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The Effects of Wind Forcing on Surface Currents on the Continental Shelf Surrounding Rottnest Island

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***Abstract*—**Surface currents play a major role in the distribution of contaminants, the connectivity of marine populations, and can influence the vertical and horizontal distribution of nutrients within the water column. This paper aims to determine the effects of sea breeze-wind patterns on the climatology of the surface currents on the continental shelf surrounding Rottnest Island, WA Australia. The alternating wind patterns allow for full cyclic rotations of wind direction, permitting the interpretation of the effect of the wind on the surface currents. It was found that the surface currents only clearly follow the northbound Capes Current in times when the Fremantle Doctor sets in. Surface currents react within an hour to a change of direction of the wind, allowing southerly currents to dominate during strong northerly sea breezes, often followed by mixed currents dominated by eddies in the inter-lying times.

***Keywords*—**HF radar, surface currents, sea breeze.

I. Introduction

OCEAN currents determine the movement of surface waters, so the ability to collect data on their direction and speed provides critical information to support pollutant tracking, search and rescue, harmful algal bloom monitoring, navigation, and ecosystem assessment. At present, ocean current measurements are not as readily available as winds, in large part due to the expense and difficulty of measuring ocean currents. Drifters have found to be influenced by the wind itself in addition to the surface currents, resulting in partially biased measurements. However, the use of High Frequency (HF) Radar systems allows us to overcome these difficulties and provide maps of surface currents over a large surface area. With data acquired using HF radars, which have been set up at two locations on the coast of WA (Turquoise Coast and Rottnest Shelf), a detailed analysis of the surface currents will be possible. Oceanic surface currents have been studied at scales of 10km – basin scale as well as 10m down to dissipation scale, however not abundantly within the mesoscale and less even within the sub-mesoscale. This study will take the next step in utilizing HF radar data to create a detailed analysis of the surface currents along the coast of South-west WA within the size range of 200m up to 2km. The resulting findings will increase the knowledge on the response of surface currents and eddies to wind forcing and may hence aid in the forecasting of predicting of surface currents and eddies along the coast of Western Australia. Eddies and surface currents play an extensive role in surface transport, ocean mixing, which again effects nutrient transport and connectivity of reefs and fish populations. They also reflect largely on the transfer of energy between the wind field and the upper ocean, which again will allow for an interpretation of divergence and vorticity within the water column.

Consistent, diurnal sea breeze activity occurs along two thirds of the world's coastline, especially in the tropics and subtropics [7]. Strong sea breezes have been shown to support the creation of sea breeze wave-driven nearshore currents and can lead to an increase in the mean longshore current from <0.05ms^{-1} to 1.0ms^{-1} [10]. Perth is affected by one of the strongest and most consistent sea breeze systems on earth with ~200 sea breezes annually (nearly daily during the summer months). The sea breeze in southwestern Australia differs from the 'typical' shore-normal sea breeze as it typically blows parallel (north-south) to the shore due to the interactions between the breeze and geostrophic winds from the synoptic weather patterns [8]. The sea breeze starts at 13:45 hr and blows until 20:45 hr with an average mid-afternoon velocity of 5.7 ms^{-1}[8], although Pattiaratchi et al. (1997) [10] found that velocities of 10 ms^{-1} can occur in the summer months of January and February. The Perth land breeze that occurs at night typically has speeds of less than 5 ms^{-1}. At the onset of the sea breeze, the wind direction changes rapidly from an easterly to a southerly direction and is associated with a rapid increase in velocity [7]. Inman and Filloux (1960) [5] noted that at most locations worldwide the effect of the sea breeze is usually masked by high wave energy, large tidal ranges and phase-coupling between the diurnal sea breeze and semi diurnal tide. This makes the study of the sea breeze effects especially relevant in low energy, microtidal coastlines such as Perth.

Previous findings such as by Rosenfleld (1988) have shown diurnal currents to be strongly surface intensified due to diurnal period wind stresses. Diurnal sea breezes have however been found to both support as well as inhibit the formation of eddies [13], [4]. Whether or not the eddies in the Perth coastal region are supported or inhibited by the local sea breeze will be determined in this study.

The ocean currents along WA's coast are ruled by the southbound Leeuwin Current and its counter current, the Capes Current, which occurs closer to shore during the austral summer (Fig. 1).

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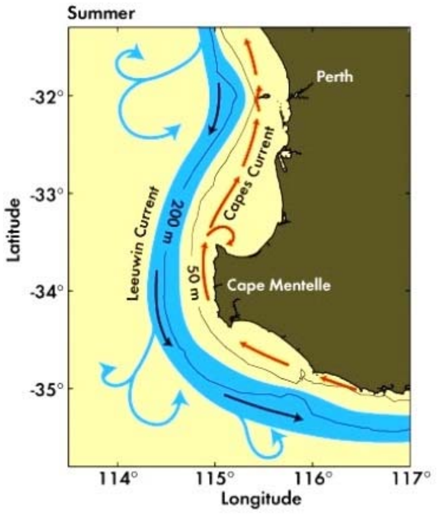

Fig. 1 Map depicting the seasonally dominating ocean currents along the coast of Western Australia

Previous studies such as by Feng et al, 2003 [1] and Pearce, 1991 [11], show the Leeuwin Current to be strongest in June and July, decreasing in volume over the austral summer months during which it is accompanied by the Capes Current.

Surface currents are defined to be the dominating currents within the top 1m of the water column and can differ significantly from the general direction of largescale currents at times. There are three general classes of surface currents which can be described by cause: related to seawater density gradients (including gradient currents), wind-driven currents (directly produced by wind stress on ocean surface, frequently resulting in inertial oscillations (Pollard, Millard, 1970)), long-wave induced currents [2]. The methods used to measure these surface currents are typically drifting buoys, moored buoys, measured ship drift and satellite pattern tracking (which usually follows the sea surface temperature). However, these measuring techniques have proven to have several faults, such as uneven drift characteristics (drogues), no agreed standard of measurement (ship drift), and no spatial representation of measured currents (moored buoys). HF radars on the other hand offer both spatial and temporal measurements of surface currents in high resolution of detail of direction, allowing for the differentiation of eddies, large and small scale surface current patterns. HF radars can also measure wave height and wind direction by utilizing the second order spectrum peaks. Previous studies have allowed for comparisons of the Rottnest Shelf HF radar currents and the ADCP data from the ANMN to be compared and showed high correlation, leading to the justified assumption that the collected data is a good representation of actual currents.

HF radars gain their data using the Doppler Effect, comparing the frequency of transmitted and received radar signals. Frequencies of 7MHz to 50MHz are applied depending on the wished range of data to be collected. Lower frequencies will allow for greater ranges (up to 200km) yet less spatial resolution [3]. Fig. 2 (modified figure based on [9]) depicts the principles of this procedure, giving examples for advancing waves both with and without underlying currents.

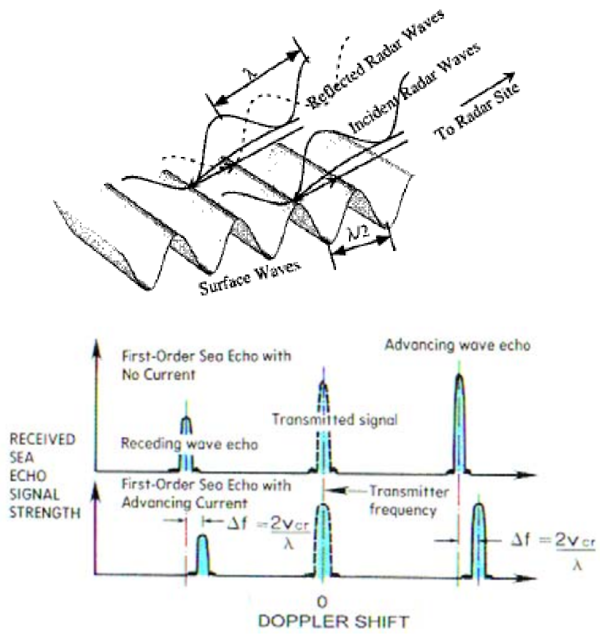

Fig. 2 Principle functionality of HF radars (Adapted from [9])

II. Methods

Data have been collected at the Rottnest Island region from March 2009 till present, allowing for a total of approximately two years of data to be analysed. The set up of the HF radars has been calculated to allow for the highest amount of GDOP (geometric dilution of precision) points.

The precise positioning of the radars is extremely important as a high number of QC (quality controlled) data is required in order to achieve a detailed velocity field (Fig. 3).

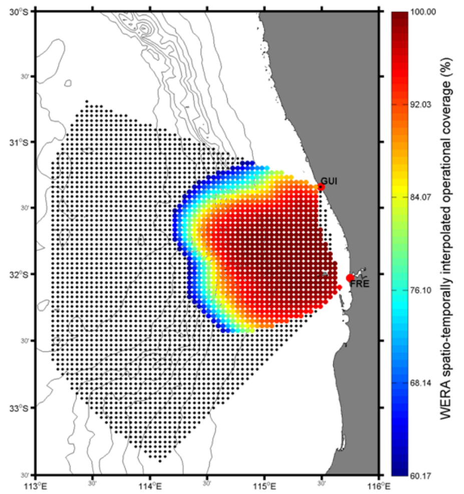

Fig. 3 Number of GDOP points (710, coloured) and total available points (1369, black) covering the Rottnest Island region

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Data was loaded and analysed using Matlab, focusing on the variation of current direction and strength in response to the sea breeze by subtracting the overall average daily flow and tidal movement, suggesting the residuals to be wind-induced surface currents.

Special attention was rendered to the time period from 03 March 2010 to 21 March 2010 as it offered alternating sea breeze patterns (Fig. 4). This made it possible to analyse the exact impact of the sea breeze in its cyclic and non-cyclic patterns on the surface currents of the affected are in the

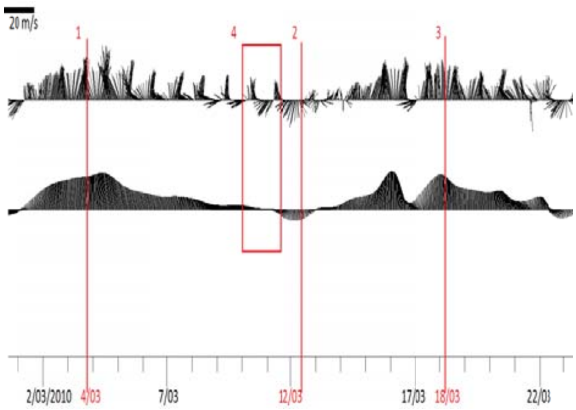


Fig. 4 Wind vector measured on Rottnest Island. Three wind incidents (04 March, 12 March and 18 March, 2010) are marked by a red solid line and numbered respectively

Rottnest Island region (by specifically analyzing the currents at the times 1, 2 and 3). During the sea breeze of altering directions (4), the overall average of wind cancels out and affectively equals 0 m/s.

III. Results

Periods 1 and 3 showed northerly flow with eddies occurring randomly throughout the region (Fig. 5 and 7).

Period 2 was dominated by a southerly current, showing similar velocities throughout the majority of the region, most of weaker velocity than those found in periods 1 and 3 (Fig. 6).

The 24 hour period of period 4 expressed a full cyclic rotation of the surface currents, corresponding to the direction of winds throughout this period (Fig. 4). There were several mesoscale eddies found in the early morning hours, leading up to noon at which point southbound currents began to form due to the lack of the insetting of the south-westerly Fremantle Doctor. By 3pm the southerly currents dominated the region, heading slightly westwards in some areas. As the sea breeze died down, the surface currents turned north-westerly, again corresponding to the wind pattern, and eventually fell back into the eddie-strewn, northerly flow pattern as the southerly winds picked up again and dominated over night.

Period 1:

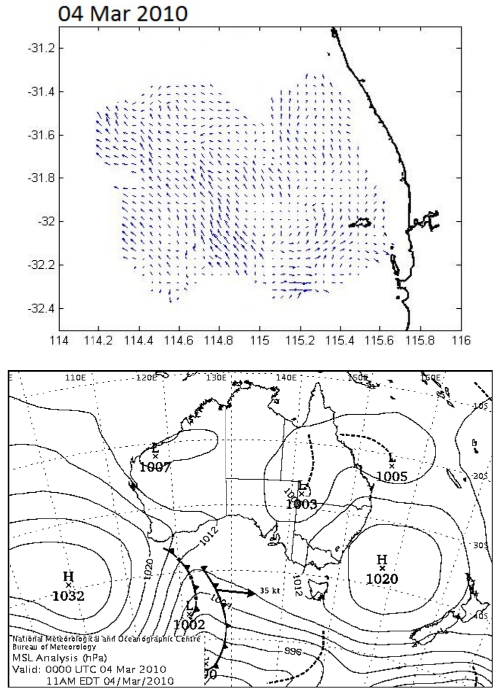


Fig. 5 Top: Wind induced currents during a period of non-cyclic sea breeze patterns
Bottom: Synoptic map of Australia depicting an incoming high pressure system, the low trough east of the WA coast

Period 2:

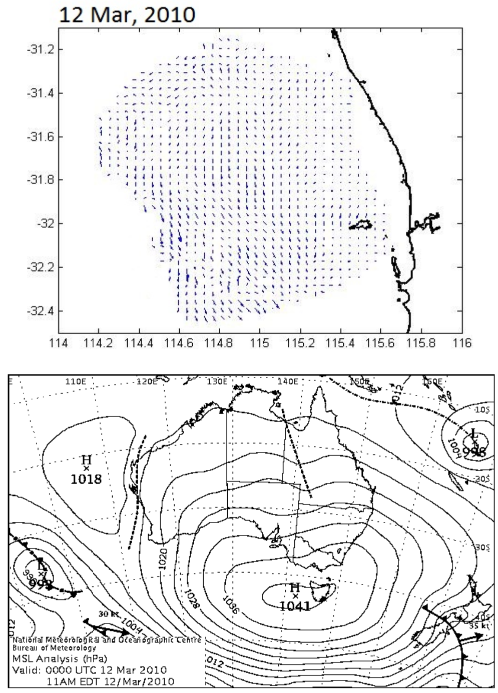
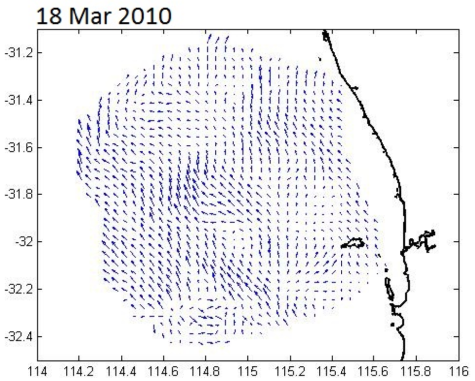


Fig. 6 Top: Wind induced currents during a period of cyclic sea breeze patterns
Bottom: Synoptic map of Australia depicting an incoming high pressure system, the low trough west of the WA coast

Period 3:



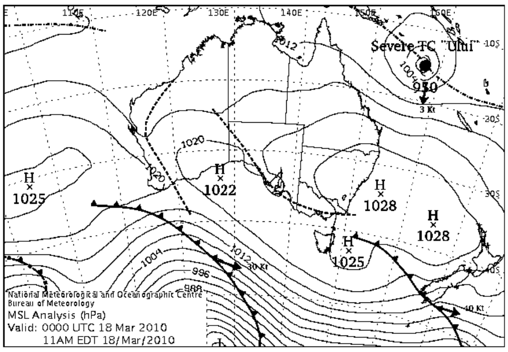
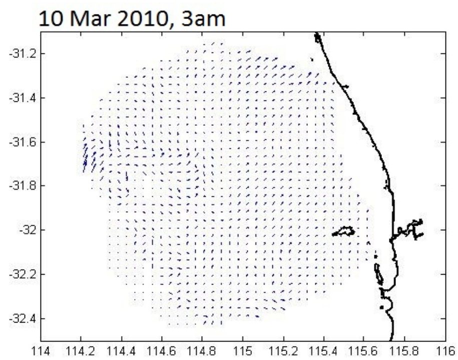
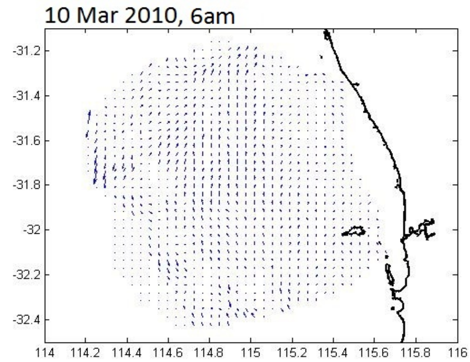
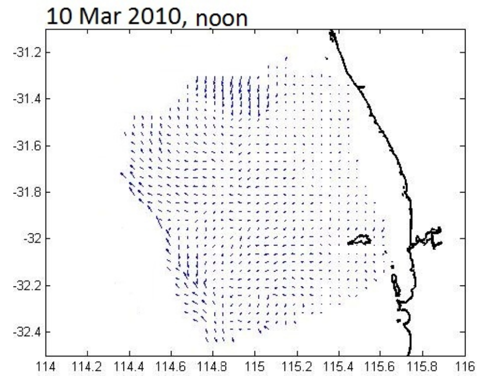


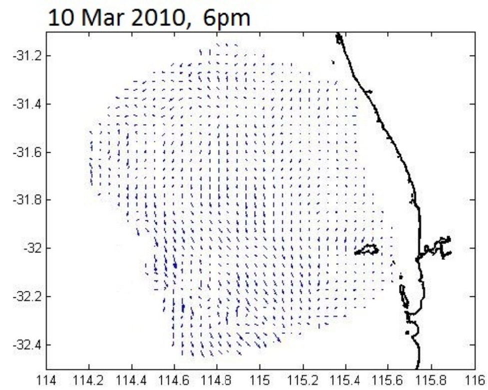
Fig. 7 Top: Wind induced currents during a period of non-cyclic sea breeze patterns
Bottom: Synoptic map of Australia depicting a passing high, the low trough east of the WA coast

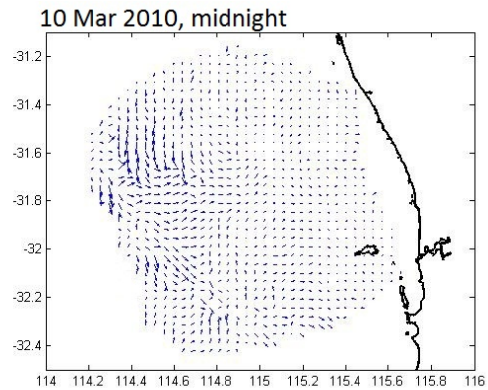
Period 4:











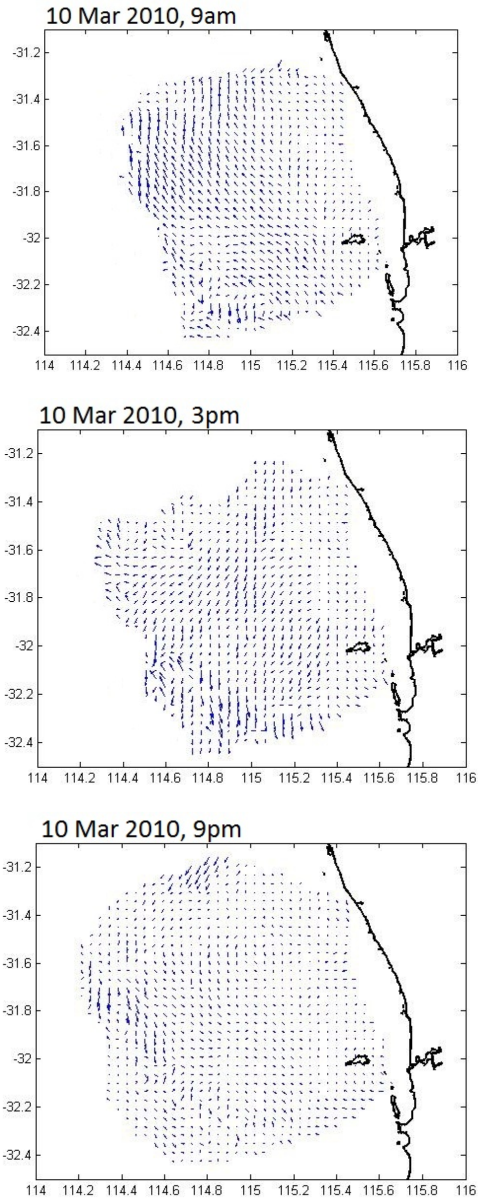


Fig. 8 8 consecutive figures depicting the wind induced surface currents of the Rottnest Island region in 3 hourly steps

IV. Discussion

It was found that the surface currents of the Rottnest Island region are strongly imposed upon by the daily sea breeze. During periods of strong southerly winds, such as periods 1 and 3, the Capes Current is easily recognizable within the surface currents. The general direction of flow is northwards, coinciding with the Capes Current, yet also allowing for the formation of eddies at the surface of the water column. When the so-called Fremantle Doctor does not set in however, the surface currents undergo complete cyclic rotations, allowing for a southward flow in the late afternoon and northerly flow over night as seen in the 24-hour period 4. This proves the intensity of effect that the wind has upon the surface currents in this region, allowing for a complete reversal of flow direction.

The formation of eddies could aid in the vertical mixing of sea water, altering the depth of the mixed layer [12]. This could lead to potential upwelling, vertical and horizontal transport of nutrients as well as contaminant distribution.

It has been found that the population genetic structure of marine populations, for example fish, coral or mollusks, is not necessarily dependent on physical distance but more so on the climatology of the surface currents [15]. Circuitous currents, such as eddies, can prevent mixing and diffusion of pelagic larvae, prohibiting pelagic larval dispersal from Euclidean distance [14]. Near sites may never mix whilst distant sites may be strongly connected by a current, implementing strong genetic resemblances amongst the populations. In order to ensure the sustainability of marine populations along the coast, fisheries must be aware of the ongoing movement of the surface currents in order to account for larval distribution and hence population connectivity [6]. The results show that northbound transport of larvae will only occur during sea breeze events originating from the south-west, allowing the Capes Current to travel northwards along the coast. During periods of strong northerly winds however, the frequency of eddie occurrences increases, inhibiting the distant transport of larvae (and/or nutrients and pollutants) up the coast, but rather capturing them within the region or even allowing for a southerly distribution (Fig. 5 and 7).

Further investigation shall be undertaken to determine the significance of wind strength and bathymetry of the underlying region on the formation, duration and vorticity of sub-mesoscale eddies.

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