High Frequency Internal Solitary Waves – Measurement and Modelling

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Background

Solitons (or solitary waves) are the names widely used in the Oil & Gas industry to describe large amplitude, high frequency internal waves, associated with strong and rapidly varying currents. The hazardous and costly disruption to drilling operations in the Andaman Sea led to the first identification of solitons in the ocean and prompted much of the subsequent academic study. We now know that solitons are a common world-wide feature of the internal dynamics of the slope and shelf regions of the ocean. Due to the strong tides and strong density stratification, solitons are a ubiquitous feature on Australia's North West Shelf, but remain largely unpredictable due to the complexities of the non-linear, non-hydrostatic processes involved. This means that engineering design criteria for solitons with return periods ranging from 10 to 1000 years cannot be reliably estimated because measurement programmes are of insufficient duration (typically only a year or less), and models required to extend measured databases are not available.

Our measurement programmes over the past 30 years clearly demonstrate the existence of solitons. On the continental slope, solitons can generate near-seabed currents which exceed those caused by tropical cyclones, making solitons the controlling criterion for pipeline design, and an important factor in understanding seabed sediment dynamics, habitat stability and water quality. In deeper waters, solitons can generate pronounced shear (vertical gradients of horizontal current speed and direction), which can present controlling design conditions for riser and mooring design, and design of suspended cooling-water intakes. Near-surface solitons can also be critical to assessment of operability of floating facilities (particularly for sensitive operations like LNG transfer in deeper waters).

Presently, our ability to provide reliable, non-conservative soliton design criteria is hampered by lack of understanding of the oceanographic influences on such issues as soliton areal distribution, frequency of occurrence, peak magnitude, timescale (or duration of soliton events), spatial structure (most simply – crest length) and longer-term variability. Measurements provide part of the solution – but economics preclude them from being a 'complete' solution.

Industry Requirements

Solitons arise from a balance of nonlinear and dispersive processes in density stratified water, resulting in high frequency, small length-scale motions of significant vertical excursion. As such, they require the introduction of non-hydrostatic terms into circulation models which may be used to simulate their behaviour.

It is highly unlikely that numerical models will ever become the standard tool for setting soliton criteria (at least not within the foreseeable future) because the spatial extent from the generation regions to the area of interest is typically too large for high-resolution non-hydrostatic simulations. However, a reliable soliton model should allow investigation of

- likely areal extent of soliton activity
- sensitivity to density structure (and its temporal and spatial variability)
- sensitivity to seabed slope
- sensitivity to background (ambient) currents and eddies
- dependence on tidal forcing
- direction and speed of propagation
- timescales (or duration of soliton events)
- associated current and temperature responses including the 'shape' – or at least crest-length – and the vertical profiles of currents

In practice, it is envisaged that measurements would still be used to set base soliton criteria, but once 'calibrated' or 'tuned' against measurements, models would be used to extrapolate to adjacent locations, assess longer-term variability due to changing background conditions, and to set spatial structure and timescales associated with peak soliton activity.

Accordingly, we intend to implement an existing non-hydrostatic model to simulate internal waves, and in particular solitons, in three dimensions and time on the North West Shelf. The modelling will benefit from the most extensive and best available soliton (high frequency current and temperature) measurements, which have been acquired over the last 30 years.

To ensure compliance with the best available engineering standards, and to provide optimal design solutions which avoid unnecessary conservatism in increasingly marginal developments, the offshore industry will require a combination of the best available high frequency measured data, and sophisticated non-hydrostatic modelling to allow complete metocean design criteria determination.

It is also hoped that coupling a competent non-hydrostatic current model with a limited suite of key real-time measurements, may allow development of effective Early Warning Systems for facilities located in regions of complex internal wave activity.

Available Data

Since 1985, RPS MetOcean Pty Ltd has been conducting long-term, high frequency current and water temperature measurements, principally on Australia's North West Shelf – but also in waters off east and west Africa, and in Indonesian Seas. Our CM04 acoustic single point current meter routinely allows deployments of up to a year at continuous 1 minute sampling. We now have archives of over 1000 years of high frequency current data – all of which are backed by tow tank or flume calibration.

Typically, high frequency phenomena exhibit timescales of the order of 10 to 60 minutes (set by the prevailing buoyancy frequency). Recently, we have obtained excellent measurements of seabed solitons with timescales of less than 3 minutes, such that for future measurements at that location, we shall deploy our current meters at continuous 20 second sampling.

Most of the data collected are proprietary to the Oil & Gas companies who commissioned the measurements, but a significant portion of these data have been released to universities and research institutes for detailed analysis. These high frequency measurements formed the basis of the pioneering work of Dr Peter Holloway in his studies of internal hydraulic jumps and solitons on Australia's North West Shelf (Holloway 1987). In particular, his work identified North Rankin location (in 124 m of water about 130 km off the Dampier coast), as a region of intense internal wave activity.

Taking advantage of logistics available from commercial operations, we have recently completed a 3 year measurement programme of continuous 1 minute current and water temperature sampling at North Rankin location, using 6 acoustic current meters (at height of 2.6, 30, 60, 76, 91 and 111 m above sea bed), and 16 temperature loggers. Together with the temperatures measured by the current meters, this provided temperature measurements every 5 m through the water column. Overall data return from the programme was in excess of 95%. These data are the property of RPS MetOcean Pty Ltd, and should serve as an excellent foundation for the setup and validation of our non-hydrostatic modelling.

North Rankin location and regional bathymetry are illustrated in Figure 1.

Types of High Frequency Events

The wide variety of 'non-linear wave shapes' identified by Holloway (1987, 1988, 1992) and theoretically addressed by Holloway et al. (1999) and Grimshaw et al. (2006), are clearly apparent in the North Rankin high frequency current data. They include:

- leading and trailing tidal bores
- solitons of elevation and of depression
- 'breaking' solitons
- topographically enhanced jets.

Some examples of these phenomena are illustrated here.

Internal Tidal Bores

Figure 2 illustrates the evolution a near-seabed bore as the internal tide shoals and steepens during shoreward progression across the continental slope. The steep rise in near-seabed current speed is accompanied by pronounced drop in lower water column temperatures. Such events can affect pipeline scour and stability, and potentially hydrate formation in other cooler water (deeper) locations.

Surface Solitary Waves of Depression

Figure 3 illustrates the occurrence of a packet of surface solitary waves of depression, causing potential difficulties with operation of surface vessels, with significant swings of up to 180° in direction, and sudden surges in current speed, on timescales of the order of 10 minutes.

Seabed Solitary Waves of Elevation

Figure 4 illustrates the variability in timescales of near-seabed solitary waves of elevation, associated with upslope currents of 10 minutes timescale, and downslope currents of 30 minute timescale. Such events can have implications for pipeline stability and scour around seabed facilities.

Controlling Factors

The wide variety of non-linear wave shapes arises from the multiplicity of controlling factors, including:

- density stratification
- tidal forcing
- seabed slope
- background (ambient) currents and eddies
- Coriolis effect

The spatial variability of these factors also means that there is substantial spatial variability in the manifestations of these phenomena, and it becomes necessary to employ numerical simulation in order to effectively extrapolate the results of high frequency measurements to peripheral locations.

Three-dimensional Modelling of Internal Solitary Waves

Hydrodynamic Model

We used MITgcm for this study because (i) it is an open-source model, (ii) it runs efficiently in parallel computers, and (iii) it has been successfully used for three-dimensional internal solitary wave modelling in recent studies (Vlasenko and Stashchuk 2007; Vlasenko et al. 2009, 2014; Guo et al. 2011; Dorostkar 2012).

Validation against Laboratory Experiments

Before conducting three-dimensional simulations in realistic oceanic conditions, we reproduced two laboratory experiments to understand the basic characteristics of internal solitary waves simulated by MITgcm.

First, we reproduced the results of the non-rotating tilted tank experiments by Horn et al. (2001). The results showed that numerical dispersion slows down the propagation of internal solitary waves by increasing overall wave dispersion in the model (Figure 5), as pointed out by Vitousek and Fringer (2011).

Second, we reproduced the results of the rotating tank experiments by Grimshaw et al. (2013), which included the Coriolis effects. MITgcm captured the propagation speed correctly with sufficient grid resolution; however, simulated amplitudes were always over-predicted (not shown). One of the possible causes of the discrepancy is that the reservoir gate was opened instantaneously in the model but slowly in the experiments (*pers. comm.* Prof. R. Grimshaw and K. Helfrich).

Three-dimensional Simulations in Realistic Conditions

Our final aim is to conduct a suite of simulations around the North Rankin location. These simulations are currently being set up.

As an example of three-dimensional internal solitary wave modelling under realistic conditions, we show the results from the Australia's Browse Basin, on the northeastern part of the North West Shelf (Figure 6). In this relatively simple modelling, we chose topographic features that generate internal solitary waves in a relatively small area to avoid the necessity for nesting and long model runs. The model was forced with barotropic tides, and included realistic stratification and full non-hydrostatic effects including the non-traditional effects (e.g., Gerkema et al. 2008).

The simulation produced a highly complex internal wave field. Since the model was forced with barotropic tides, internal tides were generated by topographic interaction, and subsequently degenerated into a train of internal solitary waves. Most of the internal solitary waves had mode 1 structure in the vertical and wavelengths of ~1 km. The results support the need for modelling to 'extrapolate' measurements because the interference of internal solitary waves produced a complex internal wave field with a typical lateral length scale of less than 5 km.

The Next Step

Having successfully demonstrated the capability of the MITgcm to simulate internal solitary waves in realistic conditions, we are implementing the model to encompass the North Rankin region, including the potential internal wave generation regions indicated by Holloway (1996), Holloway et al. (2001) and Van Gastel et al. (2009). We will use the measured thermal structure at North Rankin to 'inform' stratification across the model domain, and look to tune the model to replicate the rich array of observed high frequency current phenomena.

Acknowledgement

This research is partly funded by the Research Connections grant from Australian Department of Industry and Science. Thanks to Dr Peisheng Huang for figure preparation.

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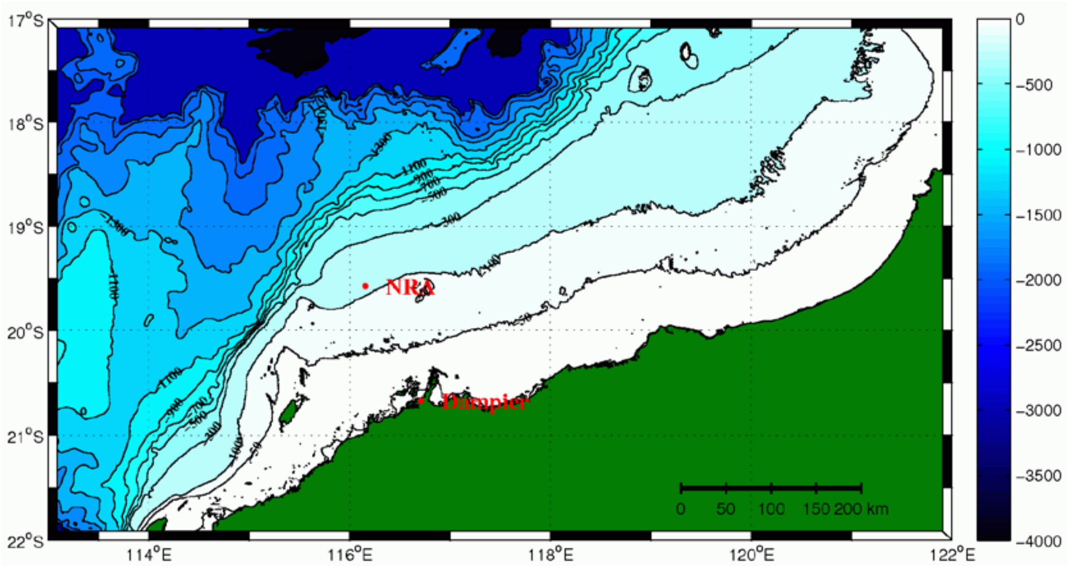

Figure 1. North Rankin location and regional bathymetry.

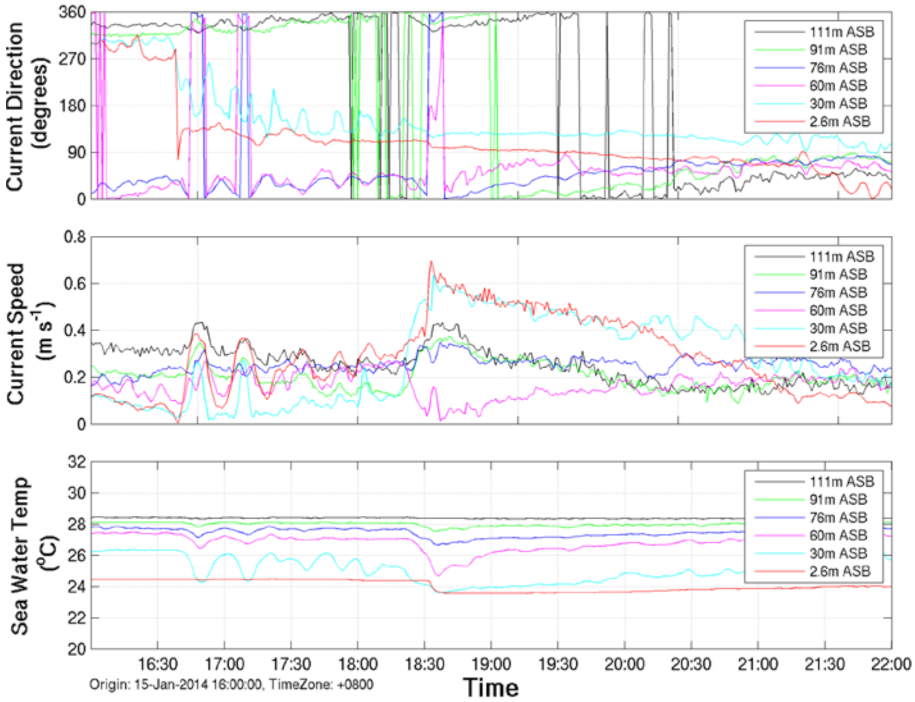

Figure 2. Illustration of near-seabed internal bore at North Rankin location. Note that ASB means above sea bed.

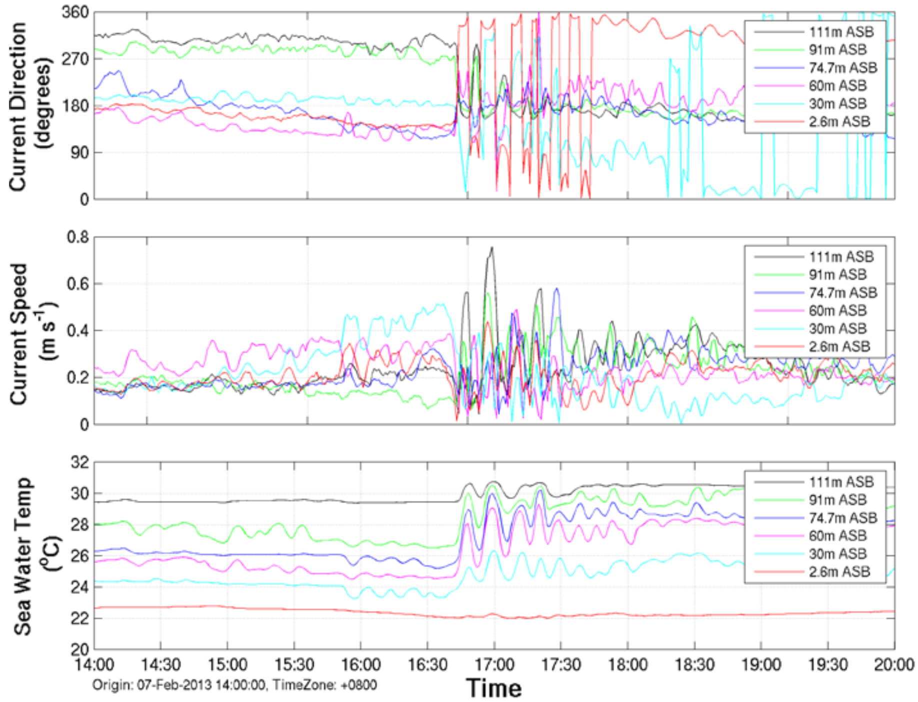

Figure 3. Illustration of near-surface internal solitary waves of depression at North Rankin location.

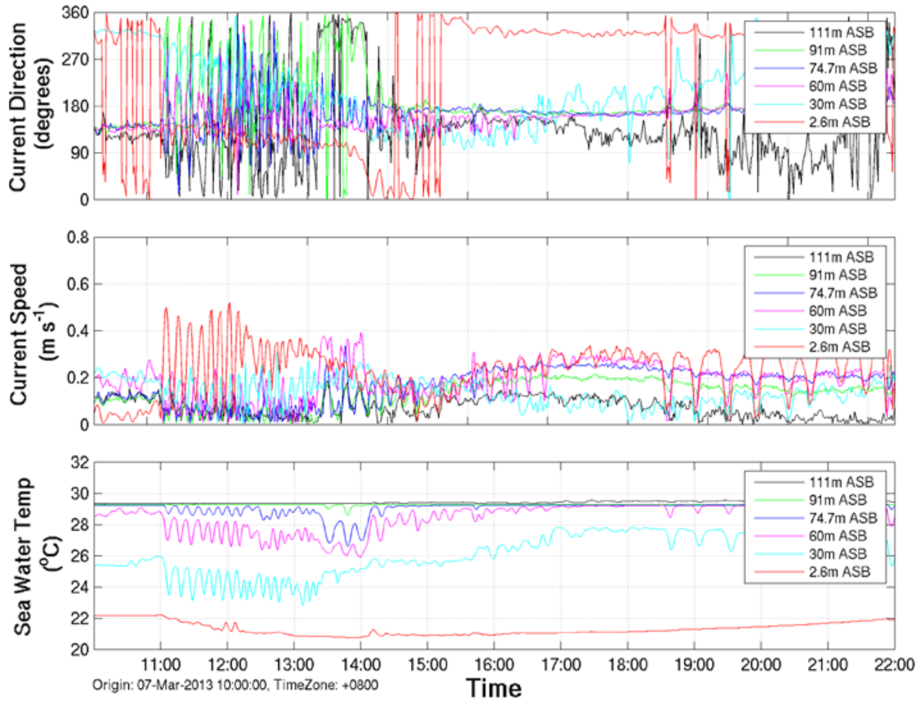

Figure 4. Illustration of near-seabed internal solitary waves of elevation at North Rankin location.

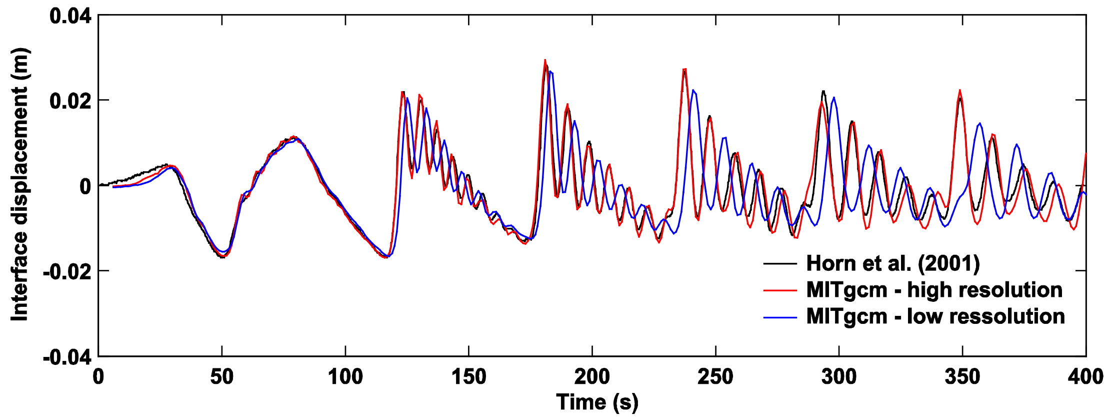

Figure 5. Comparison of experimental data (black) and MITgcm simulations (colored) for the tilted tank experiments by Horn et al. (2001).

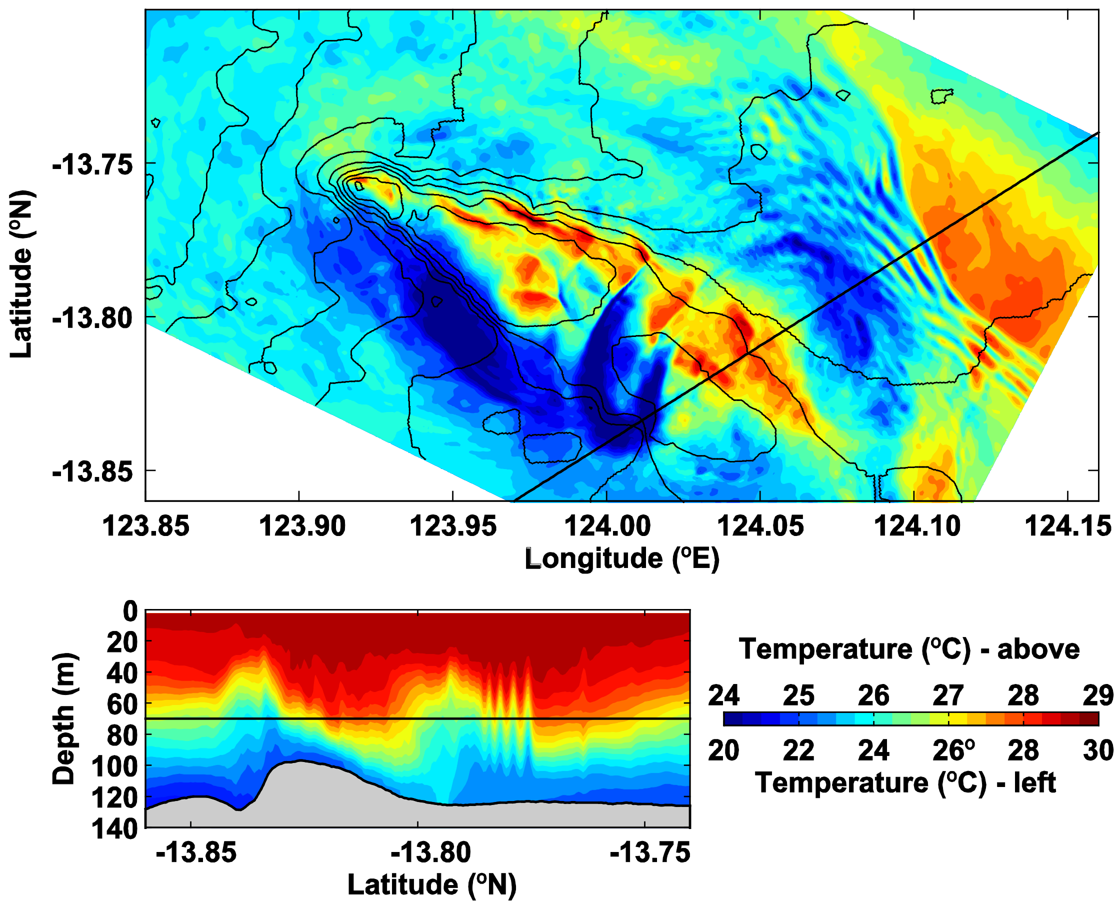

Figure 6. A snapshot of MITgcm simulation in the Australian Browse Basin. (a) Temperature at 70 m depth, and (b) along the cross section indicated by thick black line in (a). Thin black lines in (a) show 90 to180-m isobaths at 10-m interval. At the time plotted, barotropic tidal currents flow towards northeast. Note the difference of temperature scale in the two panels.