ARTICLE TYPE: Research Note**The influence of extreme winds on coastal oceanography and its implications for coral population connectivity in the southern Arabian Gulf**

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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., 1992; 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 Thoppil, 2010a), 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, 2010). The Gulf bathymetry is shallow and narrow, with an average depth (asymmetric along its axis) of 36m, 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, 2010). Wind stress at a Gulf-wide level is predominantly associated with northwesterly low-pressure frontal systems (Perrone, 1979; El-Sabh & 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 & 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 & 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 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. 2015; Burt et al., 2013; 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; Riegl and Purkis, 2012; Riegl and Purkis, 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 are 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; Burt et al., 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; Burt et al., 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 metres (m) depth offshore of the UAE (Dubai Emirate: 25.179⁰N, 55.020⁰E) (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 minutes, with 10 minute 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 minute 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 minutes 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).

2.2 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 were 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, 2007) 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 & 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 nodes and 18,314 elements, with 16 sigma layers in the vertical resolution. This domain extended northward from 23.7°N and westward from 58.0°E, including all of the maritime system within the Arabian Gulf. Within this model modeled bathymetry data was derived from global bathymetry and elevation data (SRTM30_PLUS) and utilized at 1 km horizontal grid spacing resolution (Becker et al., 2009). The model was driven by wind velocity and direction, air temperature (2 m above sea level), atmospheric humidity (2 m above sea level), surface shortwave and longwave heat

fluxes, and precipitation. These atmospheric variables were also utilized within the model's calibration and validation period (February to March, 2009) in a Cartesian grid covering the area 47°E to 59°E longitude and 21°N to 31.5°N latitude. All atmospheric data were obtained at hourly intervals across the experimental time period from the Research Data Archive held within the Computational and Information Systems Laboratory at the National Center for Atmospheric Research (Colorado) (<http://rda.ucar.edu>).

Oceanographic conditions of the southern Gulf region within the mesh file (northward from 23.7°N and westward from 58.0°E) were then simulated using a 60-second time step for the period 1 April to 30 June 2009, to include the main coral spawning period known for this region (April/May annually, see Bauman et al. 2011 and Howells et al. 2014), plus an additional month to allow for pelagic larval development and transport, where most coral larvae become competent to settle within 10 days but may delay metamorphosis for longer periods (Baird 2001). This oceanographic model was run based on the output produced during the calibration and validation period, such that the initial velocity field and initial boundary forcing were not initiated in "cold-start" mode. Wind (as pressure and two velocity components) was modeled as a 1-hour average of the effective neutral wind at a height of 10 m and within grid spacing of 0.5 degrees in both directions. The datum value of MSL+1m was selected for the entire Gulf model.

3. Results

3.1 Spatial/temporal variability of winds

The alongshore component (u) and resultant vectors of the wind across the Gulf in early, mid, and late May 2009 are shown in Fig. 2. The shows that a sequence of strong wind events occurred in May and in the beginning of June 2009 within the Gulf region. These strong wind events were characterized by temporal pulses of short duration (24 to 36 hours), with peak cycles over a time scale of approximately two weeks (Fig. 2). In the central Gulf, the winds showed a predominant directionality from WNW and NW, ranging from 12 m/s in the most northern area up to 16 m/s within the southeast coast (Fig. 2); these winds are known locally as '*shamal*' winds, from the Arabic word for 'north'. Overall, these strong wind events occurred first in the northwestern Gulf, gradually spreading south and east, taking ca. 12 hours to transit the Gulf as a whole. The strongest winds (~16 m/s) on May 2

covered an extensive area of the Gulf, encompassing the region between 25.5- 27.5 N and 52- 55 E (Fig. 2a). A smaller area was encompassed by the strong wind events on both the 14 May and 31 May (Figs. 2b and 2c).

In general, alongshore (u) and cross-shore (v) wind speed components along the UAE coast were generally low in May 2009, with average values less than 5 m/s for both components (Figs. 3a and 3b). However, peaks in wind strength were apparent during the 1st and 3rd weeks in May (i.e., days 2-4, 14-16), and between 31 May and 1 June (Figs. 3a, 3b). During the peak wind events zonal wind (u) intensity reached maximum values of approximately 14.3 and 13.4 m/s (2 May, 16 May, respectively), followed closely by zonal wind intensity of 14.8 m/s (1 June) (Fig. 3a). The corresponding meridional wind (v) component was generally weak, oscillating from 8.0 m/s to 8.4 m/s (2 May, 16 May, respectively), and reaching 8.1 m/s on 1 June (Fig. 3b). The 36h low-pass filter (red-line within Fig. 3) indicates the strong influence of atmospheric forcing on both zonal and meridional wind components (Figs. 3a,b).

3.2 Alongshore (u) and cross-shore (v) currents offshore Dubai (UAE) coastline

The alongshore and cross-shore water current components within the southern Gulf region were dominated by diurnally modulating tidal fluctuation (Figs. 3c and 3d). The strength of the tidal period on current strength within this region also resulted in a coincident modulation of current speed occurring within fortnightly tidal modulations, with average maximum and minimum following spring and neap tide cycles (Figs. 3c and 3d). The data gapped for several days was due to failure of the sonde memory card.

Both alongshore (u) and cross-shore (v) velocity components throughout the water column (near-surface, mid-water (not shown), and bottom layers) exhibited high variability in amplitude, but relatively short-term variation across the experimental period. Within the near-bottom layer (~3 m depth) u ranged between -0.20 m/s (negative values are indicative of currents flowing at a 220° bearing), and 0.25 m/s (positive values are indicative of currents flowing at 040° bearing) (Fig. 3c). The cross-shore velocity component (v), being restricted by the presence of the coastline varied between -0.15 m/s (negative values are indicative of currents flowing at 130° bearing) and 0.10 m/s (positive values are indicative of currents flowing at 310° bearing) (Fig. 3d). Maximum positive u and v near bottom currents reached approximately 0.45 and 0.23 m/s, respectively (Figs. 3c and 3d). The average speed of the predominant current (u) within mid-water and surface layers was 0.26 and 0.38 m/s,

respectively, while reaching a maximum of 0.35 m/s (mid-water) and 0.45 m/s (surface). The cross-shore current (v) in both mid-water and bottom layers were 0.08 and 0.05 m/s, respectively.

Current direction throughout the water column was closely aligned with coastline orientation, encompassing two distinct bearings (220° and 040°), which is reflected by the predominant alongshore current (u) compare to cross-shore (v) (Figs. 3c and 3d). Such strong directional alignment is characteristic of a system that is structured by tidal currents flowing alongshore during the ebb/flood tide cycle. The strong peak current velocities (u and v) recorded at the offshore station (OS) were predominantly attributed to energetic forcing events recurring within two weeks period apart being more evident on the alongshore current (u) component (Fig. 3c). The relatively low magnitude of the infrequent cross-shore currents pulses (v), were predominantly due to the coastline orientation of the surrounding area (aligned southwest/northeast).

3.3 Impact of wind variation on currents and water properties offshore Dubai (UAE) coastline

Temperature and salinity at the offshore station (OS) showed anomalous spikes in bottom water temperature that were closely associated with the development of short-term strong wind events and corresponding water velocity peaks (Fig. 4a, b). Bottom water temperature at OS increased from 23.2 to 24.7 °C from 21 to 23 April (Fig. 4c), rising rapidly again between 2 and 5 May (23.4 to 26.3 °C), 13 and 16 May (27.4 to 29.7°C) and then between 30 May and 1 June (28.9 to 31.6°C) during periods of peak winds (Fig. 4c). However, the majority of these thermal spikes were relatively ephemeral, lasting from 2 to 3 days (Fig. 4c). A similar dynamic is observed at the nearshore station (NS - see Fig.1 for location), located 2 km from the coast and separated by approximately 20 km from the OS, with bottom-water temperatures rising abruptly starting 21th April at 26.5 °C and reaching a high value of 28.1 °C on 23rd April, after which a less intense temperature rising between 2 and 5 May from 28.4 to 29.5 °C, and again between 14-16 May (31.1 to 32.1 °C), followed by a slight rising varying from 33.5 to 34.2 °C between 30 and 31 May. In concordance with the temporal consistency in water temperature spikes with both wind and current velocity peaks, sea-bottom salinity showed abrupt reductions across similar time periods (Fig. 4c). Between 2 to 4 May bottom water salinity dropped from 39.1 to 38.5 psu, then dropped again on 17 May

(39.3 psu to 38.2 psu) and 1 June (from 39.7 to 36.9 psu) (Fig. 4c). In all instances salinity remained low approximately 2 days following each salinity drop (Fig. 4c).

The frequency of each recorded strong wind event closely matched water flow peaks and episodes of temperature and salinity change (Fig. 5). For example, the most intense frequencies for water current (peak energy: mean frequency 0.065 cycle per day (cpd); lower energy: mean frequency 0.0137 cpd), corresponded to peaks periods of wind speed (14.2 days, 7.2 days, respectively), while also corresponding to periods of increasing temperature and decreasing salinity (Fig. 5).

3.4 Comparison of modelled and experimental southern Gulf circulation

Across the southern Gulf there was a high level of consistency (r -square = 0.94) in current velocity between modeled and *in situ* oceanographic data (Supplementary material - Fig. S1). In addition, observed and modeled currents both showed large shifts in current speed amplitude that were associated with increases in wind intensity in May and June (Fig. 2a,b; Supplementary material - Fig. S1).

Short-term reversals in current flow direction were apparent within both *in situ* and modeled oceanographic data. Such reversals were driven by large-scale strong wind forcing events associated with strong and temporally stable changes in wind direction (Fig. 4b). The modeled oceanographic data showed that cyclonic eddies developed between 25.5 – 25.8° N and 54.5 – 54.8° E approximately 100 km north of the Dubai coast in May and the beginning of June (Fig. 6), extending from the Iranian Islands of Abu Mussa and Tunb to within 25 km of the Dubai coast with an eddy diameter of ca. 52 km. Eddy development correlated with variation in speed in the zonal wind component within the Dubai coast (Fig. 3a), which was influenced by the large-scale wind forcing off the UAE coastline (Fig. 2). Such large-scale wind forcing then resulted in each eddy shifting southward from the Iranian islands and flowing parallel to the UAE coast. The average velocity of water in the eddy periphery was 0.15 m/s, indicating that transport from the Iranian islands to the UAE coast would take approximately 27 days and from the Iranian mainland coast would take approximately 32.5 days. The spatial maps of the modeled currents revealed a northwestward flow followed by an abrupt southwestward return flow across the experimental period (Fig. 6). Such abrupt changes in the direction of currents within the modeled data also correlate with a presence of strong currents on the northern edge along the Iranian coast during 15-16 and 31 of May and 1 June (Fig. 6). Such patterns in current development are highly consistent with the

substantial inflow currents in the area offshore of the Dubai coast (Supplementary material - Fig. S2).

Considering the larger Gulf-wide scale currents between 26.1 - 26.5° N and along the 55° E developed a distinct circulation field in the upper part of the model area, associated with a predominant inflow entering the Gulf along the Iranian coast (Supplementary material - Fig. S2). In addition, the circulation field demonstrates that a prominent mean outflow (away from the Dubai coastline) and a weak inflow offshore of the Dubai coast (25.1 - 25.6° N) are present (Supplementary material - Fig. S2).

4. Discussion

Fluctuations in the direction and velocity of water currents and concordant changes in water temperature and salinity were closely associated with a strong northeasterly peak wind events. These events recurred on cycles of ca. two weeks, beginning in the central Gulf along the Iranian coast and extending to the southeast coast of the Gulf along the UAE. Although earlier oceanographic models for this region had indicated that long-term wind stress is a major force generating large-scale cyclonic eddies and fluctuations in water speed and temperature and salinity in the central Gulf (Thoppil and Hogan, 2009), such wind stress related fluctuations have not been linked to the infrequent but strong wind events that characterize this region (so-called ‘shamal’ events). Our results show that low frequency, high strength shamal wind events are a major phenomenon driving changes in oceanographic conditions.

Our research showed that the oceanographic impacts of strong wind events persisted along the coastal margins of the UAE for several days (2-3 days), forcing the coastal flow to substantially move northeastward. Such strong winds (shamals), which occur seasonally in the Gulf, are associated with mid-latitude atmospheric disturbances moving rapidly from west to east (El-Sabh & Murty, 1989). Although such events have been shown to structure water current variability across the wider Gulf region (Reynolds, 1993), the results of this study show that short-term strong shamal winds also substantially impact oceanographic conditions at relatively small spatial scales (i.e., UAE coastline).

In concordance with the impact of local wind events on water direction and velocity, our modeled data showed that rapid changes in the direction and intensity of local winds resulted in the development of a short-lived (2-3 days) northwestward propagating cyclonic eddy. This eddy rapidly moved towards the UAE coastline from near the Iranian islands and

created a northeastward coastal outflow that transported water offshore from the UAE. The modeled cyclonic eddy was relatively slower in mean speed (0.1 m/s) than normally reported for other areas in the Gulf (0.4 m/s) (Reynolds, 1993; Thoppil and Hogan, 2009). However, the temporal persistence of this eddy (lasting for >3 weeks) was consistent with previous modeling results in similar shallow regions of the Gulf (Thoppil and Hogan, 2009; Thoppil and Hogan, 2010; Yao and Johns, 2010). Therefore, the development of this eddy is suggested to be part of a chain of atmospheric disturbances along the southern Gulf region, which can lead to substantial water circulation instability and the formation of cyclonic circulation cells.

Eddies in the Gulf evolve from turbulent cascades, attributed to baroclinic instability, resulting from the interaction of the warmer, more fresh and lower saline water flowing into the Gulf from the Gulf of Oman (Thoppil and Hogan, 2010; Yao and Johns, 2010). The abrupt changes in water temperature and salinity accompanying fluctuations in the velocity of the sub-regional cyclonic circulation cells may reflect the influence of this warmer and less saline waters flowing toward the UAE coastline (Reynolds, 1993; Swift and Bower, 2003). In parallel, bottom-water temperatures within the nearshore station during our experimental period were essentially identical to the abruptly rising water temperatures recorded offshore. We argue that such similarities in water temperature between offshore and onshore recording sites was not the direct result of temperature changes in the atmosphere, as air temperatures from the meteorological station (GH Cavalcante unpublished data) did not show corresponding increases throughout the experimental period, while. Therefore, warming coastal temperatures and lowered salinity near the coastline of the southern Gulf across the experimental period is much more likely to have been associated with the intrusion of warmer and less saline water from the Iranian coast (originating from the Gulf of Oman) brought by cyclonic eddies pushing offshore water onto the shallow UAE coastal shelf.

Although there is no previous information on the role of velocity fluctuations in structuring temperature and salinity within the southern Gulf, the results of this work show that abrupt wind increases are associated with substantial cyclonic eddy formation at sub-regional scales, and may explain the mechanism by which deeper offshore water would move onshore in an upwelling-like circulation. This in turn plays an important role on the coastal dynamics of the UAE, not only impacting regional oceanographic processes but also creating internal salinity and temperature instability, as has been observed at the Strait of Hormuz (Johns et al., 2003; Pous et al., 2004a,b; Thoppil and Hogan, 2009). Such rapid changes in temperature and salinity would have important implications for environmentally sensitive

marine fauna that occur in the southern Gulf. While corals of the southern Gulf are generally considered to be among the most thermally tolerant in the world they live at summer temperatures that are near their maximum thermal tolerance and winter temperatures that are unusually cool (Coles, 2003; Riegl et al., 2012). Thus any wind-driven shifts in temperature during seasonal extremes could have dramatic implications for coral survival, possibly inducing hot- or cold-water coral bleaching and mortality if conditions became more extreme, or potentially reducing physiological stress and limiting mortality if temperatures become more benign during seasonal temperature extremes. Further research on the impacts of shamal wind events on the thermal environment around reefs and other critical habitats is warranted.

The occurrence of strong current variability offshore of Dubai, the rapid flow transport by eddies extending from Iran to the southern Gulf, together with the interaction with the low-frequency wind fluctuations all show that those physical factors are responsible for the abrupt oceanographic change events offshore of UAE. The model utilized within the present study was also able to capture local changes in surface forcing within the shallow waters offshore of the UAE (<20m depth). The capture of such changes resolves the importance of coastal small-scale wind features in determining the physical structure of coastal UAE waters. In addition, these oceanography mechanisms also explain the observation within the present study of the abrupt salinity decrease and temperature increase events recorded.

According to recent studies performed by Thoppil and Hogan (2010), and Yao and Johns (2010) between April and July, the coastal flow along the Iranian coast becomes progressively stronger and penetrates far into the northern gulf because of strengthening stratification, increasing inflow, and weakening winds. The thermocline develops as the ocean gains heat from the atmosphere and generates a strongly stratified water column, which in turn limits the vertical mixing under prevailing weak wind conditions. Based on the temperature and salinity dataset between April and June 2009, we may consider that it was situated in the transitioning period where we could expect strong vertical stratification associated with weak wind conditions, and reflected by the warmer and very saline water along the shallow Dubai coast. Thus, one can speculate that these abrupt rises and plunges in bottom-water temperature at the offshore station reflect the influence of these warm density currents.

This work has shown for the first time (based on detailed direct observations of currents and hydrographic properties and numerical simulations) that offshore current

development within the southern Gulf is not only influenced by winds at the local scale but also by strong, infrequent large-scale winds that lead to mesoscale eddies that disperse throughout the area through more regional-scale coastal currents. The high correlation between the local (observed) and large-scale flow (model), indicated that there was a significant portion of local flow driven by the remote influence from the cyclonic circulation cells operating at large basin-wide scales. This work has shown that eddies formed by the remote wind forcing can potentially reverse the coastal current offshore UAE, and create high-frequency temperature/salinity oscillations along the southern Gulf region. Such cyclonic recirculation cells may then have a substantial effect on basin scale circulation within this water body, and be important in affecting biological processes throughout this region.

The development of large-scale eddies in the central Gulf during *shamal* events has important implications for the ecology of fauna on reefs in the southern Gulf along the coast of the UAE. Coral reefs along the Gulf coast of the UAE have been severely impacted by historic bleaching events as well as localized urban pressure, and as such are heavily reliant on the supply of larvae that can recruit to these reefs. Recent modeling work has suggested that long term survival of some coral species is contingent on larval transport from other parts of the Gulf (Riegl and Purkis, 2009; Riegl and Purkis, 2012), and recent ecological studies have shown that settlement of coral juveniles to reefs in the southern Gulf peaks in late summer (Bauman et al., 2014), well after the April/May spawning period known for the area (Bauman et al., 2011), suggesting that these larvae may have been transported from reefs where spawning occurs later. Bauman et al. (2011) suggested that the well-developed reefs surrounding the offshore islands of Iran and the UAE, which are adjacent to the eddy cell identified here, may serve as donor sites. Although no information on the timing of reproduction from these islands is currently available, the deeper water surrounding these islands makes it is plausible that the seas here warm more slowly, causing a consequent delay in coral egg development and spawning as a result, and that these later-spawned larvae are being transported to the coast by eddy systems similar to those observed here.

The time in which larval corals could be transported across the southern Gulf is a function of the speed of the eddy's currents. There are indications from large-scale studies that surface currents in eddies formed in the southern Iranian waters travel at a velocity of 0.3 to 0.4 m/s (Thoppil and Hogan, 2010; Yao and Thoppil, 2010), suggesting that at these speeds, larvae spawned on coastal reefs in southern Iran during summer could be transported 35 km/d by these eddies and deposited into the southern Gulf within three days, or less if

particularly strong or sustained shamal winds occur. Although the eddy speed modeled in this study was slightly slower (0.2 m/s), larvae could still be transported from the Iranian islands to the UAE coast in less than a week. Given that coral larvae are able to delay their settlement without consequent impacts on post-settlement survival and growth (Graham et al., 2013), and that they are capable of surviving in the water column for several months (Graham et al., 2008), it is plausible that coral larvae could be transported from the well-developed reefs around the Iranian islands to the coast of the UAE, in effect subsidizing the recovery of the degraded reefs along the coast of the southern Gulf. Further research on the potential for larval transport using particle-tracking models and assessment of actual ecological connectivity using genetics is highly warranted.

Supplementary material

Supplementary material is available at the MPB online version of this manuscript as Figure S1, comparison of current speed between the ADCP offshore station (OS) and from the model run during May 2009. And Figure S2, a temporal/spatial variability of along-shore current velocity variability along the longitude 55° E offshore of the Dubai coast southern Gulf.

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List of Figures

Figure 1. Model bathymetry in meters. Contours are drawn for 40 and 60 with thick lines for 60-m isobaths. The model domain extends northward from 21° to 31.5°N and eastward from 47° to 59°E. The location of the moored offshore stations (OS) indicates where the ADCP and water quality monitor (WQM) were deployed, and also the nearshore station (NS) and meteorological station (MS) are shown.

Figure 2. Distribution maps of zonal winds and resultant vectors for the Persian/Arabian Gulf at three different times during strong wind events. a) 2 May, 2009. b) 14 May, 2009. c) 31 May, 2009.

Figure 3. (a) Time series of zonal wind (u) component and (b) meridional wind (v) component from the meteorological station (MS) during the period of April-June 2009. The 36h low-pass filter (red line) is superimposed on both u and v wind components to isolate the

high frequency wind effects; (c) time series of the near-bottom ($\sim 3\text{m}$) alongshore current and (d) cross-shore current from the offshore ADCP (OS) during the period of April-June 2009. A superimposed 36h low-pass filter is shown in red line. Figs 2a, 2b also have superimposed both the tidal component and a 36h low-pass filter (red line) to isolate the sub-tidal signal.

Figure 4. (a) Stick plot of 36-hour low-pass filter of depth-averaged current from the ADCP at the offshore station (OS); (b) Stick plot of 36-hour low-pass filter of wind from meteorological station (MS). The direction indicates the motion for both parameters (i.e., oceanographic, not meteorological, convention). (c) Time series of bottom temperature at offshore station (heavy line) and nearshore station (dot line), and salinity (dashed line). The offshore and nearshore stations revealed a similar pattern with abrupt rise in temperature and the dashed line shows the corresponding drop/rise in salinity data.

Figure 5. Spectral analysis of hourly current, wind, temperature and salinity data from the offshore station (OS). Peak energy of the variables marks periods of low-frequency events seen in the observations during April-June 2009. Current and salinity are plotted in the left y-axis and wind and temperature in the right y-axis.

Figure 6. Daily snapshots of model current for every salinity episodic events interval during April-June 2009. The cyclonic eddies form in the vicinity of $25.5 - 25.8^{\circ}\text{N}$ and $54.5 - 54.8^{\circ}\text{E}$, and nearly at the same place ($25.4 - 25.8^{\circ}\text{N}$ and $55.2 - 55.5^{\circ}\text{E}$), where the inflow turns offshore towards Dubai coast and subsequently joins the outflow circulation.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6