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Dense Shelf Water Cascades along the North-West Australian Continental Shelf

T. Mahjabin[1], M.H. Bahmanpour[1], C. Pattiaratchi[1], Y. Hetzel[1], E.M.S Wijeratne[1] and C. Steinberg[2]

[1]School of Civil, Environmental and Mining Engineering & The UWA Oceans Institute
The University of Western Australia, Perth, Western Australia 6009, Australia

[2]Australian Institute of Marine Science
Townsville, Queensland 4810, Australia

Abstract

High evaporation during the summer and cooling during winter along the coastal regions of the Australian north-west shelf (NWS) results in a cross-shelf density gradient. This drives a gravitational circulation with the offshore transport of higher density water along the sea bed, defined as Dense Shelf Water Cascades (DSWC). Ocean glider data available from the Integrated Marine Observing System (IMOS) were used to measure cross-shelf density gradients under varying wind and tide conditions along the Kimberley and Pilbara regions of the North-West Australian shelf. Analysis of 41 transects from 26 missions of high spatial and temporal resolution data collected between 2011 and 2015 confirmed that DSWC occur on a regular basis during the winter months, mainly due to cooling of the coastal waters that were pre-conditioned with higher salinity resulting from evaporation during the summer months. The cross-shelf transects indicated that both temperature and salinity contributed to the dense water formation. The dense water flow along the sea bed was identified to depths of up to 150m. The strongest density gradient calculated in the Kimberley was 5.123 × 10^{-6} kgm^{-4}, whilst for Pilbara it was 14.23 × 10^{-6} kgm^{-4}. The temporal variability and controlling mechanisms of the DSWC were investigated using data from current meter moorings deployed on shelf regions of the Kimberley and Pilbara. Although these two regions are macro-tidal and are subject to wind mixing, the vertical temperature stratification and monthly mean cross-shore velocity profiles indicated the presence of cascades during winter months. It is shown that even in the presence of high tidal mixing DSWCs persist due to the strength of the cross-shelf density gradient.

Introduction

Dense Shelf Water Cascades (DSWC) have important ecological and biological implications in Australian Waters. Cascades help to transport nearshore water and dissolved and suspended material (e.g., terrestrial carbon, nutrients, larvae, low-oxygen water, sediments, pollutants etc.) off the continental shelves. Australia has a high rate of evaporation, around 2.5 m per year [15] with less rainfall and river run-off that generally results in coastal waters having higher salinity than offshore. Along the majority of Australian shallow coastal regions, summer evaporation leaves the shallow coastal waters more saline and subsequently in autumn and winter the nearshore waters become cooler due to heat loss by convection [7]. In combination, strong horizontal density gradients develop with density increasing from the ocean towards the coast. This causes the formation of buoyancy driven gravity currents named Dense Shelf Water Cascades that flow offshore along the sea bed [4, 10, 13, 14]. DSWC are controlled by vertical mixing resulting from either wind mixing and/or tidal mixing [5, 10]. When wind and tidal mixing are weak either a bottom gravity current or surface plume will form and when vertical mixing is strong the water column will be well mixed [7]. The balance between the major destratifying and stratifying influences neglecting air-sea exchanges can be expressed as [8]:

$$\underbrace{\frac{4\varepsilon k_D\rho}{3\pi}\frac{\boldsymbol{u_b}^3}{h}}_{Tidalmixing} + \underbrace{\delta k_S\rho_a\frac{\boldsymbol{W}^3}{h}}_{Windmixing} = \underbrace{\frac{1}{320}\frac{g^2h^4}{\rho K_{mz}}\left(\frac{\boldsymbol{\partial\rho}}{\boldsymbol{\partial x}}\right)^2}_{Gravitational\ circulation} \qquad (1)$$

Where, h is the mean water depth; ρ_a is the air density; ρ the mean seawater density; k_D drag coefficient for bottom stresses; ε is tidal mixing efficiency; δ the wind mixing efficiency; u_b is near-bed tidal velocity; W is the wind speed; K_{mz} is the vertical eddy diffusivity; and, k_S is the drag coefficient for surface wind stress.

For a particular water depth h, when the gravitational circulation term (RHS of equation (1)) is higher than the combined wind and tidal mixing terms (LHS of equation (1)), the water column is vertical stratified allows for the formation of DSWC. Equation (1) implies that when the horizontal density gradient (dρ/dx) is higher and is able to overcome vertical mixing through tidal and wind action, DWSC can occur. In contrast if the action of tidal and/or wind induced vertical mixing is relatively higher (i.e., higher values of $\boldsymbol{u_b}$ and/or W) the water column is vertically mixed thus inhibiting the formation of DSWC even in the presence of a horizontal density gradient.

This study is based on field measurements obtained from the inner continental shelves of the Australian North-West Shelf specifically in Kimberley and Pilbara regions. Although both regions consists of a very high tidal range (up to 10 m) (Figure 1) and thus are subject to high tidal mixing. DSWC were identified on the inner continental shelves particularly during the winter months. DSWC have previously been identified in the Kimberley region through examination of the oceanic response to large outgoing heat and freshwater fluxes using data collected on research cruises and moored instrument deployments for individual events in a single season [3, 14]. DSWCs have also been identified in other locations around Australia [7]: Shark Bay [9]; Great Australian Bight [11]; Spencer Gulf [2]; and, the Rottnest continental shelf [10]. However, none of these studies focused on the seasonality of DSWC formation, which we considered in this work.

We used data from ocean gliders (41 transects from 26 missions) and mooring data deployed along the North-West Australian Shelf over the past six years (2010-2015) to identify the temporal variability and controlling mechanisms of the DSWC. All data are available through the Integrated Marine Observing System

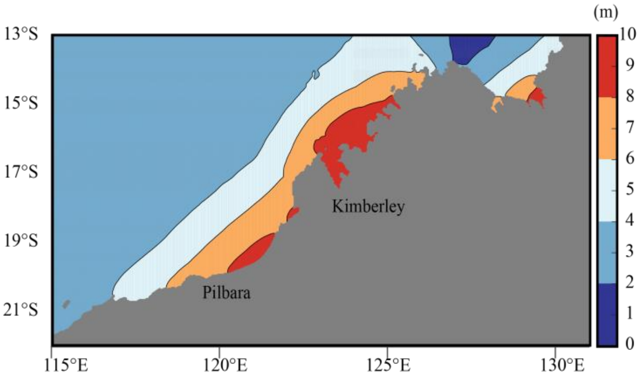

Figure 1: Tidal range in Kimberley and Pilbara regions of the Australian North-West shelf.

(IMOS). The ocean glider data (temperature, salinity, density, fluorescence, sediment and oxygen) are operated by the Australian National Facility for Ocean Gliders (ANFOG) located at the University of Western Australia. Mooring arrays are maintained under the Australian National Mooring Network (ANMN) and provide observations of physical and biological parameters including: temperature, salinity, sea level, currents, turbidity, and chlorophyll.

Methods

Both the Kimberley and Pilbara regions in north-west Australia are macro-tidal with moderate wind forcing during the winter months [6,14]. Seasonal variations in DSWC were expected mostly to be affected by the relative balance between the cross shelf density gradient and the strength of vertical mixing generated through tidal and wind action. To identify when and under what conditions DSWC events occurred, individual events were identified through analysis of cross shelf density profiles recorded by ocean gliders adjacent to two mooring sites. The mooring data, which consisted of multi-year velocity profile time series, were then analysed to determine the temporal variability in more detail. Wind data from nearby weather stations and satellite sea surface temperature (SST) data were also used to determine conditions required for DSWC formation.

Glider Data

To study this region, we used Teledyne Webb Research Slocum Electric Glider [12] data for high spatial and temporal resolution vertical profiles of temperature, salinity and density. The data are publicly available through the Integrated Marine Observing System (IMOS). Slocum gliders measure data at 2Hz from the surface to within 5 m above the seabed up to a depth of 200 m with mean horizontal speed of 25 km per day [12]. Gliders traverse a saw-tooth pattern using buoyancy control whilst moving forward to the target destination and navigating to a series of pre-programmed waypoints using GPS, internal dead reckoning and altimeter measurements. A Seabird-CTD, Chlorophyll-a fluorescence measuring sensor, coloured dissolved organic matter (CDOM) sensor, 660 nm Backscatter WETLabs BBFL2SLO optical sensor and an Aanderaa Oxygen Optode were attached to the ocean glider for this study. Slocum Gliders are small in size (1.8 m), efficient and economical to sample for much longer periods and higher spatial resolution compared to ships.

For this study, 41 transects from 26 glider missions for the Kimberley and Pilbara collected over the period 2011 to 2015 were analysed. This included a total of 105006 vertical profiles and over 29 million data points. The data included a range of varying tide and wind conditions. The data analyses was designed to identify the presence of DSWC and the effects of wind and tide on the formation of gravity currents. Quality control of the data were undertaken subsequent to the recovery of each glider and then the vehicle trajectory was transposed onto the Pilbara transects as a straight line. Each variable was interpolated onto a grid with vertical and horizontal resolution of specific time and depth respectively. Horizontal density gradients were calculated by subtracting the depth-mean density of a point at the seaward end of the transect from the depth-mean density at a point closest to the coast and dividing by the distance between the two points. The resulting density gradient was positive when the nearshore waters were denser than offshore waters.

Mooring Data

Vertical velocity profiles were obtained through a series of moorings as part of Australian National Mooring Network (ANMN) off North-Western Australia. Moorings consisted of a bottom mounted upward-looking ADCP located several meters over the period 2012-2014. Stations K1 and P1 are located at 55 m depth and have measured the horizontal velocity profile at 10 min intervals (Figure 2). Cross-shelf velocity profiles for K1 and P1 were obtained by rotating the eastward (u) and northward (v) velocities to their respective depth-mean major and minor axes of variance. To obtain monthly averages, velocities were first decimated to hourly values and then low-pass filtered with cut-off frequency of 48 hr. Velocity measurements were then sub-sampled to calculate monthly means.

Results

Kimberley and Pilbara, both in the North-West Australian shelf, had deployments of several glider missions coincident with the ADCP mooring data (Figure 2). A typical sea surface temperature image during the winter indicates a band of cooler water along the coast (Figure 2). The cooler dense water near the coast results in a positive cross-shelf horizontal density gradient driving the DSWC (Figures 3c, 4c). Both regions experience a large tidal range with Kimberley tidal range on the order of 7-10 m and the Pilbara 4-5 m [7]. The observed mean wind speeds in the Kimberley and Pilbara are between 3.5 and 4 m/s [7].

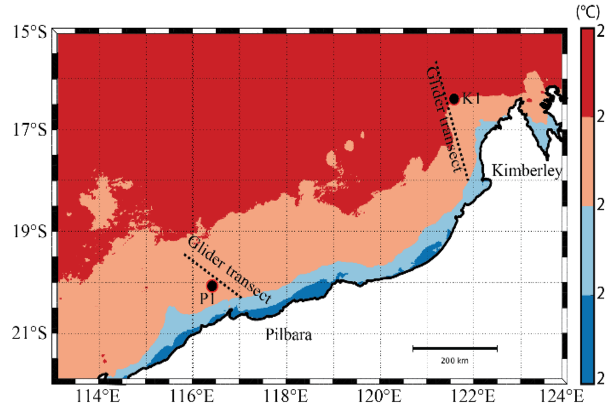

Figure 2: Locations of the Kimberley and Pilbara Glider transects and moorings (K1 and P1) overlaid on Modis SST data during winter.

Seasonal changes along the inner continental shelves of these regions were investigated using the ocean glider observations and the presence of DSWCs were confirmed during the winter months (Figure 3 and 4).

Because of the high evaporation during the summer and cooling during winter along these coastal regions (data not shown), the cross-shelf density gradient became the dominant force for DSWC formation during winter. The density gradient in the Kimberley during winter was 5.123×10^{-6} kgm^{-4} (Figure 3c), whereas for Pilbara it was 14.23×10^{-6} kgm^{-4} (Figure 4c). When the cross-shelf density gradient was weak or sometimes even negative in summer, autumn and spring seasons DSWC was not

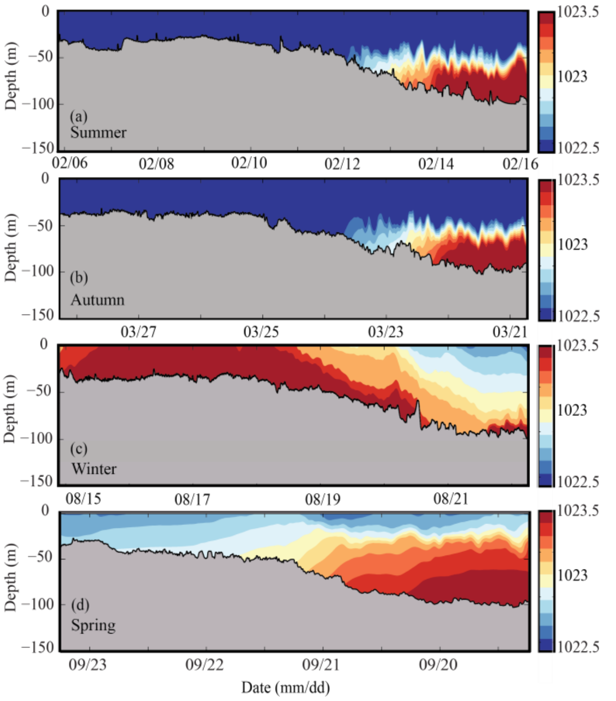

Figure 3: Cross-shelf density profiles showing the seasonality of DSWC formation along the Kimberley coast represents the presence of DSWC in winter. All profiles are in same density range and plotted according to date (month/day) along the x-axis in (a) 2014, (b) 2015, (c) 2014 and, (d) 2012 respectively.

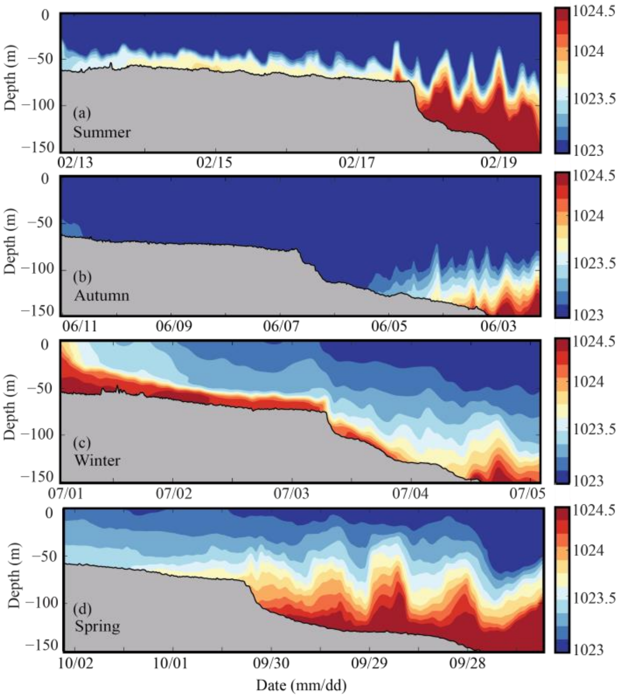

Figure 4: Cross-shelf density profiles showing the seasonality of DSWC formation along the Pilbara coast represents the presence of DSWC in winter. All profiles are in same density range and plotted according to date (month/day) along the x-axis in (a) 2014, (b) 2014, (c) 2012 and, (d) 2014 respectively.

present (e.g. Figures 3 a,b,d and 4 a,b,d). During these months, the nearshore regions were mostly vertically mixed as the density gradient was weak to overcome the mixing generated by tidal and wind induced vertical mixing. In winter, DSWCs spread across the entire shelf as well as onto the slope and the shelf became vertically stratified with colder, more saline water along the sea bed.

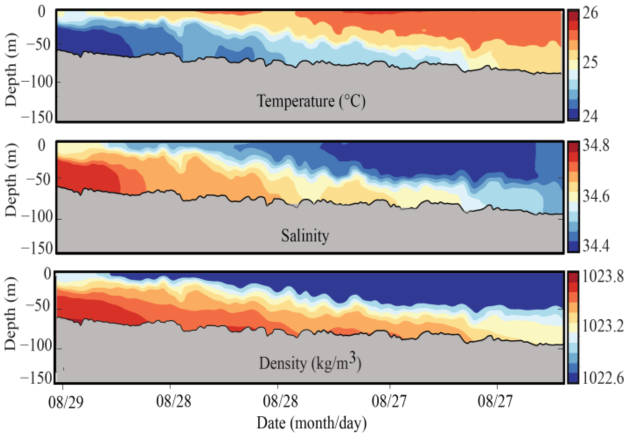

Figure 5: Cross-shelf profile of DSWC as measured by Slocum glider on the Kimberley coast during August 2014.

Cross-shelf transects for Kimberley and Pilbara indicated that both temperature and salinity contributed to the dense water formation (Figures 5 and 6). The dense water flowing offshore along the sea bed may be identified to depths of up to 100m for the Kimberley and up to 150m for the Pilbara region. These DSWC were observed in the Kimberley during August 2014 (Figure 5) and in the Pilbara during July 2012 (Figure 6), when higher salinity water was present near the coast due to summer evaporation and subsequently the water was cooled down and the cross-shelf gradient became sufficiently strong to establish the gravity current.

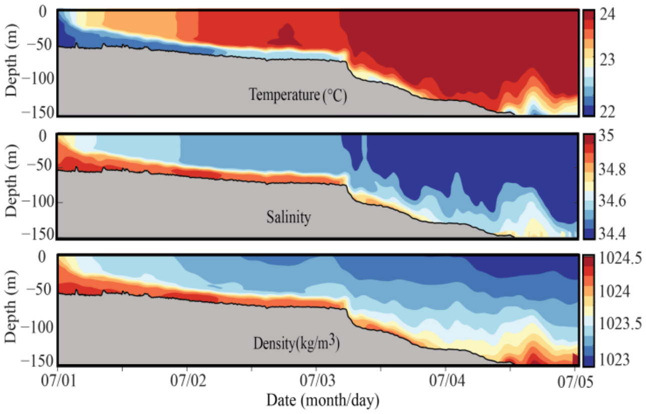

Figure 6: Cross-shelf profile of DSWC as measured by Slocum glider on the Pilbara coast during August 2014.

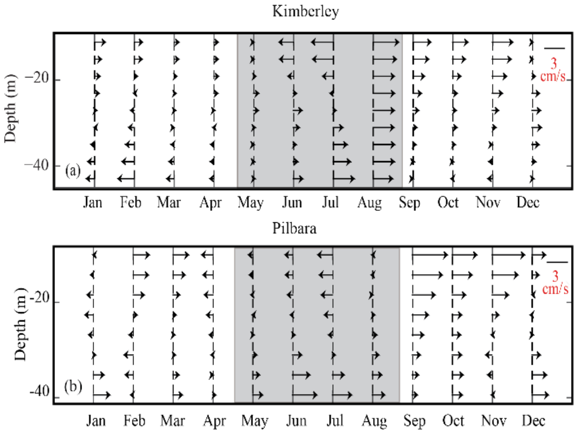

Figure 7: Vertical profiles of cross-shore velocities, averaged over three years (2012~2014) from two ADCP moorings in the (a) Kimberley and (b) Pilbara. Offshore direction is positive in both cases.

The monthly mean cross-shore component of velocity in both Pilbara and Kimberley indicated positive (offshore) flow near the sea bed in Jun~Aug (Figure 7a, 7b) with return flow at the surface. Offshore velocities in this period were ~3 cm/s near the bottom and were positive throughout the water column in August in the Kimberley region. The same feature was evident in Glider data in August (Figure 5). The two layer flow structure developed in May and ended in August corresponding to the time when convective cooling had a maximum effect on the water column structure, evident in the glider data (Figure 3c and 4c). In June-August winds in the region are often upwelling favourable and generally oppose the formation of DSWC. However, the cooling effect appeared to be sufficiently strong to overcome the effects majority of the time.

Discussion

Analysis of 41 transects from 26 glider missions for the Kimberley and Pilbara regions over the period 2011 to 2015 confirmed that DSWCs were a common occurrence in winter seasons, even under strong tide and wind conditions. Moored ADCP current velocity profiles during 2012 to 2014 also verified the seasonal variability of cascade formation, with mean two layer flow structure evident during the winter months resulting in the offshore transport of water along the sea bed. Data suggested that only during May~August, the density gradient become strong enough to compete against vertical mixing energy. Cascades were observed to occur in this period with velocities between 2~3 cm/s in the Kimberley and Pilbara regions [1]. DSWC have been documented previously for a single season in North-west Australian shelf [3, 14] but here several years of glider and ADCP data allowed us to observe the seasonality of cascade formation for both regions. Results indicated that even in the presence of high tidal mixing DSWC can persist due to the strength of the cross-shelf density gradient during winter, whilst they do not generally occur during other seasons when the gradient is weak or reversed.

Conclusions

The broad range of ocean glider data from IMOS and several years of mooring deployments from ANMN present a unique opportunity to examine DSWC in different coastal regions. In this study, we focused on the Kimberley and Pilbara regions along North-west Australian shelves. Due to high evaporation in summer, the nearshore water becomes more saline. In winter, this water is cooled at the surface, becoming denser and contributing to the formation of strong positive horizontal density gradients, which leads to DSWC formation over the continental shelf and the slope. Tide and wind have the capability to mix the shallower water column, when the density gradient is weak. In general, during winter the cross-shelf density gradient remains positive and dominates over mixing in both the Kimberley and Pilbara, despite relatively strong tides and winds.

Acknowledgments

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