nature geoscience

SUPPLEMENTARY INFORMATION

DOI: 10.1038/NGEO2821

Ocean planning in a changing climate

Catarina Frazão Santos, Tundi Agardy, Francisco Andrade, Manuel Barange, Larry B. Crowder, Charles N. Ehler, Michael K. Orbach and Rui Rosa

correspondence to: cfsantos@fc.ul.pt

This PDF file includes:

Materials and Methods

An analysis of existing scientific publications related to ocean planning and climate change was performed using ISI Web of Knowledge. Data was collected from all databases, since 1900 until 2015. The analysis aimed to assemble information to support the selection of main ocean uses and main climate-related drivers of change.

Following the rationale that ocean uses will undergo spatial and temporal change due to climate change, and that their redistribution will affect ocean planning, we searched for publications pertaining to climate change impacts on specific ocean uses. Main ocean uses were selected based on examples from ocean planning guiding documents (e.g. ref. 1) and information from specific ocean planning processes (e.g. ref. 2), and are: *fisheries*, *conservation*, *aquaculture*, *tourism*, *shipping*, *renewable energy*, and *deep sea mining.*

To effectively analyse how climate change can affect specific ocean uses, impacts had to be individualized according to different drivers of change, i.e. vectors that induce changes in marine ecosystems. Eight key climate-related drivers of change were identified: *warming*, *acidification*, *distributional shifts*, *sea level rise*, *circulation and winds*, *extreme events*, *diseases and harmful algae blooms*, and *hypoxia*.

Based on information from scientific publications related to climate change effects on specific ocean uses, and taking into account the different drivers of change, a summary table was developed identifying the direct impact degree of each climate-related driver of change on each ocean use: Table S1. Direct impact degrees can present the following values: *0* (none), *1* (low), *2* (medium), and *3* (high). The assignment of impact values resulted from the authors' interpretation of available information on the subject (key data sources are identified in the summary table). In general, the coastal zone (including estuaries and coastal lagoons) was not considered in the assessment of impacts, only the ocean realm. However, because shipping cannot exist without ports, and because marine tourism is accessed from the coast, in these two cases coastal impacts are also identified.

Table S1 | **Direct impact degree of each climate-related driver of change on each ocean use.** Direct impact degrees can present the following values: *0* (none), *1* (low), *2* (medium), and *3* (high). Abbreviations: WARM, Warming; ACID, Acidification; DSHIFT, Distributional shifts; SLR, Sea level rise; CIRCW, Circulation and winds; EXT, Extreme events; DISHAB, Diseases and harmful algae blooms; HYPO, Hypoxia; N/A, Not applicable; ENSO, *El Niño*-Southern Oscillation; OMZ, Oxygen minimum zone; MPA, Marine protected area.

Ocean use	Driver of change	Brief description of direct impacts (with key references)	Impact degree
Fisheries	WARM	The direct effects of warming on stocks result from physiological changes at individual level that ultimately affect populations, communities and the functioning of ecosystems[3-8]. Decrements in organism's aerobic performance in future warming seas may be the first process to cause extinction or relocation[3].	3
	ACID	Organisms producing calcium carbonate shells and skeletons seem to experience the strongest negative impacts of acidification[9,10]. Future responses may include reduced calcification and weakened calcified structures, but responses are very species-specific and different among taxonomic groups[4,11,12].	2
	DSHIFT	From ocean warming to hypoxia, from changes in ocean currents to sea level rise, marine biodiversity will undergo distributional shifts that will lead to changes in stocks location, diversity and productivity[4,13-17]. These spatial shifts will mainly cause species richness to increase at mid- and high latitudes (high confidence) and to decrease at tropical latitudes (medium confidence)[4].	3
	SLR	Due to global warming, namely the added water from melting land ice and the expansion of sea water as it warms, sea level rise is expected to induce loss of breeding and/or nursery habitats (e.g. coral reefs)[18-20].	2
	CIRCW	Predicted changes in the ocean's heat content and salinity will continue to affect circulation patterns, and consequently affect fisheries[19]. Changes in the direction and strength of circulation and winds may alter species dispersal and connectivity patterns, transport/retention of contaminants, and nutrients along the neritic zone[4]. Nonetheless, there is low confidence in projections of changes in large-scale patterns of natural climate variability (e.g. ENSO)[4].	2
	EXT	Increased frequency of storms and other extreme weather events are expected to increase danger at sea, thus increasing vulnerability of fishing communities and infrastructures/gear[4,19]. Extreme events may also promote loss of important breeding and/or nursery habitats[21].	3
	DISHAB	Marine pathogens and protist diseases have been moving poleward as oceans warm[22,23]. These shifts may weaken the immune response of some commercially-important invertebrates and fish – and consequently of humans[24] – and increase their susceptibility to disease. Although episodic, harmful algal blooms (HABs) will also be enhanced by ocean warming, acidification, enhanced surface stratification and eutrophication in neritic waters, which will induce increased mortality on stocks[4,25].	2
	HYPO	Hypoxia-induced mass mortality and decline in fisheries production are not uncommon in many coastal areas of the world[26]– "dead zones". General circulation models predict that CC alone will enhance the depletion of oceanic oxygen by increasing stratification and warming[4,27,28], especially in tropical oceans[29-31]. Moreover, CC also has the potential to increase the occurrence of mesopelagic OMZs expansion into neritic waters of some eastern boundary systems[32], damaging fisheries in the same way that eutrophication-driven hypoxia does. Nonetheless, the occurrence of "dead-zones" is not globally widespread[33].	2

Table S1 | Cont.

Ocean use	Driver of change	Brief description of direct impacts (with key references)	Impact degree
Conservation	WARM	Cumulative impacts of warming and acidification are expected to alter the spatial scale of connectivity of marine ecosystems. Functional connectivity may be decreased by reduced mean dispersal distances (altering the duration of, trajectory and survival during larval life cycle), while structural connectivity may be reduced by increased distance between habitats[34]. MPAs will need to be redesigned to ensure the maintenance of ecological connectivity processes[35] – e.g. being closer together (compensating for reduced larval input) and larger in size (compensating for habitat loss[34.] However, as mentioned for fisheries, responses to ocean acidification are very species-specific and different among taxonomic groups.	3
	ACID		2
	DSHIFT	Shifts in the distribution and composition of marine ecosystems may lead priority habitats and species to move beyond the limits of MPAs, either within a nation exclusive economic zone or to international waters[36.] Climate-aware conservation planning should therefore consider dynamic MPAs[37].	3
	SLR	Sea level rise is expected to induce loss of keystone shallow-water habitats (e.g. coral reefs). Concomitantly, many low-lying oceanic islands will be entirely submerged due to sea level rise, threatening most of their marine biodiversity and respective MPAs[38].	2
	CIRCW	Changes in the direction and strength of circulation and winds can have profound impacts on marine ecosystems by altering species dispersal and connectivity patterns, transport/retention of contaminants, and nutrients along the neritic zone[4]. This may lead to a redefinition of MPAs boundaries.	2
	EXT	Increased frequency of extreme events (e.g. hurricanes, storms) may promote loss of keystone habitats such as coral reefs[21]. These are, nevertheless, episodic events.	1
	DISHAB	Climate change can increase the emergence of new diseases by increasing the rate of contact between novel pathogens and susceptible hosts, and by altering the environment in favor of the pathogen. Disease outbreaks may affect marine biodiversity by removing e.g. ecological dominants. However, besides the fact that such outbreaks are episodic and often unpredictable, it is difficult to calculate the extent to which increasing diseases will lead to biodiversity losses[39].	1
	HYPO	Hypoxia raises species conservation issues, as it elicits reduced growth rates, loss of reproductive ability and enhanced mortality[26]. However, as stated for fisheries, the occurrence of “dead-zones” is not globally widespread.	2

Table S1 | Cont.

Ocean use	Driver of change	Brief description of direct impacts (with key references)	Impact degree
Aquaculture	WARM	Warming can also induce the migration of optimal conditions for a given culture. Species with a wider optimal range of temperature and higher thermal limits will benefit from warming, by increased metabolism, growth rates and hence overall production. On the other hand, as for species with a very narrow optimal range of temperature and a relatively low upper thermal limit, warming may significantly enhance mortality and affect productivity[19,40].	3
	ACID	Weakened $CaCO_3$ shells and skeletons and slower growth rates are expected, mostly in shell-borne organisms[4,11,12].	2
	DSHIFT	The background conditions for particular cultures can change with shifts in the distribution and composition of biological resources. Changes in the distribution and biomasses of planktonic plant and animal groups may occur, resulting in changes in food webs[19]. For example, if primary production drops in a region[13] local shellfish cultures will be affected.	2
	SLR	Sea level rise can induce a direct loss of intertidal area for aquaculture, as well as loss of areas providing physical protection [19].	1
	CIRCW	Fluctuations on ocean's heat content will affect circulation patterns, and consequently affect aquaculture[19]. Changes in the direction and strength of circulation and winds may alter transport/retention of contaminants, and nutrients along the neritic zone[4].	2
	EXT	More intense and frequent extreme weather events will result in stock losses and increased damage of infrastructures (rafts, lines or cages)[19,40].	3
	DISHAB	Warming stimulates growth, transmission and survival of marine pathogens (parasites, bacteria, viruses), which make cultivated species more vulnerable to infectious diseases. Because aquaculture is spatially limited to relatively "small" areas (when compared to other ocean uses) and has unnaturally higher host densities, increased occurrence of diseases is expected. Concomitantly, the impact of HABs in caged stocks will be more deleterious than those expected for fisheries. All these issues are especially relevant because they pose human health risks[19,40].	3
	HYPO	The emergence of increasing areas of hypoxia and anoxia, mostly in upwelling systems, is expected with consequent deleterious effects to the cultured stocks[32,41].	2

Table S1 | Cont.

Ocean use	Driver of change	Brief description of direct impacts (with key references)	Impact degree
Tourism	WARM	Local weather is key to tourism, and ocean temperature is a relevant component. Ocean warming is expected to cause significant changes in species and habitats, some of which are essential for the development of marine tourism activities. For example, bleaching of coral reefs in tropical regions[4,25] decreases the demand for diving or underwater photography[42]. However, the extent to which marine tourism activities are depended on CC impacts is highly variable, depending on both the activity and the destination. Concomitantly, impacts on activities such as e.g. whale watching, windsurf, kitesurf, and sailing are poorly studied[42].	2
	ACID	Similarly to warming, ocean acidification may affect organisms that are essential for the development of marine tourism activities. However, responses to acidification are very species-specific and different among taxonomic groups[11,12].	1
	DSHIFT	Touristic activities that rely on marine biological resources, such as marine wildlife watching, diving, snorkeling, underwater photography, or recreational fishing, will be affected by shifts in the composition and distribution of marine resources[42].	2
	SLR	Small island states that are highly dependent on tourism as their major economic activity (supporting numerous marine tourism activities) are very vulnerable to sea level rise[42,43]. Sea level rise is expected to induce loss of habitats (e.g. coral reefs) that are essential for touristic activities, as well as loss of recreational area (e.g. beach area)[44]. Although detailed studies are not available, sea level rise is also expected to result in the loss and destruction of surf breaks around the world [45].	2
	CIRCW	Alterations in wind and wave potential may affect activities that depend on such physical resources, such as surfing, windsurfing, kitesurfing, and sailing[42].	2
	EXT	More frequent and intense extreme events, such as hurricanes and tropical storms, may devastate touristic destinations (both physically, i.e. infrastructures, or in regards to the destination competitiveness)[44]. This is especially relevant to island nations (e.g. Caribbean region) that rely on the tourism industry as their major source of income[43]. Increased danger at sea can also reduce the occurrence of touristic activities such as yacht cruising, sailing, and big game fishing, while compromising infrastructures (e.g. vessels)[42].	3
	DISHAB	Increased emergence of new diseases may affect human health and constrain touristic activities that require a physical contact with the marine environment (e.g. surfing, diving, and swimming).	1
	HYPO	As for warming and acidification, hypoxia may affect organisms that are essential for the development of marine tourism activities. However, the occurrence of "dead-zones" is not globally widespread[33].	1

Table S1 | Cont.

Ocean use	Driver of change	Brief description of direct impacts (with key references)	Impact degree
Shipping	WARM	Melting of glaciers due to ocean warming will open new navigable routes/areas in the poles, which will considerably affect navigation patterns around the world[46,47].	3
	ACID	N/A	0
	DSHIFT	N/A	0
	SLR	Shoreline-based infrastructures associated to shipping (seaports) may have to be relocated due to sea level rise with implications for international trade[48].	2
	CIRCW	Shifts in circulation and wind patterns may alter international transportation networks, namely because wind strength and wave height affect the risk of shipping incidents[49]. As well, if wind propulsion technologies are accepted in international shipping[50] changing wind patterns may significantly affect shipping in the future.	2
	EXT	Increased frequency of storms and other extreme events may threaten shipping by damaging ships and related infrastructures (seaports), increasing danger at sea, and causing loss/gain of navigation routes.	3
	DISHAB	N/A	0
	HYPO	N/A	0
Energy	WARM	Because icing on wind turbines represents a major challenge to their installation and operation, expected substantial declines in icing frequency in face of climate change[51] will make new sites available for wind energy development (namely in artic latitudes)[52]. Concomitantly, decreases in sea ice (particularly drifting sea ice) due to warming will positively impact deployment of wind turbines offshore[53]. Moreover, increasing air temperature is expected to lead to slight declines in air density and power production[52]. However, expected positive/negative impacts in wind energy developments will depend on the region under consideration[52].	2
	ACID	N/A	0
	DSHIFT	N/A	0
	SLR	Sea level rise is expected to affect wave energy shoreline-based devices, while systems that are moored in deeper waters might experience limited impacts[54].	2
	CIRCW	Changes in wind patterns (both onshore and offshore) are widely anticipated in face of climate change[55], and wave power is also expected to change under future climate scenarios[54,56]. Wind energy will be primarily impacted by spatial and temporal changes in wind speeds and in energy density[52]. Concomitantly, wave energy potential can be vulnerable to wind forcing changes[55]. Moreover, loading on offshore wind turbines is subject to the combined action of wind and wave loads, and for that reason expected changes in wave heights will also affect wind energy potential[52].	3
	EXT	Increased storm activity, and other extreme events are likely to enhance survival risk of energy infrastructures[54] and to limit maintenance procedures.	3
	DISHAB	N/A	0
	HYPO	N/A	0

Table S1 | Cont.

Ocean use	Driver of change	Brief description of direct impacts (with key references)	Impact degree
Deep sea mining	WARM	N/A	0
	ACID	N/A	0
	DSHIFT	N/A	0
	SLR	N/A	0
	CIRCW	N/A	0
	EXT	Increased frequency of storms and hurricanes is expected to threaten mining infrastructures and to increase danger at sea (limiting operational procedures). Infrastructures survival risk is especially important when hazardous substances are being drilled (e.g. oil products)[57]. In such cases, if infrastructures are damaged major pollution events can take place with severe environmental and socioeconomic impacts[58,59].	3
	DISHAB	N/A	0
	HYPO	N/A	0

References

1. C. Ehler, F. Douvere, *Marine spatial planning: a step-by-step approach toward ecosystem-based management* (IOC Manual and Guides no. 53 - ICAM Dossier no. 6, UNESCO, 2009).
2. Portuguese Government, *The POEM Spatialization* [In Portuguese] (vol. 2, no. 1, MAMAOT, Portugal, 2012).
3. H. O. Pörtner, A. P. Farrell, Physiology and climate change. *Science* 322, 690 (2008).
4. H. O. Pörtner et al., in *IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, C. B. Field et al., Eds. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014), pp. 411-484.
5. H. O. Pörtner, R. Knust, Climate Change Affects Marine Fishes Through the Oxygen Limitation of Thermal Tolerance. *Science* 315, 95 (2007).
6. S. D. Simpson et al., Continental shelf-wide response of a fish assemblage to rapid warming of the sea. *Current Biology* 21, 1565 (2011).
7. G. N. Somero, The physiology of global change: linking patterns to mechanisms. *Annual Review of Marine Science* 4, 39 (2012).
8. R. Ter Hofstede, J. G. Hiddink, A. D. Rijnsdorp, Regional warming changes fish species richness in the eastern North Atlantic Ocean. Marine Ecology Progress Series 414, 1 (2010).
9. V. J. Fabry, B. A. Seibel, R. A. Feely, J. C. Orr, Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science: Journal du Conseil* 65, 414 (2008).
10. J. P. Gattuso et al., Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science* 349, 45 (2015).
11. K. J. Kroeker et al., Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology* 19, 1884 (2013).
12. K. J. Kroeker, R. L. Kordas, R. N. Crim, G. G. Singh, Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters* 13, 1419 (2010).
13. M. Barange et al., Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nature Climate Change* 4, 211 (2014).
14. M. Fossheim et al., Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature Climate Change* 5, 673 (2015).
15. A. L. Perry, P. J. Low, J. R. Ellis, J. D. Reynolds, Climate Change and Distribution Shifts in Marine Fishes. *Science* 308, 1912 (2005).
16. E. S. Poloczanska et al., Global imprint of climate change on marine life. *Nature Climate Change* 3, 919 (2013).
17. L. A. Rutterford et al., Future fish distributions constrained by depth in warming seas. *Nature Climate Change* 5, 569 (2015).
18. K. G. Abrantes, A. Barnett, R. Baker, M. Sheaves, Habitat-specific food webs and trophic interactions supporting coastal-dependent fishery species: an Australian case study. *Reviews in Fish Biology and Fisheries* 25, 337 (2015).
19. K. Cochrane, C. De Young, D. Soto, T. Bahri, *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge*. (FAO Fisheries and Aquaculture Technical Paper No. 530, Rome, 2009), pp. 212.
20. J. G. Titus, K. E. Anderson, *Coastal sensitivity to sea-level rise: a focus on the mid-Atlantic region*. (Government Printing Office, vol. 4, 2009).

21. P. J. Mumby, Bleaching and hurricane disturbances to populations of coral recruits in Belize. *Marine Ecology Progress Series* 190, 27 (1999).
22. C. Baker-Austin et al., Emerging Vibrio risk at high latitudes in response to ocean warming. *Nature Climate Change* 3, 73 (2013).
23. C. A. Burge et al., Climate change influences on marine infectious diseases: implications for management and society. *Marine Science* 6, 249 (2014).
24. S. Altizer, R. S. Ostfeld, P. T. Johnson, S. Kutz, C. D. Harvell, Climate change and infectious diseases: from evidence to a predictive framework. *Science* 341, 514 (2013).
25. L. Kwiatkowski, P. Cox, P. R. Halloran, P. J. Mumby, A. J. Wiltshire, Coral bleaching under unconventional scenarios of climate warming and ocean acidification. *Nature Climate Change* 5, 777 (2015).
26. J. S. Gray, R. S.-s. Wu, Y. Y. Or, Effects of hypoxia and organic enrichment on the coastal marine environment. *Marine Ecology Progress Series* 238, 249 (2002).
27. R. F. Keeling, H. E. Garcia, The change in oceanic O2 inventory associated with recent global warming. *Proceedings of the National Academy of Sciences* 99, 7848 (2002).
28. R. F. Keeling, A. Körtzinger, N. Gruber, Ocean deoxygenation in a warming world. *Marine Science* 2, 199 (2010).
29. E. D. Prince, C. P. Goodyear, Hypoxia-based habitat compression of tropical pelagic fishes. *Fisheries Oceanography* 15, 451 (2006).
30. R. Rosa, B. A. Seibel, Synergistic effects of climate-related variables suggest future physiological impairment in a top oceanic predator. *Proceedings of the National Academy of Sciences* 105, 20776 (2008).
31. L. Stramma, G. C. Johnson, J. Sprintall, V. Mohrholz, Expanding oxygen-minimum zones in the tropical oceans. *Science* 320, 655 (2008).
32. B. A. Grantham et al., Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature* 429, 749 (2004).
33. R. J. Diaz, R. Rosenberg, Spreading dead zones and consequences for marine ecosystems. *Science* 321, 926 (2008).
34. L. R. Gerber, M. D. M. Mancha-Cisneros, M. I. O'Connor, E. R. Selig, Climate change impacts on connectivity in the ocean: Implications for conservation. *Ecosphere* 5, 1 (2014).
35. R. A. Magris, R. L. Pressey, R. Weeks, N. C. Ban, Integrating connectivity and climate change into marine conservation planning. *Biological Conservation* 170, 207 (2014).
36. K. S. G. Gormley, A. D. Hull, J. S. Porter, M. C. Bell, W. G. Sanderson, Adaptive management, international co-operation and planning for marine conservation hotspots in a changing climate. Marine Policy 53, 54 (2015).
37. A. J. Hobday, Sliding baselines and shuffling species: implications of climate change for marine conservation. *Marine Ecology-an Evolutionary Perspective* 32, 392 (2011).
38. F. Courchamp, B. D. Hoffmann, J. C. Russell, C. Leclerc, C. Bellard, Climate change, sea-level rise, and conservation: keeping island biodiversity afloat. *Trends in Ecology and Evolution* 29, 127 (2014).
39. K. Kim, A. P. Dobson, F. M. D. Gulland, C. D. Harvell, in *Marine Conservation Biology: the Science of Maintaining the Sea’s Diversity*, E. A. Norse, L. B. Crowder, Eds. (Island Press, 2005), pp. 149-166.
40. R. Rosa, A. Marques, M. L. Nunes, Impact of climate change in Mediterranean aquaculture. *Reviews in Aquaculture* 4, 163 (2012).
41. F. Chan et al., Emergence of anoxia in the California Current large marine ecosystem. *Science* 319, 920 (2008).

42. A. Moreno, B. Amelung, Climate Change and Coastal & Marine Tourism: Review and Analysis. *Journal of Coastal Research* SI 56, 1140 (2009).

43. C. Lewsey, G. Cid, E. Kruse, Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy* 28, 393 (2004).

44. D. Scott, M. C. Simpson, R. Sim, The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *Journal of Sustainable Tourism* 20, 883 (2012).

45. A. Knights, *Climate Change: A Surfers Perspective* (Cornwall, UK, 2007).

46. L. C. Smith, S. R. Stephenson, New Trans-Arctic shipping routes navigable by midcentury. *Proceedings of the National Academy of Sciences* 110, E1191 (2013).

47. E. Bekkers, J. F. Francois, H. Rojas-Romagosa, *Melting Ice Caps and the Economic Impact of Opening the Northern Sea Route* CPB Discussion Paper 307 (2015).

48. A. H. Becker et al., A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. *Climatic Change* 120, 683 (2013).

49. C. Heij, S. Knapp, Effects of wind strength and wave height on ship incident risk: Regional trends and seasonality. *Transportation Research Part D: Transport and Environment* 37, 29 (2015).

50. I. Rojon, C. Dieperink, Blowin' in the wind? Drivers and barriers for the uptake of wind propulsion in international shipping. *Energy Policy* 67, 394 (2014).

51. N.-E. Clausen et al., in *Impacts of Climate Change on Renewable Energy Sources*, J. Fenger, Ed. (Nordic Council of Ministers, Copenhagen, 2007), pp. 105-128.

52. S. C. Pryor, R. J. Barthelmie, Climate change impacts on wind energy: A review. *Renewable and Sustainable Energy Reviews* 14, 430 (2010).

53. A. Mróz, J. Holnicki-Szulc, T. Kärnä, Mitigation of ice loading on off-shore wind turbines: Feasibility study of a semi- active solution. *Computers & Structures* 86, 217 (2008).

54. G. P. Harrison, A. R. Wallace, Sensitivity of wave energy to climate change. *IEEE Transactions on Energy Conversion* 20, 870 (2005).

55. D. E. Reeve et al., An investigation of the impacts of climate change on wave energy generation: The Wave Hub, Cornwall, UK. *Renewable Energy* 36, 2404 (2011).

56. I. Grevemeyer, R. Herber, H. H. Essen, Microseismological evidence for a changing wave climate in the northeast Atlantic Ocean. *Nature* 408, 349 (2000).

57. Z. Ismail et al., Evaluating accidents in the offshore drilling of petroleum: Regional picture and reducing impact. *Measurement* 51, 18 (2014).

58. White HK, Hsing P-Y, Cho W, Shank TM, Cordes EE, Quattrini AM, et al. Impact of the Deepwater Horizon oil spill on a deep-water coral community in the Gulf of Mexico. *Proceedings of the National Academy of Sciences* 109, 20303 (2012).

59. Zengel S, Bernik BM, Rutherford N, Nixon Z, Michel J. Heavily oiled salt marsh following the Deepwater Horizon oil spill, ecological comparisons of shoreline cleanup treatments and recovery. *Plos One* 10, e0132324 (2015).