.40	1.00	0.99	1.03	1.02
Christmas Island	0.75	0.67	0.94	0.96	0.93	0.95
Cape Ferguson, Qld	0.58	0.56	0.56	0.60	0.67	0.71
Rosslyn Bay, Qld	0.66	0.73	0.62	0.74	0.74	0.87
Port Kembla, NSW	0.75	0.72	0.97	1.00	1.08	1.10
Spring Bay, SW Tas	0.76	0.56	0.90	0.90	0.92	0.92
Portland, Vic	0.65	0.39	0.64	0.71	0.68	0.69
Port Stanvac, SA	0.34	0.26	0.39	0.42	0.43	0.44
Thevenard, SA	0.38	0.28	0.42	0.42	0.45	0.45
Esperance, WA	0.46	0.37	0.57	0.58	0.61	0.61
Darwin, NT	0.56	0.62	0.97	0.99	0.99	1.00
Groote Eylandt, NT	0.56	0.41	0.76	0.78	0.77	0.78
Hillarys, WA	0.33	0.34	0.60	0.60	0.63	0.63
Burnie, Tas	0.68	0.55	0.66	0.71	1.03	1.06
Broome, WA	0.76	0.85	0.88	0.95	0.93	0.97
Port Vila, Vanuatu	1.88	0.96	1.48	1.48	1.35	1.35
Apia, Samoa	2.08	1.17	1.59	1.59	1.34	1.37
Funafati, Tuvalu	1.85	1.40	1.41	1.45	1.53	1.57
Nuku'alofa, Tonga	1.03	1.06	1.08	1.07	1.15	1.15
Suva, Fiji	1.30	0.71	1.02	1.04	0.96	0.96
Lautoka, Fiji	0.90	0.69	1.10	1.09	1.12	1.10
Lombrum, Manus Island, PNG	0.84	0.77	0.97	0.97	0.97	1.00
Ponape, Micronesia	1.26	0.87	1.10	1.10	1.09	1.11
Point Murat, WA	1.21	0.46	0.73	0.73	0.78	0.78
Luganville, Vanuatu	1.57	0.57	1.09	1.06	1.18	1.14
Jackson Bay, NZ	0.81	0.81	0.74	0.74	0.91	0.91
Betio, Tarawa, Kiribati	1.09	1.10	0.97	0.97	1.08	1.09
Honiara, Solomon Islands	0.43	0.48	1.00	1.00	0.99	0.99

HA = Harmonic tide method, **LP** = Lowpass filter tide method

APPENDIX B SPECIAL CASE STATIONS

These tables summarise stations that were associated with issues that may compromise direct comparison of results with other stations.

Table 7 **Short data sets.**

Station Name	State
Suva, Fiji	PAC
Point Murat, (Exmouth)	WA
Luganville, Vanuatu	PAC
Jackson Bay (South Island)	NZ
Betio, Tarawa, Kiribati	PAC
Honiara, Guadalcanal, Solomon	PAC

Table 8 **Stations subject to low value clipping.**

Station Name	State
Christmas Island	IND
Cape Ferguson (Townsville), Qld	QLD
Rosslyn Bay (Rockhampton), Qld	QLD
Port Kembla, NSW	NSW
Portland, Vic	VIC
Port Stanvac (Adelaide), SA	SA
Thevenard (Ceduna), SA	SA
Esperance, WA	WA
Darwin, NT	NT
Hillarys (Perth), WA	WA
Burnie, Tas	TAS
Broome, WA	WA
Luganville, Vanuatu	PAC

APPENDIX C STATION LOCATION DETAILS

Table 9 **Tide Gauge Location Details.**

Station Name	Station ID Codes		Tide Gauge Location		Distance to grid point [km]
	Tide	**SLP**	**Lat**	**Lon**	
Cocos Island	200865	96997	-12.1167	96.8917	10
Christmas Island	200870	96995	-10.4292	105.6694	9
Cape Ferguson, Qld	32182	94294	-19.2775	147.0586	3
Rosslyn Bay, Qld	33208	94374	-23.1683	150.7947	24
Port Kembla, NSW	68253	94750	-34.4739	150.9119	4
Spring Bay, SW TAS	92133	94960	-42.5464	147.9308	10
Portland, Vic	90192	94828	-38.3439	141.6136	3
Port Stanvac, SA	23899	94672	-35.1097	138.4653	5
Thevenard, SA	18207	94653	-32.1489	133.6417	14
Esperance, WA	109504	94638	-33.8733	121.895	6
Darwin, NT	14072	94120	-12.4719	130.8458	17
Groote Eylandt, NT	14406	94153	-13.86	136.4158	7
Hillarys, WA	9265	94608	-31.8256	115.7386	9
Burnie, Tas	91344	95957	-41.05	145.9147	11
Broome, WA	3102	94203	-18.0008	122.2183	9
Port Vila, Vanuatu	200857	91559	-17.7666	168.3	11
Apia, Samoa	200814	91756	-13.8264	-171.761	20
Funafati, Tuvalu	200860	91642	-8.5028	179.2092	7
Nuku'alofa, Tonga	200861	91789	-21.1383	-175.181	10
Suva, Fiji	200863	91689	-18.1325	178.4275	3
Lautoka, Fiji	200856	91679	-17.6053	177.4381	10
Lombrum, Manus Island, PNG	200862	92036	-2.0361	147.3753	9
Ponape, Micronesia	200864	91348	6.9806	158.2	9
Point Murat, WA	5096	94302	-21.8169	114.1911	6
Luganville, Vanuatu	200871	91554	-15.5156	167.1886	10
Jackson Bay, NZ	200866	93713	-43.9733	168.6161	4
Betio, Tarawa, Kiribati	200299	91611	1.3625	172.93	3
Honiara, Solomon Islands	200859	91519	-9.4289	159.9556	9

APPENDIX D TIME SERIES PLOTS

Only the time series corresponding to Assessment 1 are reproduced here. Whilst Assessment 1 was not considered the most relevant for quantifying mesoscale forecast skill, these time series represent a minimal amount of pre-processing to derive comparable data sets. These plots overlay SLA data from OceanMAPS and the variants derived from tide gauge observations. The observations have been adjusted for atmospheric pressure and de-tided, but have not had the seasonal filter applied.

The lines on each plot show:

- SLA derived from OceanMAPS *Labelled "OceanMAPS"*;
- SLA derived from observations via harmonic analysis based de-tiding method *Labelled "Obs-Harmonic"*;
- SLA derived from observations via lowpass filter de-tiding method. *Labelled "Obs-Spectral"*;

Note that each plot is displayed on the same axis ranges for both SLA magnitude and calendar date.

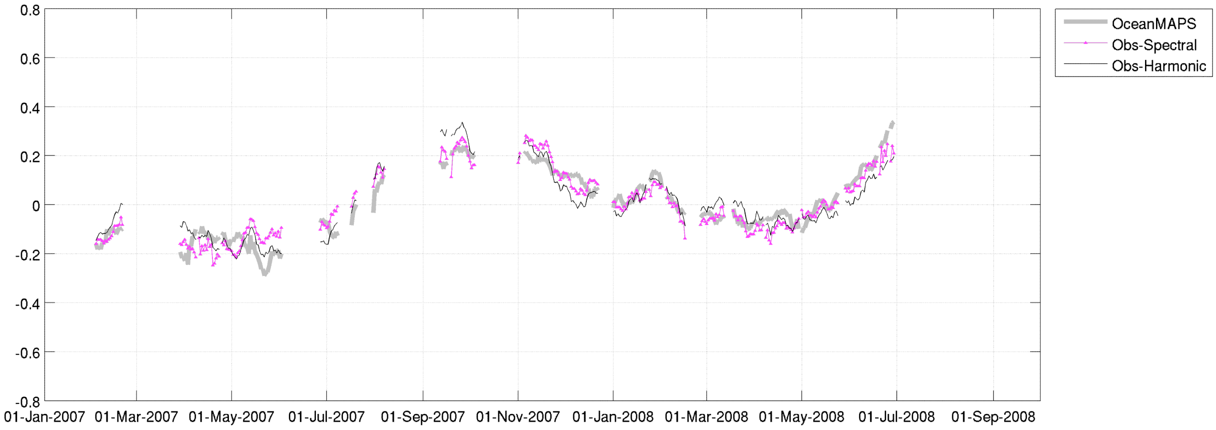


Fig. 25 SLA time series data for Station 1 Cocos Island.

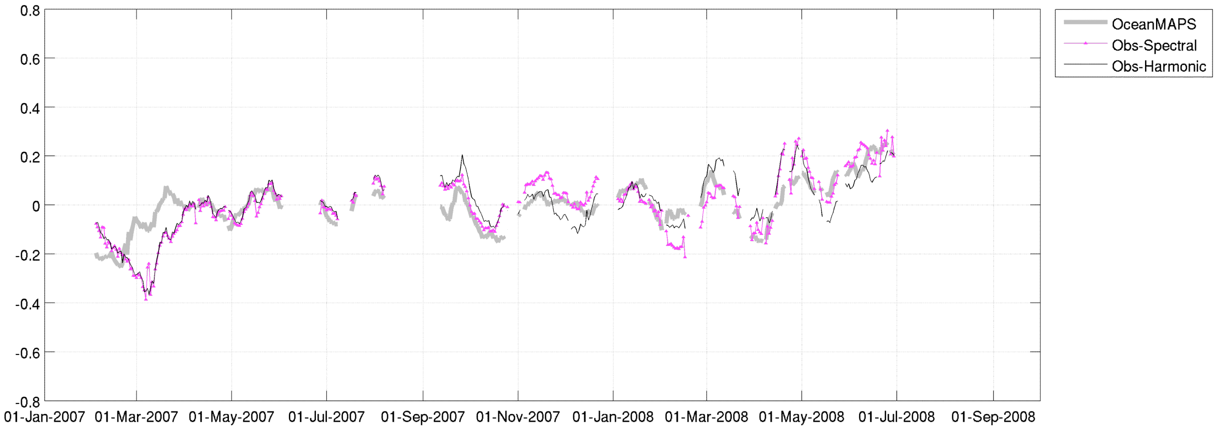


Fig. 26 SLA time series data for Station 2 Christmas Island.

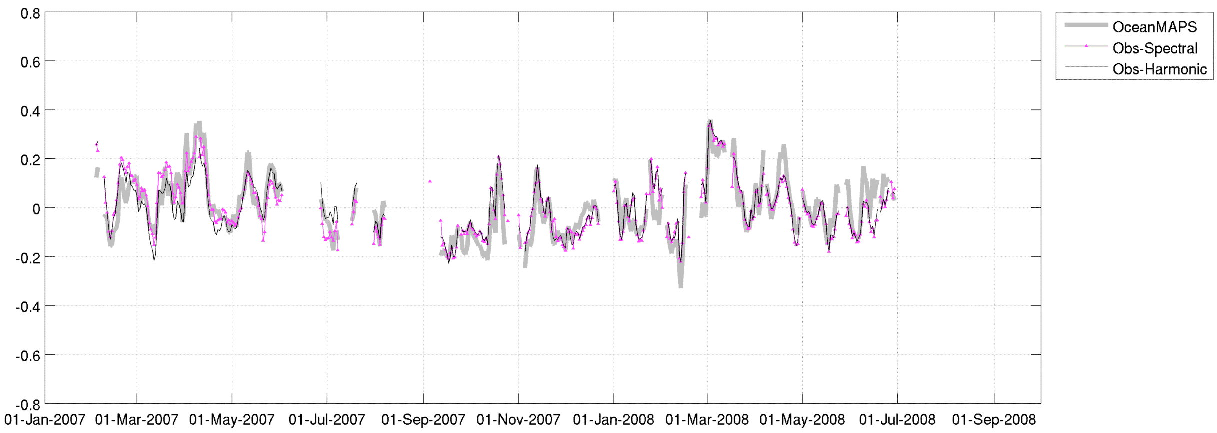


Fig. 27 SLA time series data for Station 3 Cape Ferguson (Townsville), QLD.

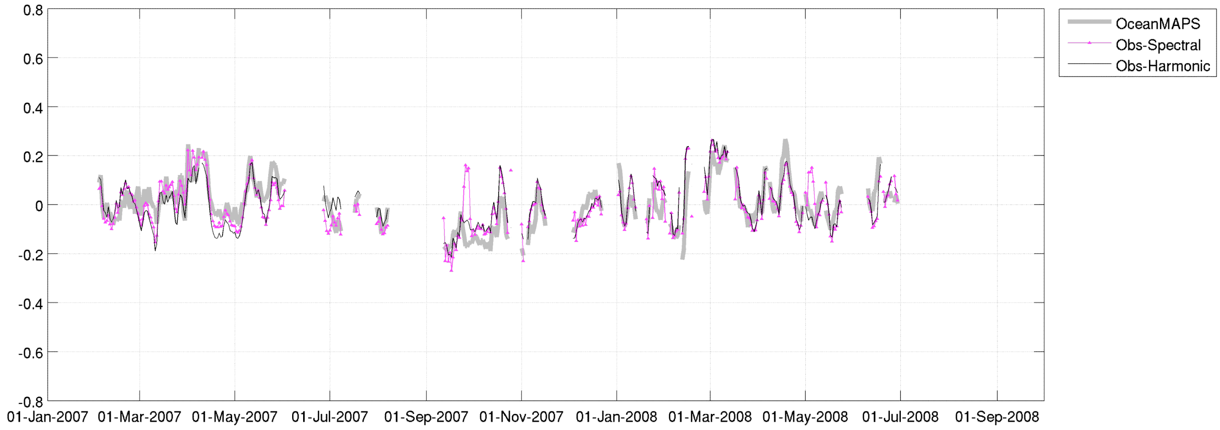
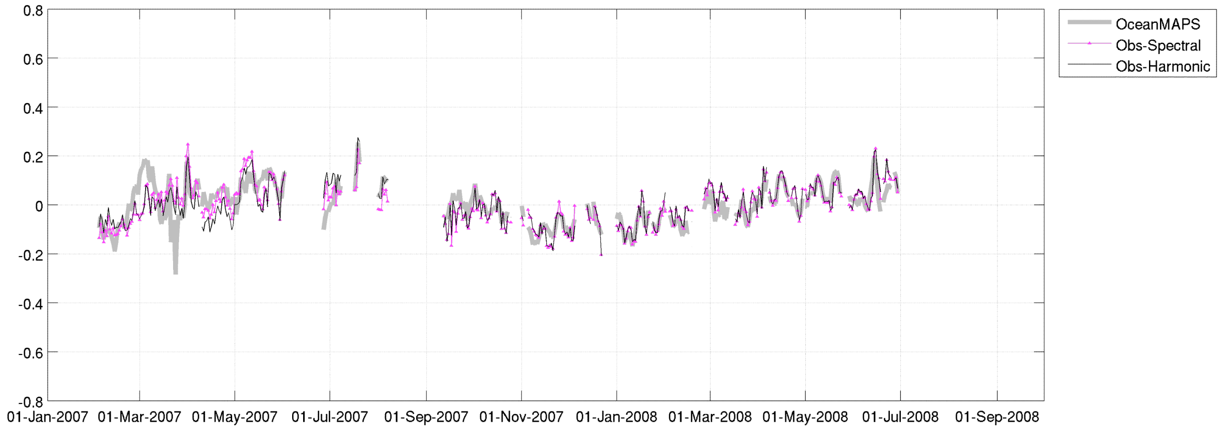


Fig. 28 SLA time series data for Station 4 Rosslyn Bay (Rockhampton), QLD.



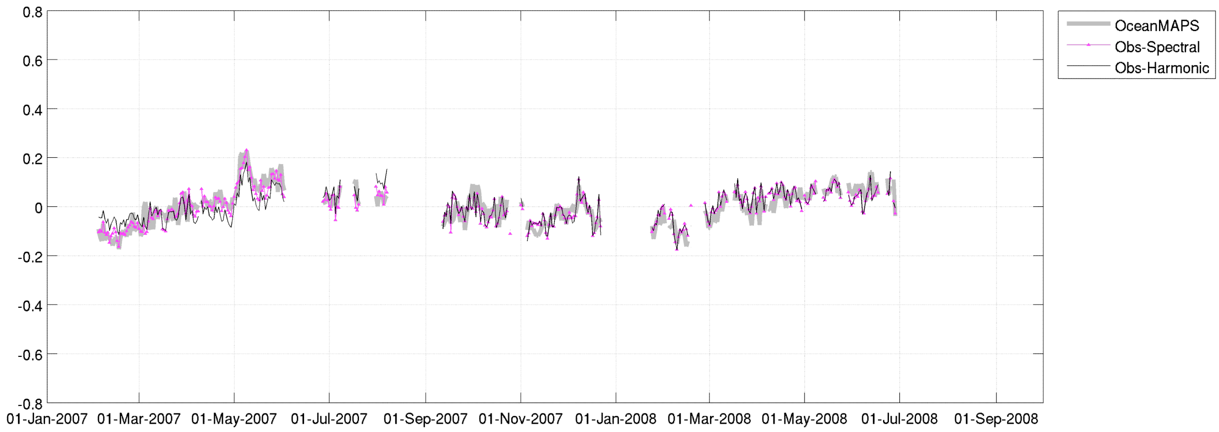


Fig. 29 SLA time series data for Station 5 Port Kembla, NSW.

Fig. 30 SLA time series data for Station 6 Spring Bay, SW TAS.

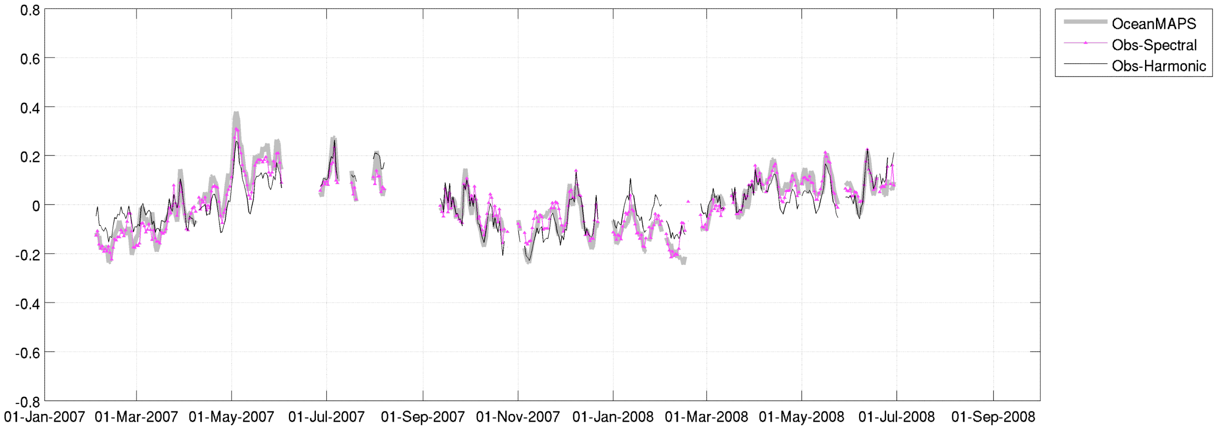


Fig. 31 SLA time series data for SLA time series data for Station 7 Portland, VIC.

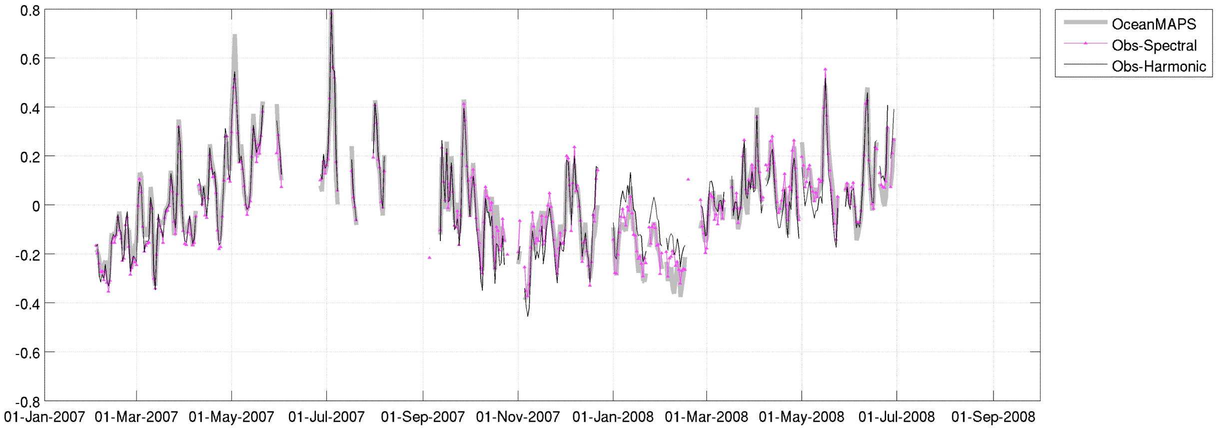


Fig. 32 SLA time series data for Station 8 Port Stanvac (Adelaide), SA.

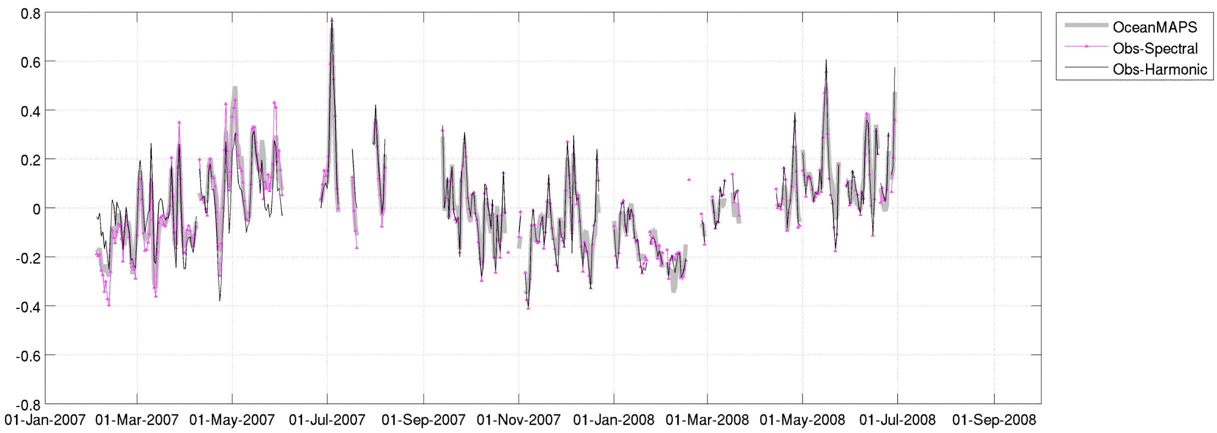


Fig. 33 SLA time series data for Station 9 Thevenard (Ceduna), SA.

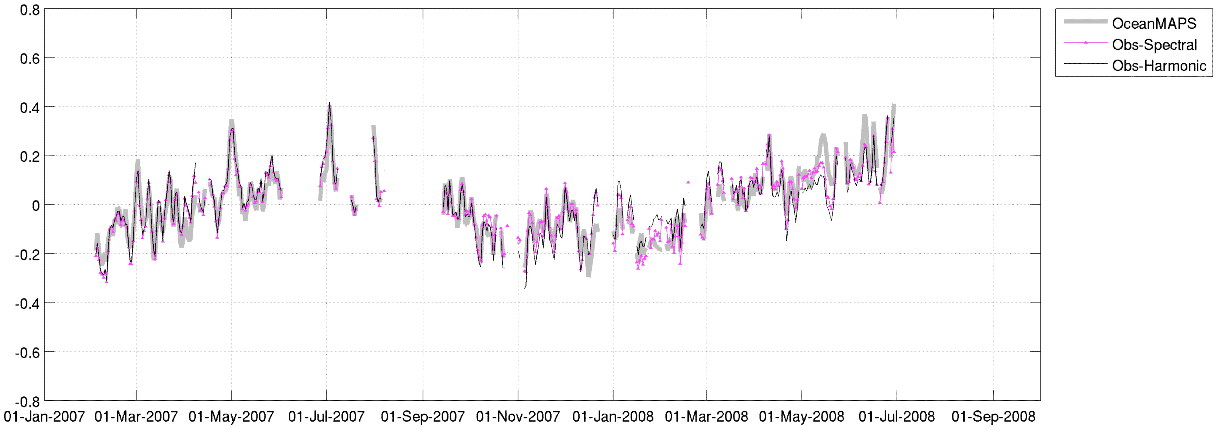
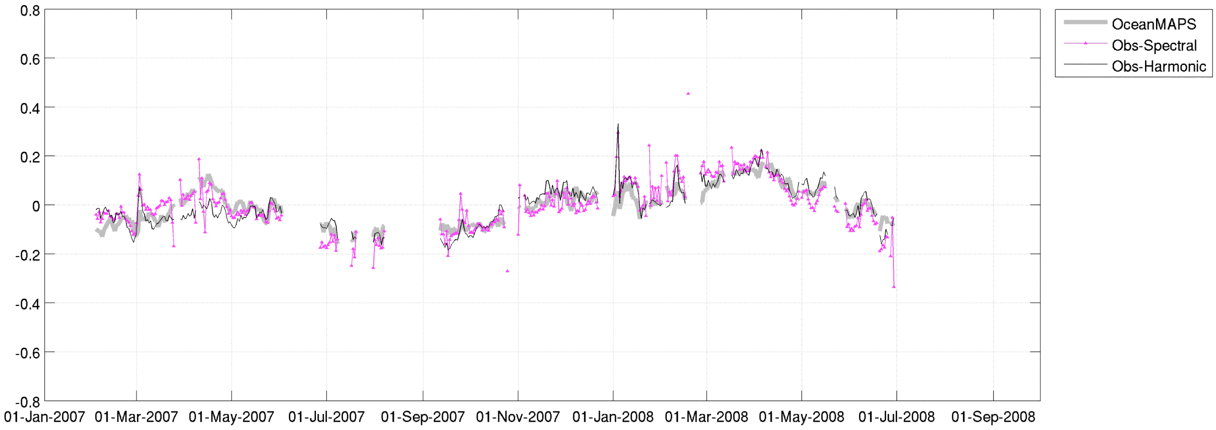


Fig. 34 SLA time series data for Station 10 Esperance, WA.



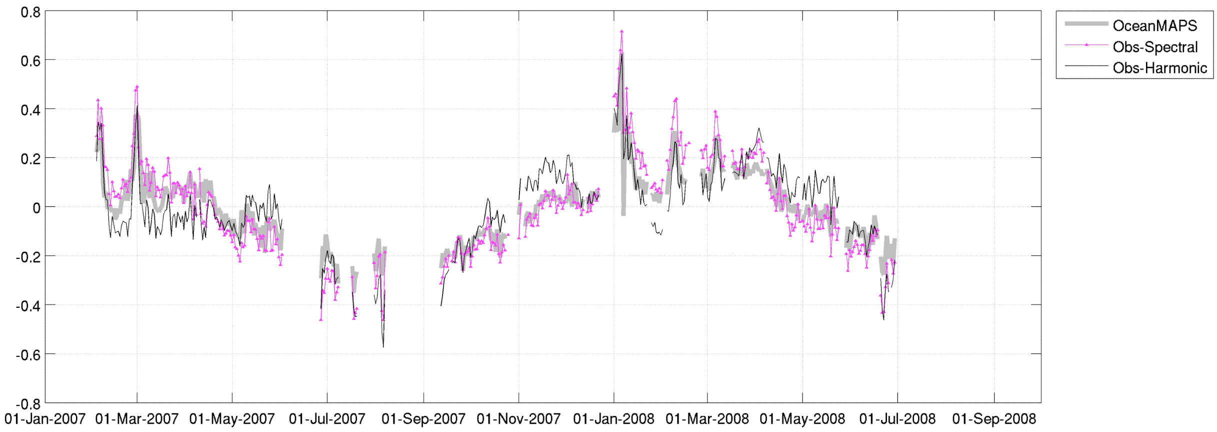


Fig. 35 SLA time series data for Station 11 Darwin, NT.

Fig. 36 SLA time series data for Station 12 Groote Eylandt, NT.

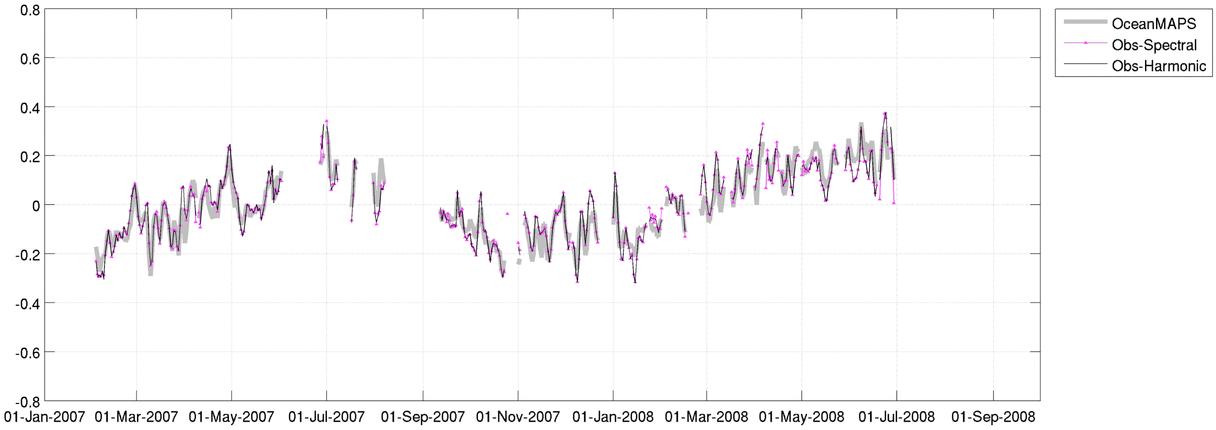


Fig. 37 SLA time series data for Station 13 Hillarys (Perth), WA.

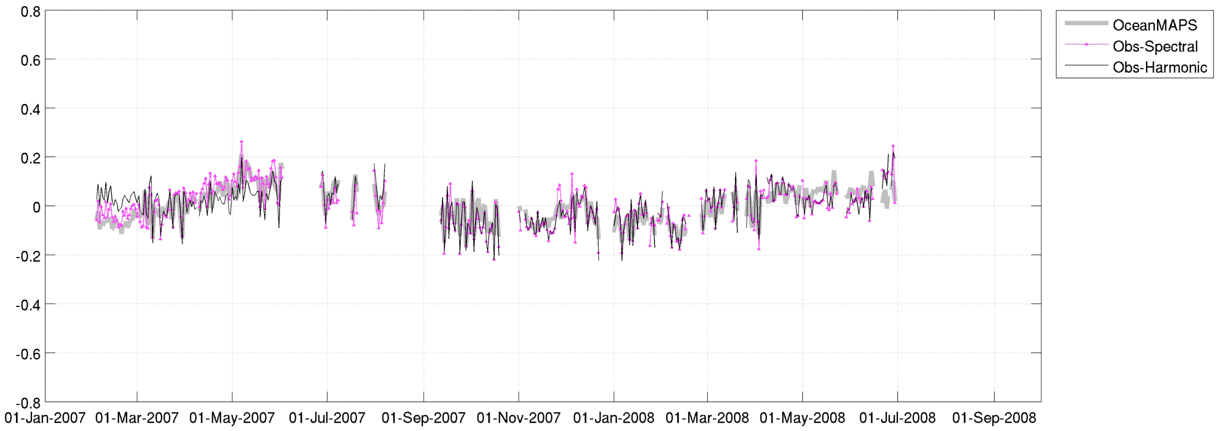


Fig. 38 SLA time series data for Station 14 Burnie, Tas.

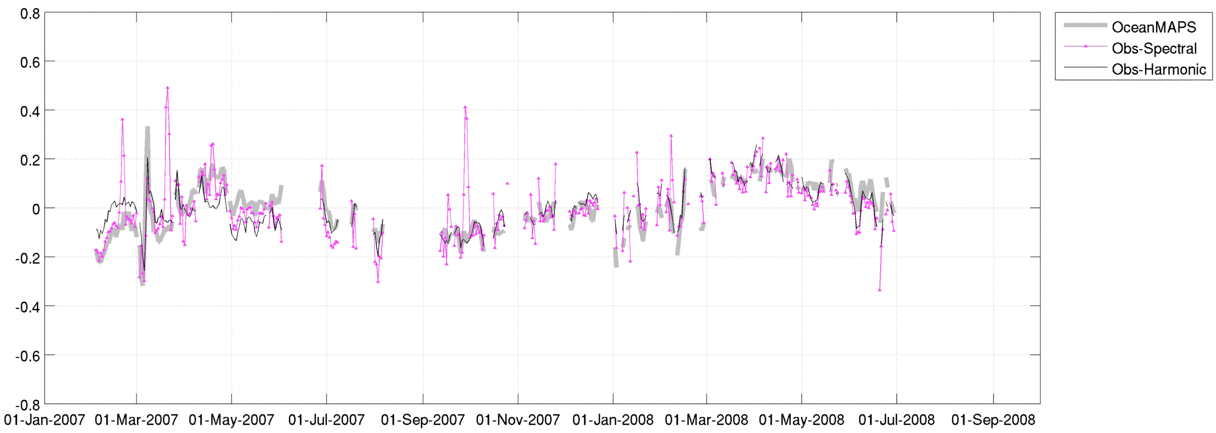


Fig. 39 SLA time series data for Station 15 Broome, WA.

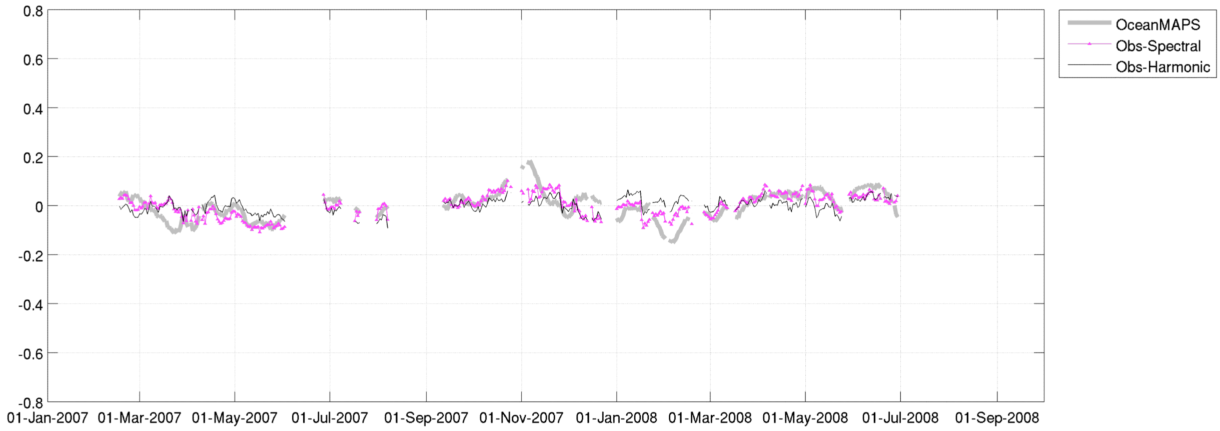


Fig. 40 SLA time series data for Station 16 Port Vila, Vanuatu.

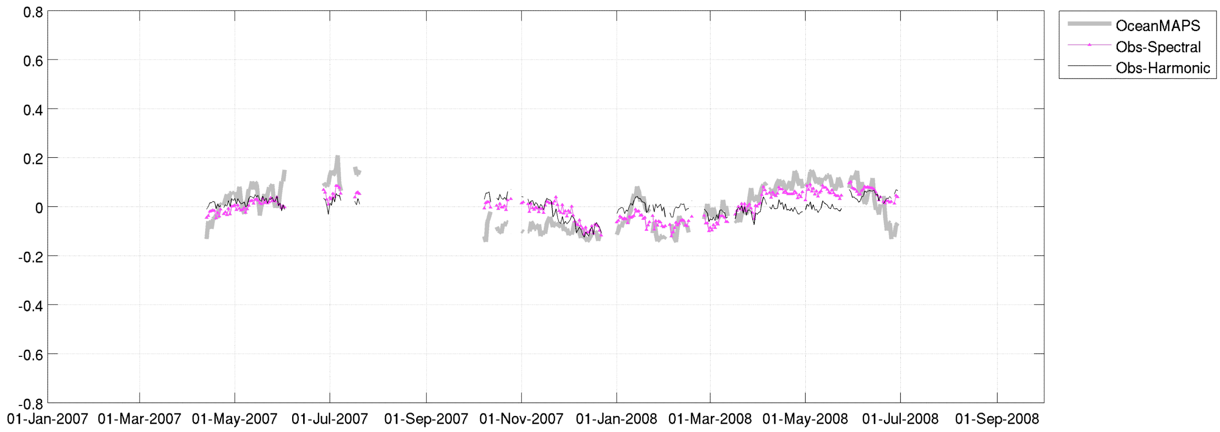


Fig. 41 SLA time series data for Station 17 Apia, Samoa.

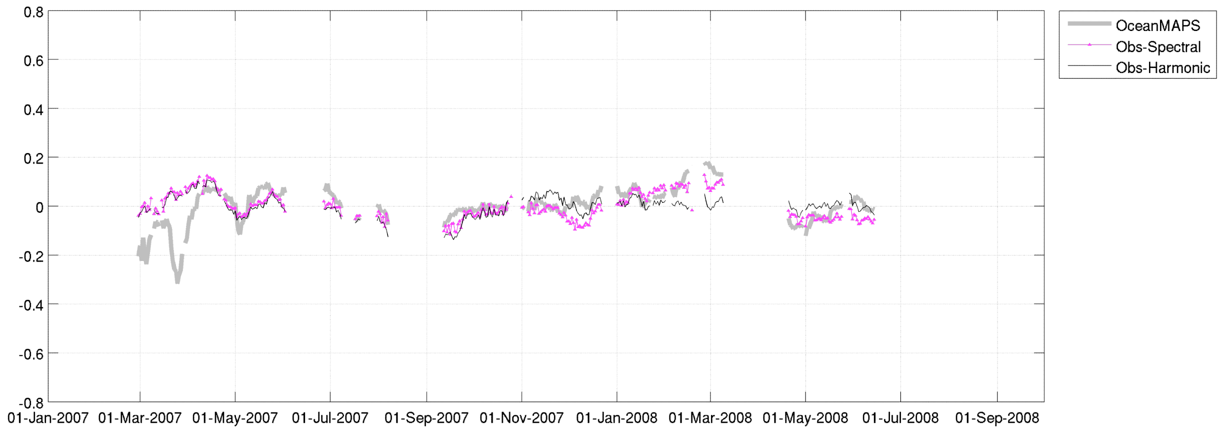


Fig. 42 SLA time series data for Station 18 Funafati, Tuvalu.

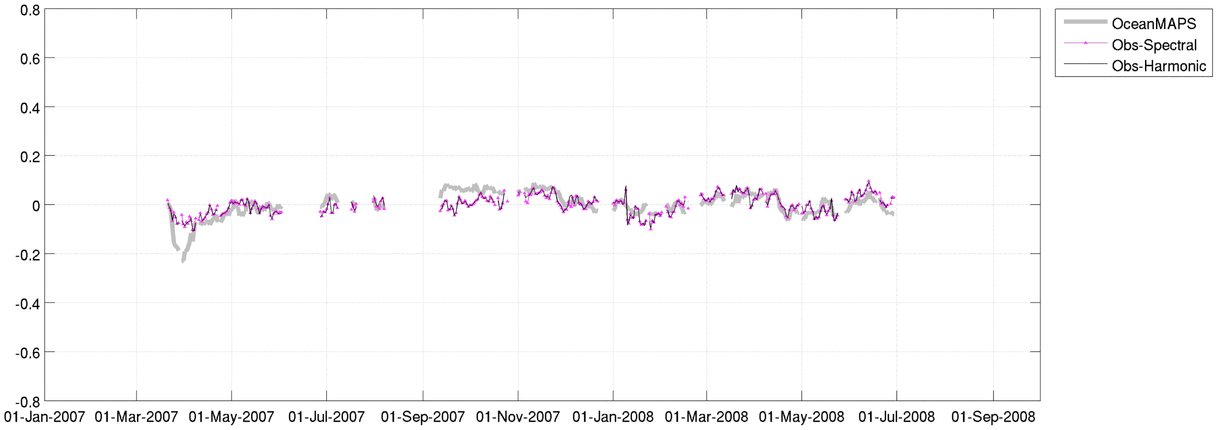


Fig. 43 SLA time series data for Station 19 Nuku'alofa, Tonga.

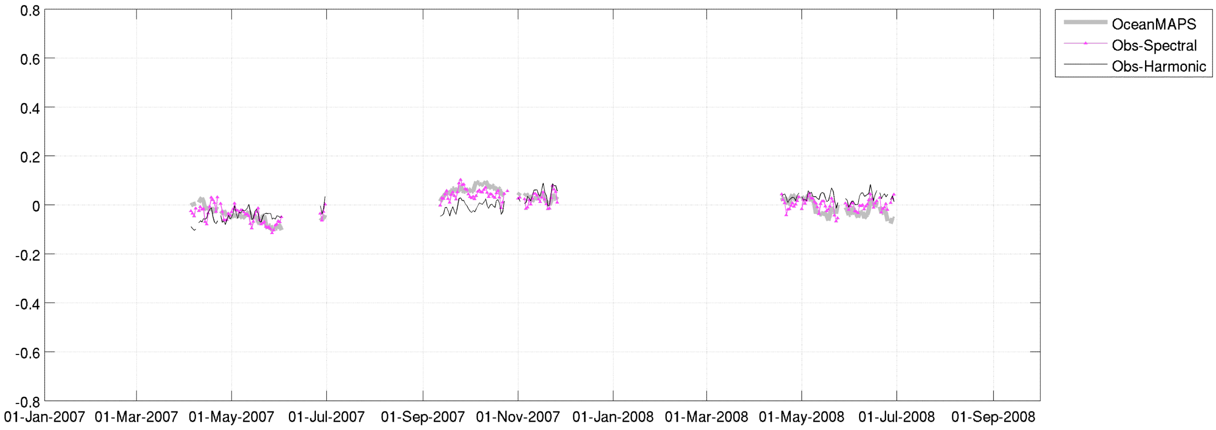


Fig. 44 SLA time series data for Station 20 Suva, Fiji.

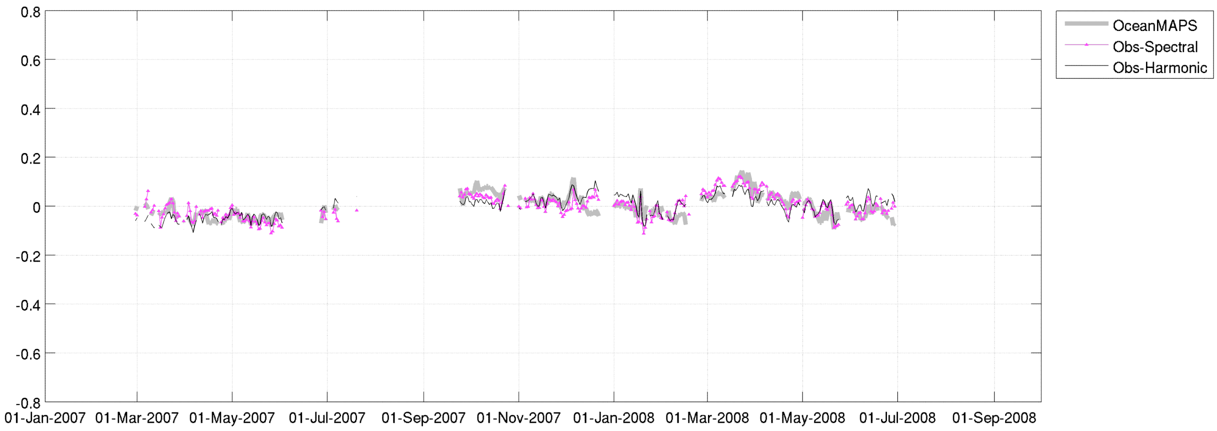


Fig. 45 SLA time series data for Station 21 Lautoka, Fiji.

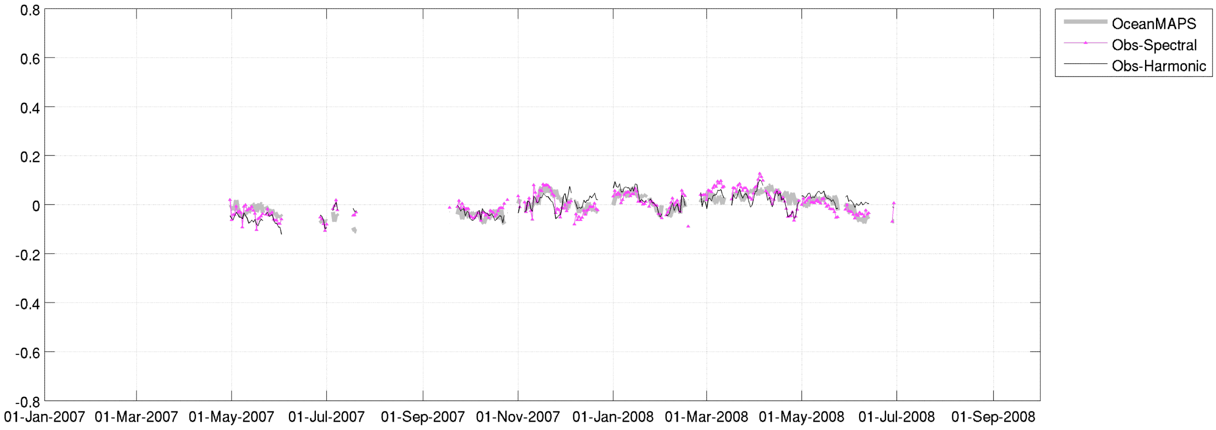


Fig. 46 SLA time series data for Station 22 Lombrum, Manus Island, PNG.

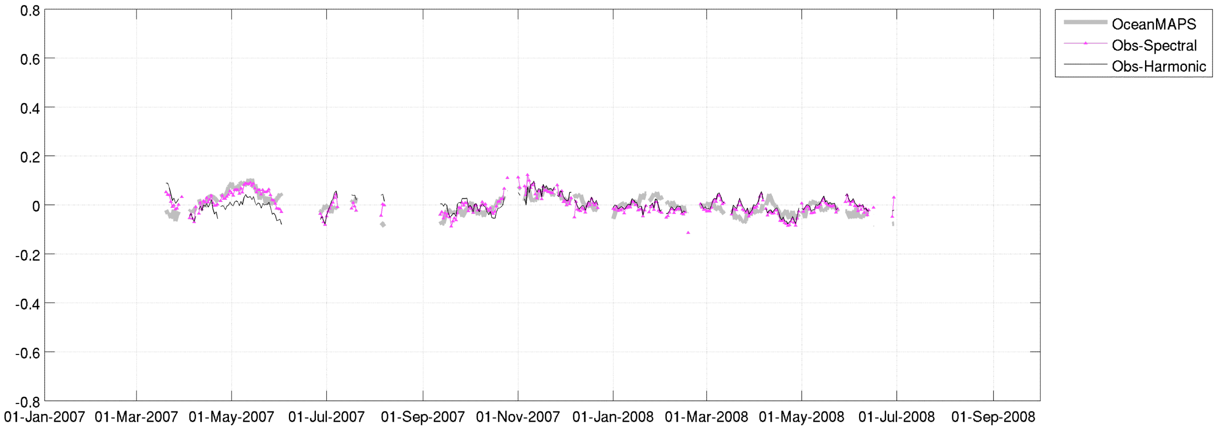


Fig. 47 SLA time series data for Station 23 Ponape, Micronesia.

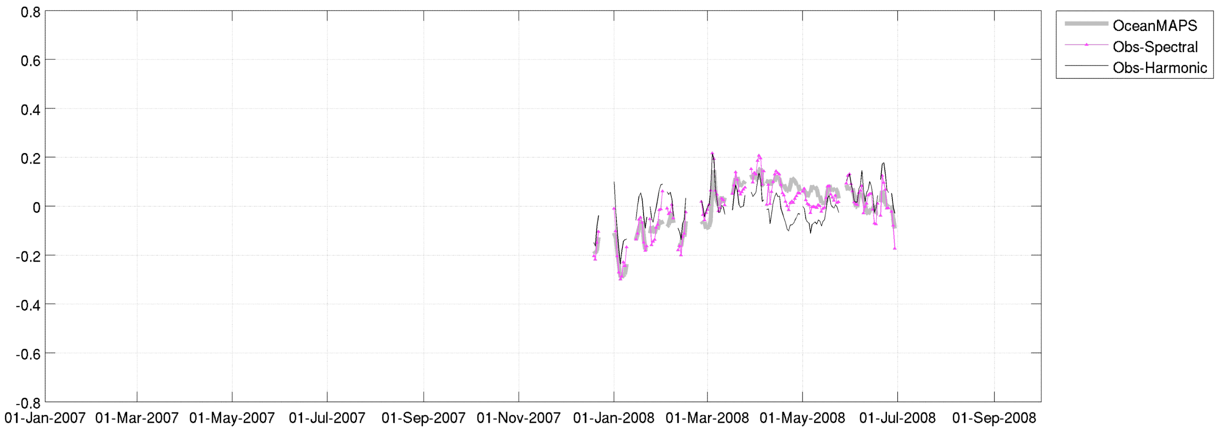


Fig. 48 SLA time series data for Station 24 Point Murat, (Exmouth), WA.

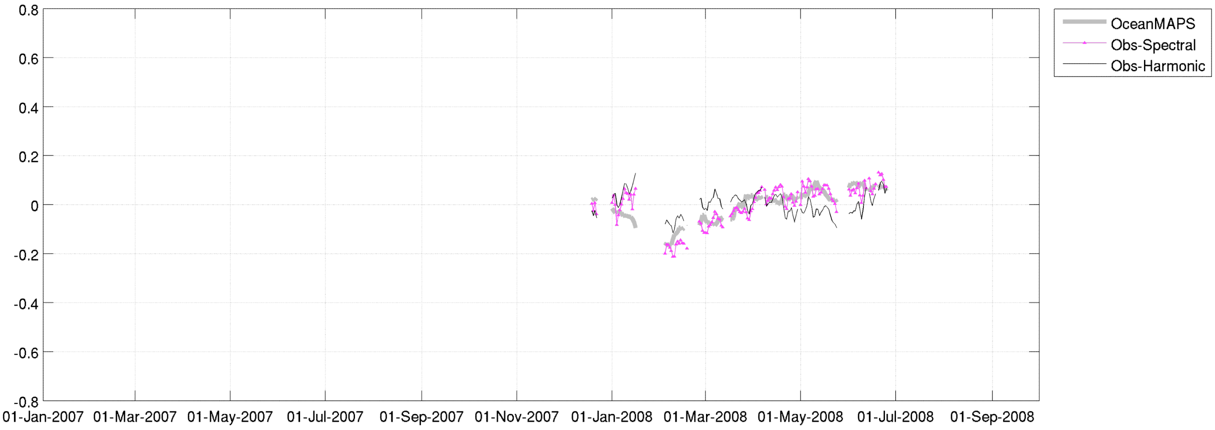


Fig. 49 SLA time series data for Station 25 Luganville, Vanuatu.

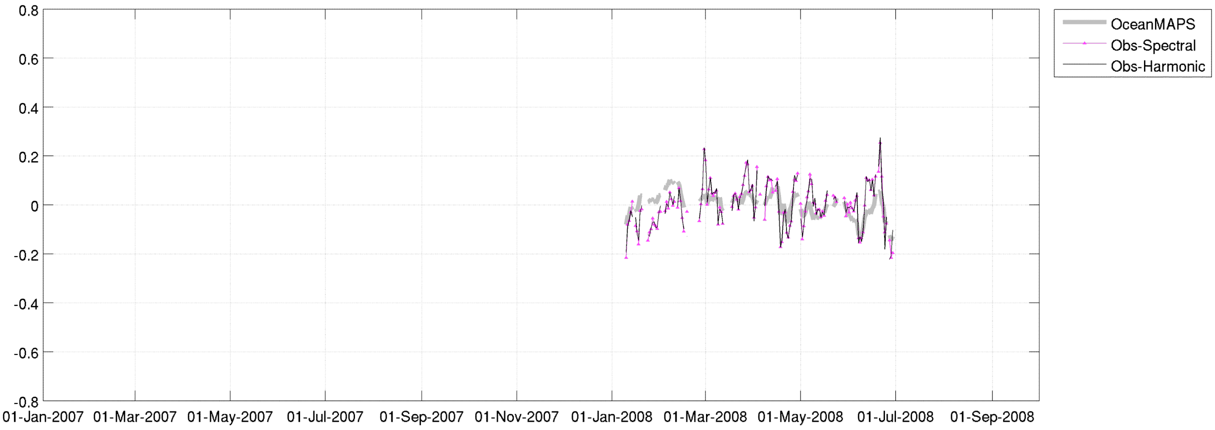


Fig. 50 SLA time series data for Station 26 Jackson Bay (South Island) NZ.

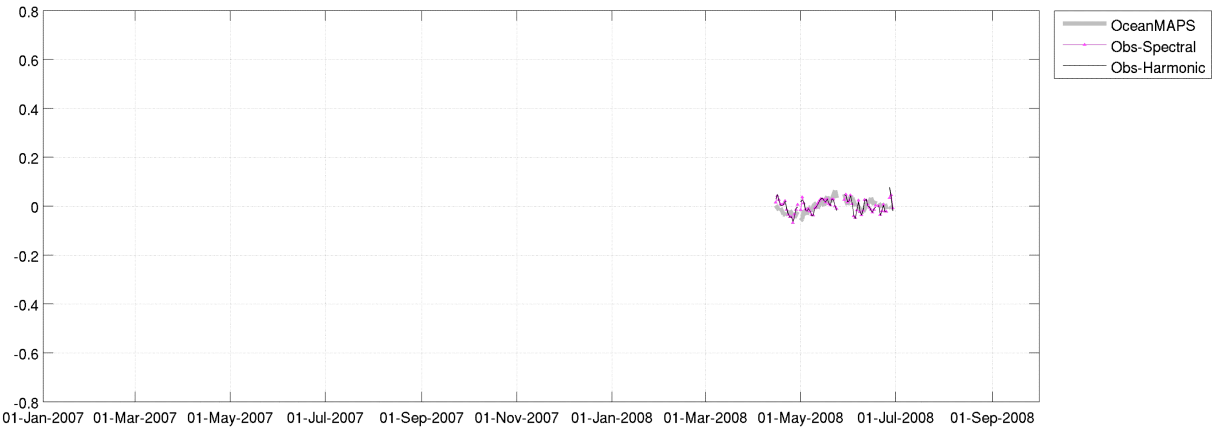


Fig. 51 SLA time series data for Station 27 Betio, Tarawa, Kiribati.

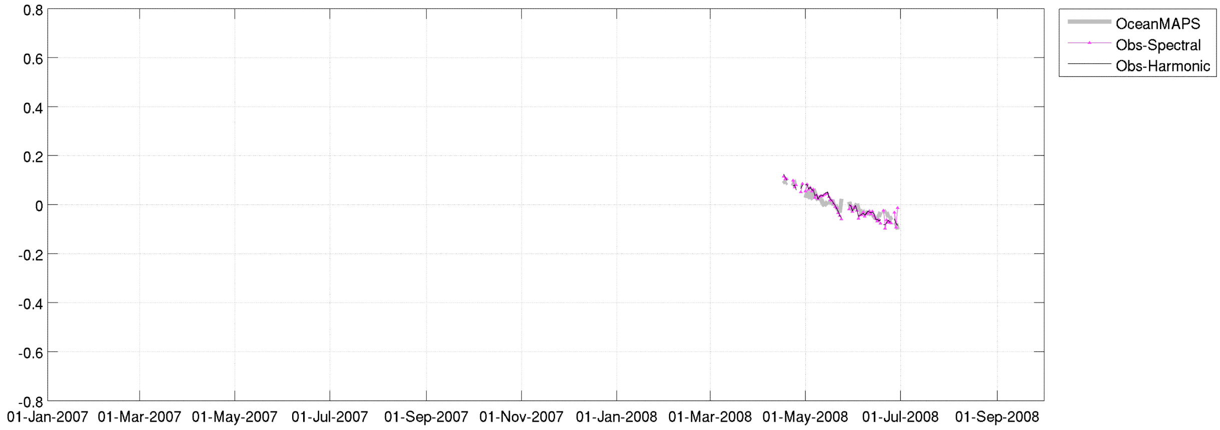


Fig. 52 SLA time series data for Station 28 Honiara, Guadalcanal, Solomon Islands.

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