Biophysical model of coral population connectivity in the Arabian/Persian Gulf

This is a summary of the following book chapter:

Cavalcante, G., Vieira, F., Mortensen, J., Ben-Hamadou, R., Range, P., Goergen, E., Campos, E., & Riegl, B. (2020). Biophysical model of coral population connectivity in the Arabian/Persian Gulf. In Advances in Marine Biology. Elsevier. https://doi.org/10.1016/bs.amb.2020.07.001

Biophysical model of coral population connectivity in the Arabian/Persian Gulf

Geórgenes Cavalcante[a,b,*]

Filipe Vieira[a]

Jonas Mortensen[c]

Radhouane Ben-Hamadou[d]

Pedro Range[d]

Elizabeth Goergen[d]

Edmo Campos[a,f]

Bernhard Riegl[e]

[a] Department of Biology, Chemistry and Environmental Sciences, College of Arts and Sciences, American University of Sharjah, Sharjah, United Arab Emirates

[b] Instituto de Ciências Atmosfericas (ICAT), Universidade Federal de Alagoas, Maceió, Brazil

[c] DHI A/S. Agern Alle 5, Hørsholm, Denmark

[d] Department of Biological and Environmental Sciences, College of Arts and Sciences, Qatar University, Doha, Qatar

[e] Department Marine and Environmental Sciences, Halmos College of Natural Sciences and Oceanography, Nova, Southeastern University, Dania Beach, FL, United States

[f] Instituto Oceanografico, Universidade de São Paulo, São Paulo, Brazil

[*] Corresponding author: e-mail addresses: gcavalcante@aus.edu; georgenescavalcante@icat.ufal.br

Contents

Abstract

The coral reef ecosystems of the Arabian/Persian Gulf (the Gulf) are facing profound pressure from climate change (extreme temperatures) and anthropogenic (land-use and population-related) stressors. Increasing degradation at local and regional scales has already resulted in widespread coral cover reduction. Connectivity, the transport and exchange of larvae among geographically separated populations, plays an essential role in recovery and maintenance of biodiversity and resilience of coral reef populations.

Here, an oceanographic model in 3-D high-resolution was used to simulate particle dispersion of "virtual larvae." We investigated the potential physical connectivity of coral reefs among different regions in the Gulf. Simulations reveal that basin-scale circulation is responsible for broader spatial dispersion of the larvae in the central region of the Gulf, and tidally-driven currents characterized the more localized connectivity pattern in regions along the shores in the Gulf's southern part. Results suggest predominant self-recruitment of reefs with highest source and sink ratios along the Bahrain and western Qatar coasts, followed by the south eastern Qatar and continental Abu Dhabi coast. The central sector of the Gulf is suggested as recruitment source in a stepping-stone dynamics. Recruitment intensity declined moving away from the Straits of Hormuz. Connectivity varied in models assuming passive versus active mode of larvae movement. This suggests that larval behaviour needs to be taken into consideration when establishing dispersion models, and establishing conservation strategies for these vulnerable ecosystems.

Introduction

Significant fluctuations of population sizes are increasingly common in coral reef organisms. These can be outbreaks of predators, like Crown-of Thorns Starfish (Shafir et al., 2008) or coral-eating snails (De'ath et al., 2012), or competitors such as brown algae (Mumby et al., 2007; Van den Hoek et al., 1995). Population collapses of fishes, corals or other organisms are increasing and frequently demonstrated (McClanahan et al., 2008; Robbins et al., 2006). An ever-growing human footprint leads to more resource-extraction by capture (fisheries, collection of ornamentals, etc.) or resource removal either by mortality events or by destruction of viable habitat (Cinner et al., 2018). Changes in populations of reproducing organisms have obvious repercussions on population dynamics and lead to feedbacks into upward or downward cycles, or in the worst case, one-way trajectories of decline (Case, 2000; Caswell, 2001). Corals and fishes are organisms that show tendencies to get ever rarer on reefs as natural and man-made environmental impacts increase (Kayal et al., 2012).

If organismic populations on coral reefs are to survive in such difficult settings, first principles of population dynamics suggest that replenishment by natural recruitment will be key to survival (Case, 2000; Caswell, 2001; Hutchinson, 1978). Population fecundity, connectivity among populations, and levels of recruitment must, therefore, be known to understand and model the potential survival of coral reef organisms (Paris et al., 2007). This is no trivial task since recruits of virtually all organisms are small and difficult, if not impossible, to track unless sophisticated genetic tools are at hand (Baums et al., 2014; Berumen et al., 2019) to determine the provenance of propagules. While much progress has been made by using traditional field methods (settlement plates, larval capture, etc.; Bauman et al., 2012; Burt and Bauman, 2019), there remains a need to know more details and to better evaluate future scenarios. Also, some predictions regarding the likelihood of population connectivity based on demographic models (Riegl and Purkis, 2015; Riegl et al., 2017) can only be verified by sophisticated analyses of propagule flow among these populations. Biophysical models of larval dispersion that integrate particle transport with physical oceanographic models have been used with much success to explain patterns in biodiversity (Cowen et al., 2000; Paris et al., 2007; Werner et al., 2007), invasion dynamics (Johnston and Akins, 2016; Johnston and Purkis, 2015), and potential pathways of larvae for population recovery (Cavalcante and Burt, 2016; Riegl et al., 2017, 2018). Such approaches bear much promise for understanding and predicting the future of marine resources in increasingly depleted coral reefs. The Arabian/Persian Gulf (hereafter termed "Gulf") is a peripheral, epicontinental sea connected to the Indian Ocean and was, until relatively recently, home to large reef areas that have since been severely restricted (Riegl et al., 2018; Sale et al., 2011; Sheppard, 2016; Sheppard et al., 2010). A thriving economy and growing human population put massive pressure on the reefs of the region (Riegl and Glynn, 2020), which is home to some of the world's largest coastal alteration (dredge-and-fill) and desalination projects (Sale et al., 2011; Sheppard et al., 2010; Van Lavieren et al., 2011). With habitat rapidly disappearing and the region being highly sensitive to climate extremes (Bauman et al., 2015; Burt et al., 2014; Riegl and Purkis, 2012), the future of most coral reef taxa and reef areas seems to depend on recruitment to replenish the frequent and severe losses (Pratchett et al., 2017; Riegl et al., 2017). The status, whether extant or soon extinct, of some ecosystem engineering species depends on the availability of upstream populations to seed and allow replenishment of depleted populations (Riegl et al., 2018).

This study uses a three-dimensional oceanographic model at 1 km resolution to model particle transport within the Gulf and to develop predictions of population connectivity. Previous biophysical models of settlement and population replenishment dynamics in this region were two-dimensional and considered only the ocean's surface layer with low resolution in the coastal areas (Cavalcante and Burt, 2016; Riegl et al., 2017, 2018). However, large areas of the Gulf harbour deeper (to >30m) coral populations and the densest reef assemblages are close to the shoreline. This new model therefore represents an advancement in technical capability to develop much finer-grained scenario-models and predictions. In this paper we use a 3D high-resolution model that reproduces the circulation features of the Gulf, together with an agent-based model that reproduces the transport and biological processes of spawned eggs to first, (i) understand whether the larvae spawned at a certain area can travel to form coral colonies at other areas and, second (ii) to explore how distinct coral populations are connected within the Gulf, which is crucial to coral conservation efforts.

Conclusions

In this study, the developed 3D hydrodynamic model performed as expected for the simulated period. The model was able to simulate the basin-scale circulation and reproduce the observed characteristics of the eddies typical for the period of study, and agreed with in situ observations, the HYCOM database, and other studies on the circulation-driven mechanisms in the Gulf. The 3D model highlighted the importance of atmospheric fields on circulation patterns and the understanding of local circulation characteristics. The hydrodynamic simulations demonstrated the potential for interpreting the key identified physical connectivity pathways of the distinct regions with regards to coral reefs in the Gulf. Coral larvae have the potential to be dispersed long distances under basin-scale currents and eddies, but tend to shorten the travel distance under localized tidal-driven currents.

Acknowledgements

This work was made possible by NPRP grant # [10-0205-170342] from the Qatar National Research Fund (a member of Qatar Foundation). The findings achieved herein are solely the responsibility of the authors. This work was partially supported by the American University of Sharjah [grant number FRG19-M-G74]. The authors would also like to thank the anonymous reviewers for their valuable comments that contributed to the final article. Wind and atmospheric pressure series data were sourced from the Research Data Archive (RDA) which is maintained by the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). NCAR is sponsored by the National Science Foundation (NSF). We are grateful to DHI Water & Environment, Brazil, for allowing us to use their software MIKE 3.

References

Al-Hashmi, A., 2012. Coral reef reproduction and its features in the Arabian gulf (Jebel Ali, UAE). Int. J. Environ. Sustain. 1 (3), 12–21.

Alosairi, Y., Imberger, J., Falconer, R., 2011. Mixing and flushing in the Persian Gulf (Arabian Gulf). J. Geophys. Res. 116, C03029.

Bauman, A.G., Baird, A.H., Cavalcante, G.H., 2011. Coral reproduction in the world's warmest reefs: southern Persian Gulf (Dubai, United Arab Emirates). Coral Reefs 30, 405–413.

Bauman, A.G., Feary, D.A., Heron, S.F., Pratchett, M.S., Burt, J.A., 2012. Multiple environmental factors influence the spatial distribution and structure of reef communities in the northeastern Arabian Gulf. Mar. Pollut. Bull. 72, 302–312.

Bauman, A.G., Guest, J.R., Dunshea, G., Low, J., Todd, P.A., 2015. Coral settlement on a highly disturbed equatorial reef system. PLoS One 10 (5), e0127874. https://doi.org/10.1371/journal.pone.0127874.

Baums, I.B., Devlin-Durante, M., Laing, B.A.A., Feingold, J.S., Smith, T.B., Bruckner, A., Monteiro, J., 2014. Marginal coral populations: the densest known aggregation of Pocillopora in the Galapagos Archipelago is of asexual origin. Front. Mar. Sci. 1, 1–11.

Berumen, M.L., Roberts, M., Sinclair-Taylor, T., Dibattista, J., Saenz-Agudelo, P., Isari, S., He, S., Khalil, M., Hardenstine, R., Tietbohl, M., Priest, M., Kattan, A., Coker, D., 2019. Fishes and connectivity of Red Sea coral reefs. In: Voolstra, C.R., Berumen, M.L. (Eds.), Coral Reefs of the Red Sea. Springer, pp. 157–179. https://doi.org/10.1007/978-3-030-05802-9_8.

Black, K.P., 1993. The relative importance of local retention and inter-reef dispersal of 553 neutrally buoyant material on coral reefs. Coral Reefs 12, 43–53.

Bode, M., Leis, J.M., Mason, L.B., Williamson, D.H., Harrison, H.B., 2019. Successful validation of a larval dispersal model using genetic parentage data. PLoS Biol. 17 (7), e3000380.

Burt, J.A., Bauman, A.G., 2019. Suppressed coral settlement following mass bleaching in the southern Persian Gulf. Aquat. Ecosyst. Health Manage. 1–9.

Burt, J.A., Van Lavieren, H., Feary, D.A., 2014. Persian Gulf reefs: an important asset for climate science in urgent need of protection. Ocean Challenge 20, 49–56.

Burt, J.A, Paparella, F., Al-Mansoori, N., Al-Mansoori, A., Al-Jailani, H. 2019. Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs. 38(4), pages567–589. https://doi.org/10.1007/s00338-00019-01767-y.

Case, T., 2000. An Illustrated Guide to Theoretical Ecology. Oxford University Press, 449 pp.

Caswell, H., 2001. Matrix Population Models. Sinauer, Sunderland.

Cavalcante, G.H., Feary, D.A., Burt, J.A., 2016. The influence of extreme winds on coastal oceanography and its implications for coral population connectivity in the southern Arabian Gulf. Mar. Pollut. Bull. 105, 489–497.

Cavalcante, G.H., Kjerfve, B., Feary, D.A., 2012. Examination of residence time and its relevance to water quality within a coastal mega-structure: the Palm Jumeirah Lagoon. J. Hydrol. 468–469, 111–119.

Chao, S.Y., Kao, T.W., Al-Hajri, K.R., 1992. A numerical investigation of circulation in the Arabian Gulf. J. Geophys. Res. 97, 219–236.

Cinner, J.E., Maire, E., Hutchery, C., MacNeil, A., Graham, N.A.J., 2018. Gravity of human impacts mediates coral reef conservation gains. Proc. Natl. Acad. Sci. U. S. A. 115 (27), E6116–E6125.

Connolly, S.R., Baird, A.H., 2010. Estimating dispersal potential for marine larvae: dynamic models applied to scleractinian corals. Ecology 91 (12), 3572–3583.

Cowen, R.K., Paris, C.B., Srinivasan, A., 2000. Scaling of connectivity in marine populations. Science 311 (5760), 522–527.

De'ath, G., Fabricius, K.E., Sweatman, H., Puotinen, M., 2012. The 27-year decline of coral cover on the great barrier reef and its causes. Proc. Natl. Acad. Sci. U. S. A. 109, 17995–17999.

DHI, 2013. Water & Environment, MIKE 21 and MIKE 3 Flow Model FM Hydrodynamic Module. DHI Group.

El-Sabh, M.I., Murty, T.S., 1989. Storm surges in the Arabian Gulf. Nat. Hazards 1 (4), 371–385.

Emery, K.O., 1956. Sediments and water of the Persian Gulf. AAPG Bull. 40, 2354–2383.

Fadlallah, Y.H., 1996. Synchronous spawning of Acropora clathrata coral colonies from the western Arabian Gulf (Saudi Arabia). Bull. Mar. Sci. 59, 209–216.

Fatemi, S.M.R., Shokri, M.R., 2001. Iranian coral reefs status with particular reference to Kish Island, Persian Gulf. In: Proceedings of the International Coral Reef Initiative Indian Ocean Regional Workshop, November 26–28, Mozambique, pp. 1–13.

Figueiredo, J., Baird, A.H., Harii, S., Conolly, S.R., 2014. Increased local retention of coral reef larvae as a result of ocean warming. Nat. Clim. Chang. 4, 498–502.

Graham, E.M., Baird, A.H., Connolly, S.R., 2008. Survival dynamics of scleractinian coral larvae and implications for dispersal. Coral Reefs. 27, 529–539.

Harrison, P.L., 1995. Status of the Coral Reefs of Kuwait. Final Rep. U. N. Ind. Dev. Organ. U. N. Dev. Programme UNIDO UNDP Vienna.

Howells, E.J., Abrego, D., Vaughan, G.O., Burt, J.A., 2014. Coral spawning in the Gulf of Oman and relationship to latitudinal variation in spawning season in the Northwest Indian Ocean. Sci. Rep. 4, 7484.

Howells, E.J., Ketchum, R.N., Bauman, A.G., Mustafa, Y., Watkins, K.D., Burt, J.A., 2016. Species-specific trends in the reproductive output of corals across environmental gradients and bleaching histories. Coral Reefs Arab. 105, 532–539.

Hutchinson, G.E., 1978. An Introduction to Population Ecology. Yale University Press, 260 pp.

Johnston, M.W., Akins, J.L., 2016. The non-native royal damsel (Neopomacentrus cyanomos) in the southern Gulf of Mexico; an invasion risk? Mar. Biol. 163 (1), 1–14.

Johnston, M.W., Purkis, S.J., 2015. A coordinated and sustained international strategy is required to turn the tide on the Atlantic lionfish invasion. Mar. Ecol. Prog. Ser. 533, 219–235. https://doi.org/10.3354/meps11399.

Jones, O.P., Petersen, O.S., Kofoed-Hansen, H., 2007. Modelling of complex coastal environments: some considerations for best practice. Coast Eng. 54, 717–733.

Kämpf, J., Sadrinasab, M., 2006. The circulation of the Persian Gulf: a numerical study. Ocean science, 2, 1-15.Lobel, P.S. 2011. Transport of reef larvae by an ocean eddy in Hawaiian waters. Dyn. Atmos. Oceans 52, 119–130.

Kayal, M., Vercelloni, J., Lison de Loma, T., 2012. Predator crown-of-thorns starfish (Acanthaster planci) outbreak, mass mortality of corals, and cascading effects on reef fish and benthic communities. PLoS One 7 (10), e47363.

Kleypas, J.A., Thompson, D.M., Castruccio, F.S., Curchitser, E.N., Pinsky, M., Watson, J/R., 2016. Larval connectivity across temperature gradients and its potential effect on heat tolerance in coral populations. Glob. Chang. Biol. 22, 3539–3549.

Lawrence, J., Kofoed-Hansen, H., Chevalier, C., 2009. High resolution metocean modelling at EMEC's (UK) marine energy test sites. In: Proc 8th Eur Wave and Tidal Energy Conf, Uppsala. www.emec.org.uk/pdf.

Lipcius, R.N., Eggleston, D.B., Schreiber, S.J., Seitz, R.D., Shen, J., Sisson, M., Stockhausen, W.T., 2008. Importance of metapopulation connectivity to restocking and restoration of marine species. Rev. Fish. Sci. 16, 101–110.

McClanahan, T.R., Hicks, C.C., Darking, E.S., 2008. Malthusian overfishing and efforts to overcome it on Kenyan coral reefs. Ecol. Appl. 18 (6), 1516–1529.

Mumby, P., Hastings, A., Edwards, H.J., 2007. Thresholds and the resilience of Caribbean coral reefs. Nature 450, 98–101.

Paris, C.B., Cherubin, L.M., Cowen, R.K., 2007. Surfing, spinning, or diving from reef to reef: effects of population connectivity. Mar. Ecol. Prog. Ser. 347, 285–300.

Pratchett, M.S., Baird, A.H., Bauman, A.G., Burt, J.A., 2017. Abundance and composition of juvenile corals reveals divergent trajectories for coral assemblages across the United Arab Emirates. Mar. Pollut. Bull. 114, 1031–1035.

Pratchett, M., McWilliam, M.J., Riegl, B., 2020. Contrasting shifts in coral assemblages with increasing disturbances. Coral Reefs 39, 783–793. https://doi.org/10.1007/s00338-020-01936-4.

Reynolds, R.M., 1993. Physical oceanography of the Gulf, strait of Hormuz and the Gulf of Oman-results from the Mt Mitchell expedition. Mar. Pollut. Bull. 27, 35–59.

Riegl, B., 1999. Coral communities in a non-reef setting in the southern Arabian Gulf (Dubai, UAE): fauna and community structure in response to recurrent mass mortality. Coral Reefs 18 (1), 63–73.

Riegl, B., Glynn, P.W., 2020. Population dynamics, human-induced environmental degradation, and the coral reef crisis. In: Riegl, B. (Ed.), vol. 87. Population Dynamics of the Reef Crisis. Advances in Marine Biology, Elsevier.

Riegl, B., Purkis, S.J., 2012. Coral Reefs of the Gulf: Adaptation to Climatic Extremes. Springer, 379 pp.

Riegl, B., Purkis, S.J., 2015. Coral population dynamics across consecutive mass mortality events. Glob. Chang. Biol. 21 (9), 3995–4005.

Riegl, B., Cavalcante, G., Bauman, A., Feary, D., Steiner, S., Purkis, S., 2017. Demographic mechanisms of reef coral species winnowing from communities under increased environmental stress. Front. Mar. Sci. 4, 344. https://doi.org/10.3389/fmars.2017.00344.

Riegl, B., Johnston, M., Purkis, S., Howells, E., Burt, J., Steiner, S.C.C., Sheppard, C.R.C., Bauman, A., 2018. Population collapse dynamics in Acropora downingi, an Arabian/Persian gulf ecosystem-engineering coral, linked to rising temperature. Glob. Chang. Biol. 24 (6), 2447–2462. https://doi.org/10.1111/gcb.14114.

Ritson-Williams, R., Arnold, S., Fogarty, N., Steneck, R.S., Vermeij, M., Paul, V.J., 2009. New perspectives on ecological mechanisms affecting coral recruitment on reefs. Smithson. Contrib. Mar. Sci. 38, 437–457.

Robbins, W.D., Hisano, M., Connolly, S., Choat, H., 2006. Ongoing collapse of coral-reef shark populations. Curr. Biol. 16 (23), 2314–2319.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y.-T., Chuang, H., Juang, H.-M.H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Delst, P.V., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J.-K., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C.-Z., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R.W., Rutledge, G., Goldberg, M., 2010. The NCEP climate forecast system reanalysis. Bull. Am. Meteorol. Soc. 91 (8), 1015–1058.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M.P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., Becker, E., 2014. The NCEP climate forecast system version 2. J. Climate 27 (6), 2185–2208. https://doi.org/10.1175/jcli-d-12-00823.1.

Sale, P.F., Feary, D.A., Burt, J.A., Bauman, A.G., Cavalcante, G.H., Drouillard, K.G., Kjerfve, B., Marquis, E., Trick, C.G., Usseglio, P., van Lavieren, H., 2011. The growing need for sustainable ecological management of marine communities of the Persian Gulf. Ambio 40, 4–17.

Shafir, S., Gur, O., Rinkevich, B., 2008. A Drupella cornus outbreak in the northern Gulf of Eilat and changes in coral prey. Coral Reefs 27, 379.

Sheppard, C.R.C., 2016. Coral reefs in the Gulf are mostly dead now, but can we do anything about it? Mar. Pollut. Bull. 105 (2), 593–598.

Sheppard, C., Price, A., Roberts, C., 1992. Marine Ecology of the Arabian Region: Patterns and Processes in Extreme Tropical Environments. Academic Press, Toronto.

Sheppard, C.R.C., Al-Hoseine, M., Al-Jamali, F., Al-Yamani, F., Baldwin, R., Bishop, J., Benzoni, F., Dutrieux, E., Dulvy, N.K., Durvasula, S.R.V., Jones, D.A., Loughland, R., Medio, D., Nithyanandan, M., Pilling, G.M., Polikarpov, I., Price, A.R.G., Purkis, S., Riegl, B., Saburova, M., Samimi Namin, K., Taylor, O., Wilson, S., Zainal, K., 2010. The Persian/Arabian Gulf: a young sea in decline. Mar. Pollut. Bull. 60, 13–38.

Shinn, E.A., 1976. Coral recovery in Florida and the Perisan Gulf. Environ. Geol. 1, 241–254.

Storlazzi, C.D., van Ormondt, M., Chen, Y.-L., Elias, E.P.L., 2017. Modeling fine-scale coral larval dispersal and interisland connectivity to help designate mutually-supporting coral reef marine protected areas: insights from Maui Nui, Hawaii. Front. Mar. Sci. 4 (381), 1–14.

Sundelöf, A., Jonsson, P.R., 2012. Larval dispersal and vertical migration behaviour—a simulation study for short dispersal times. PSZN I: Mar. Ecol. 33, 183–193.

Swift, S.A., Bower, A.S., 2003. Formation and circulation of dense water in the Persian/Arabian Gulf. J. Geophys. Res. 108, 3004.

Thoppil, P.G., Hogan, P.J., 2009. On the mechanisms of episodic salinity outflow events in the Strait of Hormuz. J. Phys. Oceanogr. 39 (6), 1340–1360.

Thoppil, P.G., Hogan, P.J., 2010a. A modeling study of circulation and eddies in the Persian Gulf. J. Phys. Oceanogr. 40 (9), 2122–2134.

Thoppil, P.G., Hogan, P.J., 2010b. Persian gulf response to a wintertime shamal wind event. Deep-Sea Res. I 57, 946–955.

Van den Hoek, C., Mann, D.G., Jahns, H.M., 1995. Algae: An Introduction to Phycology. Cambridge University Press, Cambridge.

Werner, F.E., Cowen, R.K., Paris, C.B., 2007. Coupled biological and physical models: present capabilities and necessary developments for future studies of population connectivity. Oceanography 20 (3), 54–69.

Van Lavieren, H., Burt, J., Feary, D.A., Cavalcante, G., Marquis, E., Benedetti, L., Trick, C., Kjerfve, B., Sale, P.F., 2011. Managing the Growing Impacts of Development on Fragile Coastal and Marine Ecosystems: Lessons From the Gulf, A policy report. UNUINWEH, Hamilton, ON, Canada.

Yao, F., Johns, W.E., 2010. A HYCOM modeling study of the Persian Gulf: 1. Model configurations and surface circulation. J. Geophys. Res. 115, C11017. https://doi.org/10.1029/2009JC005781.