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Sediment re-suspension processes along the Australian north-west shelf revealed by ocean gliders

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Abstract

Major drivers of sediment re-suspension events result from forcing through tides, winds, density currents and internal waves whilst extreme events such as tropical cyclones also provide in-frequent strong forcing. In this paper, sediment re-suspension events over the Australian north-west continental shelf off Pilbara are identified using an ocean glider transect and moored instruments. Ocean gliders are autonomous vehicles which provide high temporal and spatial resolution vertical profiles on temperature, salinity, particle backscatter. Data collected during a glider transect in September 2013 are presented together with current and vertical temperature structure obtained at two moorings located at 100m and 200m water depths. Although tidal action was the main background forcing, there were re-suspension events which can be related to a variety of different dominant processes related to vertical stratification: (1) effect of gravity currents; and, (2) strong tidal forcing and internal waves. Gravity currents result from a cross-shelf density gradient driven by cooling and evaporation and is clearly identified from the salinity distribution. Majority of the sediment re-suspension events in water depths ~50m were related to maximum flood/ebb currents whist in water depths > 130 m the tidal period the re-suspension events were related internal wave action.

Introduction

Globally, major drivers of sediment re-suspension events result from forcing through tides, winds, density currents and internal waves whilst extreme events such as tropical cyclones also provide in-frequent strong forcing. Vertical mixing events are particularly important on continental shelves often influencing the full water column and the seabed [6]. The resuspension and transport of suspended sediment that includes both organic and inorganic particles are important for the ecology of coastal waters as they influence the water clarity, and thus primary production; and, the transport of pollutants. Many field and numerical modelling studies have been undertaken in tidally dominated systems to examine the resuspension and transport of suspended sediment [6]. In oligotrophic waters, and when there is negligible riverine input of particulates, resuspension of particles from the seabed is the main mechanism governing the light climate [23].

In general, sediment re-suspension occurs as a direct result of turbulence generated at the seabed. The source of the turbulence can be due a variety of forcing including surface gravity waves, tidal currents, near-bed gravity currents and internal wave activity. During low energy periods, a single forcing mechanism may not exceed the threshold condition for sediment re-suspension; however, a combination of processes (e.g. the combined action of surface gravity waves and tidal currents) can lead to sediment re-suspension. This paper is mainly concerned on the influence of bottom gravity currents and internal wave activity in the presence of tidal forcing contributing to sediment re-suspension in the Australian North-west shelf (ANWS) through the analysis of field measurements undertaken using autonomous ocean gliders. Using a glider transect obtained in September 2012 two main processes (in addition to tidal forcing) are highlighted as contributors to sediment re-suspension: bottom gravity currents (also defined as dense shelf water cascades, DSWC) and internal waves.

Australia experiences high evaporation rates during the summer months resulting in higher salinity water on the inner shelf. In late autumn and winter convective cooling generates a water body with higher density when compared to that further offshore. This dense water is transported across the continental shelf (DSWC) as a near bed gravity current driven by the cross-shelf density gradient between the nearshore and offshore water. The gravity currents may be interrupted due to vertical mixing provided by the local wind and tidal conditions. DSWC have been identified in other locations around Australia such as [15]: Shark Bay; Great Australian Bight; Spencer Gulf; and, the Rottnest continental shelf [20].

Internal waves are a common feature in the stratified coastal ocean [5, 19]. In regions such as the ANWS, the internal waves (or internal tide) are generated at the shelf break propagate shoreward along the continental shelf as what are typically referred to as “boluses” or “bores” [9, 12, 22]. The amplitudes of the isopycnal displacements induced by internal waves can reach up to 90 m on continental shelves, generating strong near bed horizontal currents up to 1.0 ms^{-1} [22]. Shoreward propagating internal bores have been investigated through numerical simulations [21], laboratory experiments [3] and observations [6]. An internal bore generates a vortex core accompanied by strong vertical motion at its head [21].

Recent studies [8, 20, 18] have demonstrated the applicability of autonomous ocean gliders to measure shelf processes, such as dense shelf water cascades and resuspension events over continental shelves. The use of underwater gliders on the study of internal tides has been recently reported [13,14], although application of this platform to sediment re-suspension events due to internal wave dynamics have not been undertaken to date.

Study site

The study site is located on the Australian North West Shelf (NWS), offshore Dampier (**Error! Reference source not found.**). The region is characterized by strong semi-diurnal tides dominated by the principal lunar (M_2) and principal solar (S_2) constituents [10]. The location of the ADCP200m (and thermistors) is close to the shelf break [2]. The shelf also has a mini-shelf break at around 100km from the coast where there is rapid increase in water depth from ~50m to > 100m. The study site is located in a region of internal tide generation [11, 22]. The region is also associated with the generation of dense shelf water cascades [15].

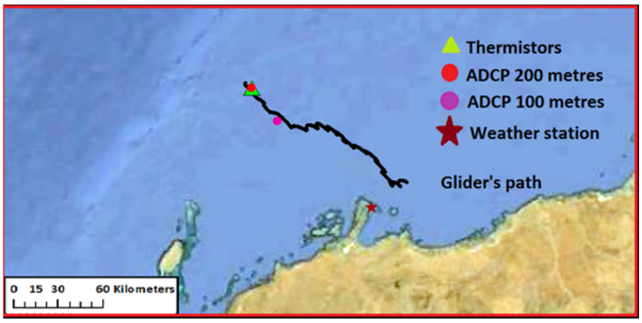

Figure 1: Location of the study region; current meter location and glider path. The weather station is located on Legendre Island.

Methods

Oceanographic data presented here were obtained from the Integrated Marine Observing System (IMOS) and include data acquired using an autonomous ocean gliders, current meters and temperature loggers. The data were obtained during the period 19 to 27 of September of 2013. Wind data were sourced from Bureau Meteorology station at the Legendre Island (Figure 1).

The ocean glider was Teledyne Webb Research Slocum Electric Gliders configured to sample the water column at 4Hz from the surface to ~5 m above the sea bed whilst moving forward at with a mean speed of 25 km per day [20]. The ocean gliders were equipped with a Seabird-CTD, WETLabs BBFL2SLO 3 parameter optical sensor (measuring Chlorophyll-a fluorescence, CDOM & 660nm Backscatter). The volumetric backscatter coefficient (VBSC) was used as proxy for suspended sediment concentration [8, 18]. The CTD data were used to calculate the Brunt–Väisälä frequency and the water vertical velocity (W). The vertical velocity was calculated by first defining the mean glider ascent/descent rates for each dive. The departure of the glider ascent/descent rate compared to the mean was defined as vertical water velocity [17].

Velocity profiles, at 10 minute intervals, were obtained using bottom mounted an upward-looking ADCPs located at 92 m (ADCP100m) and 191 m (ADCP200m) water depths (Figure 1). The vertical resolution was 8m and 10 m at ADCP100m and ADCP200m locations. The moorings also contained 10 thermistors located at intervals of 10-20 m intervals. The currents both stations were rotated to cross-shelf and along-shelf components using the local orientation of the isobaths.

The ADCP200m mooring also consisted of 7 thermistors that were located at nominal water depths of 46, 66, 76, 96, 126, 136, 166 m. The data were temporally averaged and vertically interpolated onto a common grid of 30 minutes and 1 m vertical cells, vertically integrated from 0 to 165 metres.

Results

The wind field during the study period was such that during the initial 4 days (19-22 September) the winds were weak (Figure 2A). On 23 September, the winds increased to a peak speed of 15 ms^{-1} and remained strong (> 10 ms^{-1}) until 25 September and then gradually decreased. The winds had a pronounced diurnal variability with peak wind speeds occurring around mid-night. The wind direction (not shown) was mostly from the west to south-west.

At the beginning of the deployment, spring tides (range = 3 m on 21 September) were present and neap tides (range = 1.1 m on 26 September) were present at the end of the deployment (Figure 2B). The cross-isobath component was higher than the along-isobath flow in the semi-diurnal tidal currents (Figure 2C). The temperature time series indicated strong oscillations of the thermocline with a tidal period of 12 hours (Figure 2D).

The distribution of water column properties, based on the data obtained from the ocean glider, allows us to identify 5 distinct regions across the continental shelf shown as regions A-E along the time axis in Figure 3.

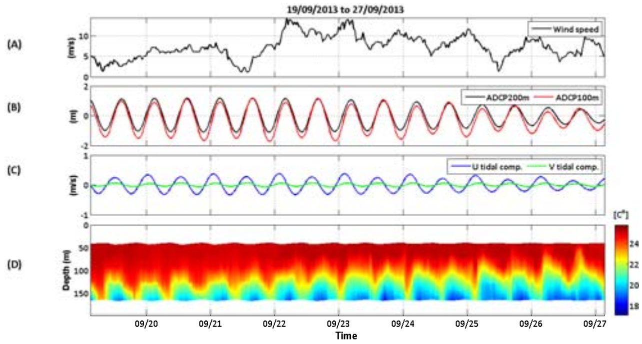

Figure 2. Time series of (A) wind-speed; (B), tidal heights at 100m and 200m; (C) along-slope and cross-slope velocity components at ADCP100m; (D) temperature from the thermistors at ADCP200m.

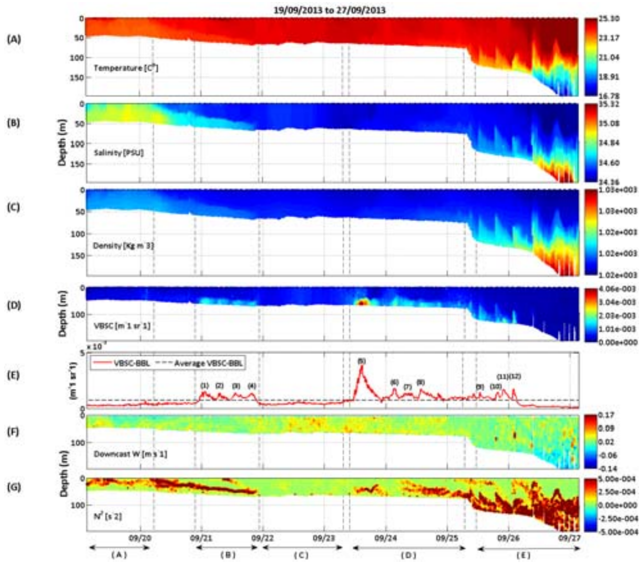

Figure 3: The cross-shelf ocean glider transect: (A) temperature; (B) salinity; (C) density (D) volumetric backscatter coefficient; (E) time series of VBSC along the bottom boundary; (F) squared Brunt–Väisälä frequency; and, (G) vertical water velocity calculated from downcast profiles.

Region A

This is the region close to the coast and extends from the start of the deployment until September 20th (Figure 3). The water column was almost vertically was mixed (shallow mixed layer of < 10 m was present) with the maximum salinity water and low values of VBSC in the bottom boundary layer (Figures 3 B, E). The winds were weak with speeds < 5 ms^{-1} (Figure 2A) and thus majority of the mixing would be through tidal mixing during the spring tides.

Region B

This region represented the dense shelf water cascade with the higher density water (salinity dominated) forming a wedge shape (Figure 3B). Beginning from almost a well-mixed water column there is strong vertical stratification with a decrease in the height of the bottom boundary layer (BBL) with distance away from the coast (Figure 3F). The wind speeds were low with mean speeds around 5 ms^{-1} (Figure 2A). The region was characterised by elevated values of VBSC which also revealed 4 peaks at 6 hour intervals that were related the maximum tidal flood/ebb flows

(Figure 4). The location of the high VBSC was coincident to the 'nose' of the gravity current.

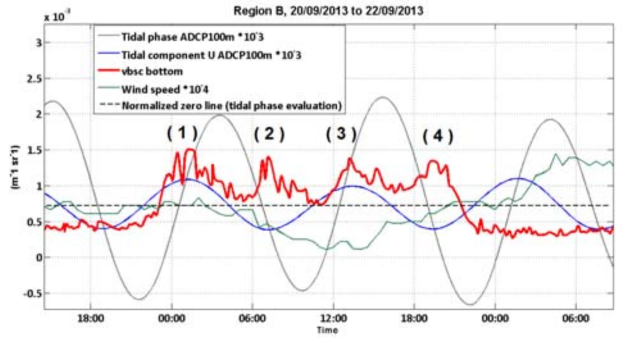

Figure 4. Time series of tidal height; cross-slope velocity; VBSC within the BBL; wind speed at Region B from 20-22 September.

Region C

Region C was characterised by a vertically mixed water column most likely due to the strong wind mixing during this period (wind speeds > 10 ms^{-1}; Figure 2A). Both N^2 and VBSC were uniform throughout the water column with no significant resuspension events during this period.

Region D

In region D, the glider encountered a section of the continental shelf which was vertical stratified. Although the N^2 values were relatively higher (Figure 3G), the density distribution (similar to temperature and salinity) does not indicate strong vertical changes in water properties (at the scales shown). Similar to Region B, there were 4 peaks of elevated VBSC values at 6 hourly intervals that were related the maximum tidal flood/ebb flows (Figure 5A). The first VBSC peak was the maximum value recorded during the whole deployment period (peak 5 in Figure 5A) and the VBSC peaks reduced in maximum values in the subsequent tidal cycles. Each of the four observed maxima during this period coincided with the maximum flood velocity (Figure 5A). This is in contrast to that observed in Region B where that corresponded with maximum flood and ebb tidal currents (Figure 4). The thermistor data from the ADCP200m indicated the presence of large (> 50 m) oscillations in the thermocline corresponding to this time period that were also in phase with the VBSC peaks 5, 6 and 8 (Figure 5B). It should be noted that the glider was in water depths of 50m whilst the ADCP200m station was located further offshore. Adjusting for the time difference between the two stations it appeared that the resuspension events occurred on the upward motion of the thermocline associated with the internal tide (Figure 5B). The vertical profiles of N^2 and the corresponding VBSC at the time of the peaks indicated higher values if VBSC along the bottom layer. There was well defined stratification (higher N^2) at peak 5, inexistent at peak 6, weaker on peak 7 and relatively broad during 8 (Figure 7). The time series of VBSC associated with peak 5 is very similar to that the resulted predicted by from a two-dimensional, nonlinear and non-hydrostatic numerical simulation of internal wave activity [4].

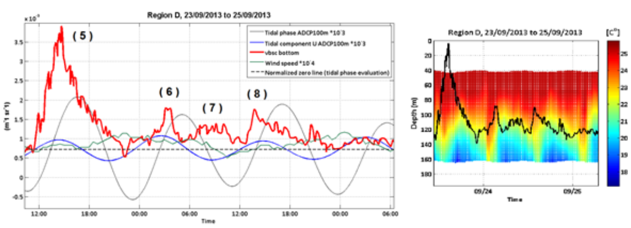

Figure 5: (A) Time series of tidal height; cross-slope velocity; VBSC within the BBL; wind speed at Region D from 23-25 September; (B) time series of VBSC along the BBL overlain on the temperature record at ADCP200m.

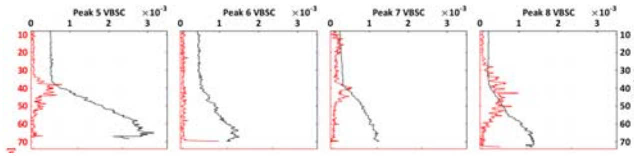

Figure 6: Vertical profiles of N^2 (red) and VBSC (black) corresponding to peaks 5-8 in Figure 5A.

Region E

Region E is the section of the deployment in deeper water and begins seaward of the mini-shelf break and extends to the end of the deployment, from September 25th to 27th. In contrast to other Regions, here the water depth was increasing with time (from ~100m to >200m; Figure 3). Large vertical excursions in the pycnocline were a distinct feature in this region as revealed by the moored thermistor and the ocean glider data (Figures 2 and 3A-C). Maximum vertical differences in temperature and salinity (8.3^o Celsius and 1.0 respectively) as well as the maximum vertical excursion of the pycnocline (> 100m) were observed in this region (Figures 3A-C). In this region, peaks in VBSC were not related to the maxima in flood/ebb tidal velocities as observed in regions B and D. Another feature is that the VBSC decreases after peak 12, corresponding to a water depths >130m and remain low until the end, even though there were large vertical excursions in temperature (Figure 7B). This could be due to the fact that the nature of the bottom sediment characteristics were changing as the depth increases. Another feature in this region is the large variability in N^2 in water depths >50 m (Figure 8). Vertical profiles obtained from the glider, reached maxima of 0.20 ms^{-1} and indicated that: (1) the vertical velocity derived from the glider movement consisted of strong upward and downward movement over distances of tens of meters (Figure 9). These velocity changes occurred over a period of ~12 minutes, the mean time for a glider downcast. The velocity reversals were related to changes in N^2 as well as the vertical temperature profile (Figure 9). Velocity profiles in other regions indicated small oscillations around zero through the whole water column (not shown); (2) negative values of N^2 occurred often, indicating instabilities within in the water column [7].

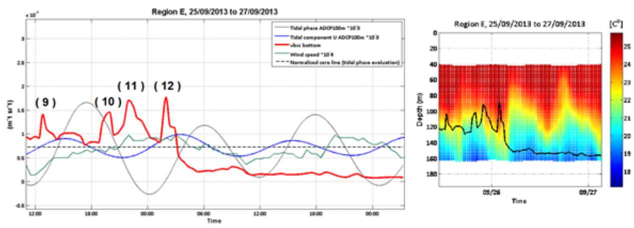

Figure 7: As Figure 5 but for Region E.

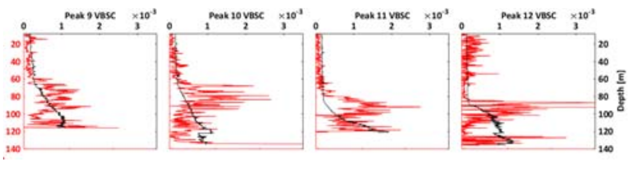

Figure 8: As Figure 6 but for Region E, VBSC peaks 9-12.

Discussion and Conclusions

Sediment re-suspension events on the continental shelf off Pilbara were examined using an ocean glider transect and moored instruments. Tidal action was the main background forcing for the re-suspension events with near bed gravity currents (DSWC) and internal wave activity also being contributing factors. Gravity currents result from a cross-shelf density gradient driven by cooling and evaporation and is clearly identified from the salinity distribution. Across the continental shelf, 5 distinct regions, defined by the stratification of the water column were identified and the processes that contributed to re-suspension events were different. In the shallower water and during periods of high wind forcing the water column was vertically mixed and no re-suspension events are identified. In two regions of the water column that were vertically stratified the re-suspension events were related to maximum flood/ebb tidal currents. In deeper water (> 120m) the sediment re-suspension events were related to vortex shedding associated with internal wave action.

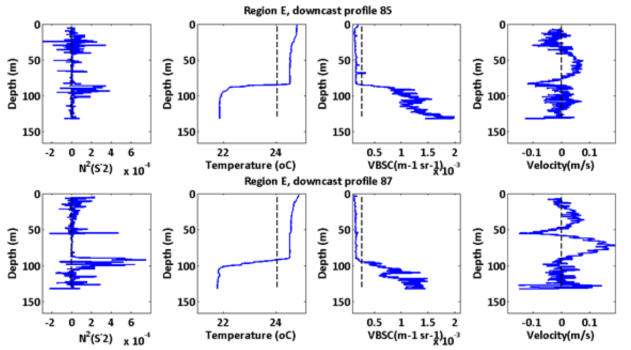

Figure 9: Vertical profiles of N^2, temperature, VBSC and vertical glider velocity in Region E.

Acknowledgments

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