ARTICLE IN PRESS
MPB-07247; No of Pages 9
Marine Pollution Bulletin xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Marine Pollution Bulletin
journal homepage: www.elsevier.com/locate/marpolbul

Note

The influence of extreme winds on coastal oceanography and its implications for coral population connectivity in the southern Arabian Gulf

Geórgenes H. Cavalcante [a,*], David A. Feary [b], John A. Burt [c]

[a] Instituto de Ciências Atmosféricas, Universidade Federal de Alagoas, Maceió, AL CEP: 57072-970, Brazil
[b] School of Life Sciences, University of Nottingham, NG7 2RD, United Kingdom
[c] Center for Genomics and Systems Biology, New York University Abu Dhabi, PO Box 129188, Abu Dhabi, United Arab Emirates

ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form 3 October 2015
Accepted 16 October 2015
Available online xxxx

Keywords:
Persian Gulf
Arabian Gulf
Shamal
Wind
Eddy
Connectivity

ABSTRACT

Using long-term oceanographic surveys and a 3-D hydrodynamic model we show that localized peak winds (known as shamals) cause fluctuation in water current speed and direction, and substantial oscillations in sea-bottom salinity and temperature in the southern Persian/Arabian Gulf. Results also demonstrate that short-term shamal winds have substantial impacts on oceanographic processes along the southern Persian/Arabian Gulf coastline, resulting in formation of large-scale (52 km diameter) eddies extending from the coast of the United Arab Emirates (UAE) to areas near the off-shore islands of Iran. Such eddies likely play an important role in transporting larvae from well-developed reefs of the off-shore islands to the degraded reef systems of the southern Persian/Arabian Gulf, potentially maintaining genetic and ecological connectivity of these geographically distant populations and enabling enhanced recovery of degraded coral communities in the UAE.

1. Introduction

The Persian/Arabian Gulf (hereafter termed the “Gulf”) is a shallow, semi-enclosed marginal sea connected to the northern Indian Ocean through the narrow Straits of Hormuz (Chao et al., 1992; Sheppard et al., 1988; Yao and Johns, 2010). Although the oceanography of this region is relatively similar to enclosed basins in other semiarid environments (e.g. Red Sea and Mediterranean Sea), (Yao and Johns, 2010), there is still little understanding of the dynamic response to strong synoptic wind events on circulation and internal mixing within this region. A particular feature of this sea is its shallow nature, which drives much of the current velocity and direction (Thoppil and Hogan, 2010a,b). The Gulf bathymetry is shallow and narrow, with an average depth (asymmetric along its axis) of 36 m, and an average width of 200 km (Emery, 1956; Kämpf and Sadrinasab, 2006). Due to this relatively restricted seafloor bathymetry, large-scale oceanographic circulation within the Gulf is primarily driven by seasonally varying surface heat flux, fresh water flux and wind stress (Reynolds, 1993; Swift and Bower, 2003; Kämpf and Sadrinasab, 2006). Although all three mechanisms are important in controlling circulation within the Gulf, fluctuations in wind stress have been regarded as the predominant mechanism structuring circulation in this system (Yao and Johns, 2010; Thoppil and Hogan, 2010a,b). Wind stress at a Gulf-wide level is predominantly associated with northwesterly low-pressure frontal systems (Perrone, 1979; El-Sabh and Murty, 1989; Shahin, 2007), which can generate storm surges that, coupled with tidal effects, lead to significant changes in water level and current strength, while also enhancing regional vertical mixing (El-Sabh and Murty, 1989).

Despite the importance of Gulf-wide wind stress events in determining large-scale circulation within the Gulf there is still little understanding of the role of this mechanism in structuring near-shore coastal dynamics (Abdelrahman and Ahmad, 1995). Recent work has argued that strong wind events at the Gulf level may be vital in structuring smaller-scale sub-regional internal mixing (Thoppil and Hogan, 2009). This lack of awareness of the connection between Gulf-wide mesoscale oceanographic features and sub-regional circulation patterns is most evident within the shallow basin of the southern Gulf. Such paucity of data on the coastal impact of Gulf-wide strong wind events in this area is most acute, as such wind events can be very strong (10–25 m/s), lasting up to several days (El-Sabh and Murty, 1989). Although there is some evidence to suggest that surface layer currents can be heavily modified by strong wind events along this coastline (Cavalcante et al., 2011), there is still little empirical assessment of the connection between Gulf-wide wind phenomena and sub-regional oceanographic processes.

Large scale oceanographic processes such as currents and eddies can have important implications for biological processes, in particular for the long-distance transport of pelagic larvae. Most reef organisms produce dispersive propagules that are transported by oceanographic

* Corresponding author.
E-mail address: georgenes.cavalcante@icat.ufal.br (G.H. Cavalcante).

http://dx.doi.org/10.1016/j.marpolbul.2015.10.031

processes, either passively or with some contribution from active swimming, and as a result oceanographic currents can ecologically and genetically connect populations on reefs that are tens to hundreds of kilometers apart (Kinlan and Gaines, 2003; Shanks et al., 2003). In the Gulf, such physically-mediated transport is likely to be critically important in maintaining populations of a variety of reef organisms. Corals in parts of the Gulf have experienced recurrent, large-scale mortality as a result of elevated temperatures and disease outbreaks in recent years, and many reef fishes are being affected by habitat loss and over-exploitation (Buchanan et al., in press; Burt et al., 2011; Grandcourt, 2012; Riegl and Purkis, 2015). The continued transport of larvae from less degraded reefs elsewhere in the Gulf is considered critical to maintenance and recovery of impacted populations (Burt et al., 2013, 2015; Grizzle et al., in press; Riegl, 2002). Several recent demographic models have highlighted the importance of larval transport in maintaining populations, showing that connectivity through larval transport is critical to the long-term persistence of some corals in the southern Gulf, and that in the absence of transport many local populations would rapidly be extirpated (Riegl and Purkis, 2009, 2012, 2015). Despite the clear importance of oceanographic processes, the dynamics of transport in the Gulf are largely unknown. It has been suggested, for example, that recovery of reefs in the southern basin of the Gulf is contingent on coral larval supply from adjacent reefs (Burt et al., 2008; Riegl, 2003), from off-shore islands (Riegl, 2003; Riegl and Purkis, 2012), from reefs in Qatar and Bahrain (Burt et al., 2013, 2015; Shinn, 1976), as well as from reefs across the Gulf in Iran (Riegl and Purkis, 2012), but in all cases these suggestions have been based on 'best guesses' of possible larval sources, guided by knowledge of where less affected reefs were located and/or coastal current patterns. In order to more accurately predict patterns of connectivity among reefs in the Gulf, and to identify high-priority areas for conservation and management (e.g. 'source' reefs), there is a strong need for the development of a basin-wide circulation model which integrates the influence of large-scale oceanographic features such as persistent offshore eddies with the more localized influence of wind-driven currents in coastal areas. This study is the first circulation simulation to provide new insights on the potential impact of wind driven currents and eddies in the transport and recruitment of the pelagic larvae and speculates about the possible geographical connectivity within the Gulf.

This study integrates both small and large-scale oceanographic processes by first focusing on prevailing mechanisms structuring the coastal dynamics on the southern Gulf coast of the UAE, and then determining the connection between sub-regional oceanographic processes and Gulf-wide wind phenomena. The southern Gulf has been subject to recurrent mass mortality of corals and is characterized by widespread and substantial fishing pressure (Burt et al., 2011, 2015; Grandcourt, 2012; Riegl and Purkis, 2015), making it an ideal system for assessment of transport patterns that may deliver larvae for replenishment of local reef populations. Preliminary analyses had suggested that development and persistence of sub-regional cyclonic circulation cells can be closely associated with infrequent, strong wind events — patterns that reflect mechanisms suggested for the wider Gulf (Thoppil and Hogan, 2009). This work then examines the role of atmospheric wind forcing in driving larger-scale cyclonic circulation cells offshore from the UAE, and argues that Gulf-wide circulation and oceanic dynamics play a major role in structuring coastal current dynamics along the UAE coast. We discuss the implications of these hydrodynamic patterns for larval transport to reefs in the southern Gulf.

2. Material and methods

2.1. Collection of oceanographic data

From 1 April to 30 June 2009, a single 600 kHz RD Instruments Workhorse Sentinel Acoustic Doppler Current Profiler (ADCP) was deployed at approximately 17 meters (m) depth offshore of the UAE (Dubai Emirate: 25.179° N, 55.020° E) (Fig. 1). The ADCP was mounted to a fixed tripod and placed in an upward facing position, with the transducer 0.5 m above the benthos. Water current velocity and direction (converted into alongshore (u) and cross-shore (v) components) were recorded every 0.5 m vertically, with the first bin 1.65 m above the head and the last bin depending on water depth. The exact number of bins used was computed from the water depth above the transducer at the time of measurement and the cosine of the beam angle; this computation avoided the incorporation of bins with interference from acoustic reflections off the water surface (Simpson and Oltman, 1993). Current velocity and directional data within each bin were recorded within a set of 120 pings at 1 Hz, with each set of pings lasting 2 min, with 10 min intervals between each set. ADCP memory failure precluded collection of current velocity or directional data between 15–23 April.

A water quality monitor (WQM) (Wetlabs, Inc. Instruments) was permanently anchored at approximately 17 m adjacent to the deployed ADCP (Fig. 1). Each hour the WQM measured in situ temperature (measured at a resolution of 0.001 °C and within a range of −5 to +35), conductivity (measured at a resolution of 0.00005 S/m, with a range 0–9), and pressure (measured at a resolution of (m) 0.002% at full-scale range (200 m)). Conductivity measurements were converted to salinity (S) according to the Practical Salinity Scale (PSS-78) and the International Equation of State of Sea Water (IES-80).

Using a HOBO® Temperature/Light (waterproof) Pendant Data Logger, near-bottom temperature was sampled every 30 min for the period of April–June 2009. The instrument was deployed at the nearshore station (NS —Fig. 1) about 2 km from the coast on the west side of Palm Jumeirah at approximately 5 m depth, and located about 20 km from the offshore station (OS —Fig. 1).

2.2. Collection of meteorological data

To determine the wind direction and velocity across the entire experimental period, both atmospheric factors were obtained (within 10 min averaged data bins) from the Saih Al Shaib Meteorological Station (MS) (24.91821° N, 54.90987° E). This station was located 31 km southwest of the ADCP and WQM deployment site (OS) (Fig. 1).

To determine the interaction between water current development and atmospheric conditions (i.e., time averaged current velocity, current direction) throughout the Gulf across the experimental time period, water and meteorological data were analyzed using both descriptive statistics and spectral analysis. Before running the analyses oceanographic and meteorological data collected at 10 min intervals were first averaged hourly, in order to match hourly temperature and salinity data collected. Spectral analyses were run using the Fast Fourier transform (FFT) method. Resulting spectra were smoothed using a Hamming windowing process, with the energy peaks significant to the 95% confidence interval (Press et al., 1992).

2.3. Development of 3-D hydrodynamic model of water circulation within the Gulf

We examined whether velocity (m/s) or direction (alongshore (u), cross-shore (v)) of coastal water currents within the southern Gulf was associated with wind direction and/or velocity across the experimental time period (April–May–June 2009). To do this we modeled water circulation using the MIKE 3 Flow Model FM in the 3D mode (MIKE 3 FM, 2003) and compared the regional structure with recorded meteorological conditions over the equivalent time period.

The MIKE 3 modeling system is based on the numerical solution of the three-dimensional incompressible Reynolds-averaged Navier–Stokes equations, which were subject to the assumption of Boussinesq and use either a non-hydrostatic pressure formulation or hydrostatic pressure assumption for understanding the hydrostatic pressure (Christodoulou and Stamou, 2010; Moharir et al., 2014).

MIKE ZERO Mesh Generator was used to produce a domain comprising ~2 km grid cells, with a resulting mesh file consisting of 15,207