Chapter 4.3 Current and Future Ocean Deoxygenation

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4.3   Current and Future Ocean Deoxygenation

4.3.1   Summary and Key Messages

Ocean ecosystems are increasingly stressed by human-induced changes of their physical, chemical and biological environment. Among these changes deoxygenation is considered as one of the major stressors of open ocean ecosystems. Concentration of dissolved oxygen (O_2) is a major determinant of the distribution and abundance of marine species globally, and therefore deoxygenation is considered as one of the four major human-induced stressors on ocean ecosystems[24]. All these stressors emerged from significant physical, chemical and biological changes that the ocean has rapidly undergone in recent decades in response to the uptake of anthropogenic carbon dioxide (CO_2) from the atmosphere (Doney 2010). Due to ever-increasing CO_2 emissions in the coming decades these changes will amplify with potentially significant consequences for marine organisms and ecosystems (Doney et al. 2012). Here, we use the most recent model simulations performed in the framework of the Coupled Model Intercomparison Project 5 (CMIP 5). The models simulate future climate states and dynamics to assess how ocean deoxygenation may evolve over the course of the 21st century based on four greenhouse-gas concentration trajectories (referred to as Representative Concentration Pathways or RCPs) adopted by the IPCC for its Fifth Assessment Report See Glossary Box 2.

Key Messages

- Concentration of dissolved O_2 is a major determinant of the distribution and abundance of marine species globally and therefore deoxygenation is considered as one of the four major human-induced stressors on ocean ecosystems;
- Open ocean deoxygenation has been recorded in nearly all ocean basins during the second half of the 20th century, with increased temperature responsible for approximately 15 per cent of the observed change and the remaining 85 per cent attributed to reduced O_2 supply due to increased ocean stratification and increased deep-sea microbial respiration;
- In most marine systems hypoxia alters physiological and metabolic rate processes, organism abundance, lifestyles, composition, complexity, diversity, and size structure (Levin 2003; Childress and Siebel 1998) resulting in mortality of benthic fauna, fish kills, habitat loss, and overall physiological stress;
- The biggest threat related to open ocean deoxygenation is that of decline in biodiversity through attrition of intolerant species and elevated dominance, as well as reductions in body size with impacts on organisms within the affected areas as well as in their vertical and horizontal proximities;
- We map and discuss the projected evolution of ocean deoxygenation for the 2030s and 2090s for two RCP scenarios using the latest generation of earth system models collated under CMIP5. Observations based regional and ecosystem-level impacts are discussed in relation to global O_2 change;
- Consistently with other studies, CMIP5 projections show an overall decline in oceanic dissolved O_2 concentration of 2 to 4 per cent in the 2090s relative to the 1990s depending on the complexity of a model and global warming scenario chosen;
- The North Pacific, the North Atlantic, the Southern Ocean, the subtropical South Pacific and South Indian oceans all undergo deoxygenation, with O_2 decreases of as much as -50 μmol kg^{-1} in the North Pacific by the end of the century for the RCP 8.5 scenario;
- The outcomes of these global changes are *very likely* to be influenced by regional differences such as wind stress, coastal processes, and the supply of organic matter. Global trend quantification remains a very challenging task. Projected O_2 changes in the subsurface layer (200-600 m) show a complex pattern with both increasing and decreasing trends reflecting the subtle balance of different competing factors such as circulation, production, remineralization, and temperature changes; and

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24   The other three are warming, changes in primary productivity and ocean acidification.

- Significant reduction in the uncertainty of model projections is needed for informed regional management interventions and policy implementation. We recommend significant strengthening of our observational capacity in both long-term, large-scale mode and process study mode, to gain better understanding of very dynamic relationships between the major ocean stressors. This, in turn, will enhance our ability to model these systems with less uncertainty.

4.3.2   Main Findings, Discussion and Conclusions

The average dissolved O_2 concentration in the ocean is presently 162 µmol kg^{-1} (Sarmiento and Gruber 2006). Concentrations range from over 500 µmol kg^{-1} in productive Antarctic waters (Carrillo *et al.* 2004) to zero in coastal sediments and in deep layers of isolated water bodies, such as the Black Sea and the Cariaco Basin. Most organisms are not very sensitive to oxygen (O_2) levels as long as the concentrations are high enough. But once O_2 drops below a certain threshold, the organism suffers from a variety of stresses, leading ultimately to death if the concentrations stay too low for too long. Such conditions are termed hypoxic. In general terms, hypoxia results from O_2 depletion in excess of supply.

Open ocean deoxygenation has been recorded in nearly all ocean basins during the second half of the 20th century (Stramma *et al.* 2008). Still relatively sparse and localized observational studies indicate a mostly negative trend in the O_2 content over recent decades in several basins of the world's ocean (Takatani et al. 2012; Keeling et al. 2010; Stramma et al. 2008; Chan et al. 2008; Whitney et al. 2007; Mecking et al. 2006; Emerson et al. 2004; Joos et al. 2003) including Black and Baltic Seas, the Arabian Sea, and the California, Humboldt, and Benguela Current systems. A recent global-scale observational study (Helm et al. 2011) supports the evidence of a widespread ocean O_2 decrease between the 1970s and the 1990s. The reduction in O_2 concentration in these reports is consistent with that expected from higher ocean temperatures and a reduction in mixing (increased stratification). A report by Helm et al. (2011) shows that the decline in O_2 solubility with increased temperature is responsible for approximately 15 per cent of the observed change. The remaining 85 per cent is associated with reduced O_2 supply due to increased ocean stratification and increased deep-sea microbial respiration. On the contrary, greater mixing and ventilation due to strengthening wind systems in the North and South Pacific, North Atlantic and Indian oceans caused an increase in O_2 concentrations.

Thresholds for hypoxia vary greatly between marine taxa, with fish and crustaceans tending to be the most sensitive. In ecological literature the threshold for hypoxia is used for water masses with O_2 concentrations below 60 µmol kg^{-1} (Gray et al. 2002; Deutsch et al. 2011; Vaquer-Sunyer and Duarte 2008). Zones with lower O_2 are effectively "dead zones" for many higher animals. The most intense (O_2 <20 µmol kg^{-1}) and largest O_2 minimum zones (OMZs), known as suboxic layers, are mainly localized in subsurface of the upwelling regions in the Eastern Pacific (both north and south of the Equator) and Northern Indian open oceans (Figure 4.34). In the Atlantic, a slightly lesser degree of O_2 depletion is reported in relatively stagnant cyclonic gyres that exist north and south of the Equator in the east of the basin.

The O_2 minimum is typically found at depths between 400 m and 1200 m, near the base of the permanent thermocline, however they are found at depths as shallow as 100 m in the eastern tropical Atlantic and tropical Pacific oceans. In the past, OMZs have probably extended and contracted in warm (interglacial) and cold (glacial) periods, associated with high and low atmospheric CO_2 respectively. In the present, and according to the last two decades of observations, OMZs increase or intensify - and even new ones appear locally and episodically - in tune with high anthropogenic CO_2 uptake by the ocean.

The biggest threat related to open ocean deoxygenation is that of decline in biodiversity through attrition of intolerant species and elevated dominance, as well as reductions in body size, with impacts on organisms within the affected areas as well as in their vertical and horizontal proximities (Levin et al. 2009; Gooday et al. 2009). Shoaling of the tropical OMZs restricts the depth distribution of tropical pelagic fishes such as marlins, sailfish, and tuna by compressing their habitat into a narrow surface layer. Restriction of these fishes toward the surface could make them more vulnerable to over-exploitation by surface fishing gear (Prince and Goodyear 2006). For many fish and

Figure 4.34. Sub-surface O_2 concentrations averaged between 200 m and 600 m from World Ocean Atlas 2009 (µmol kg⁻¹). Light and dark red stripes indicate waters with O_2< 100 µmol kg⁻¹ and O_2< 20 µmol kg⁻¹ respectively.
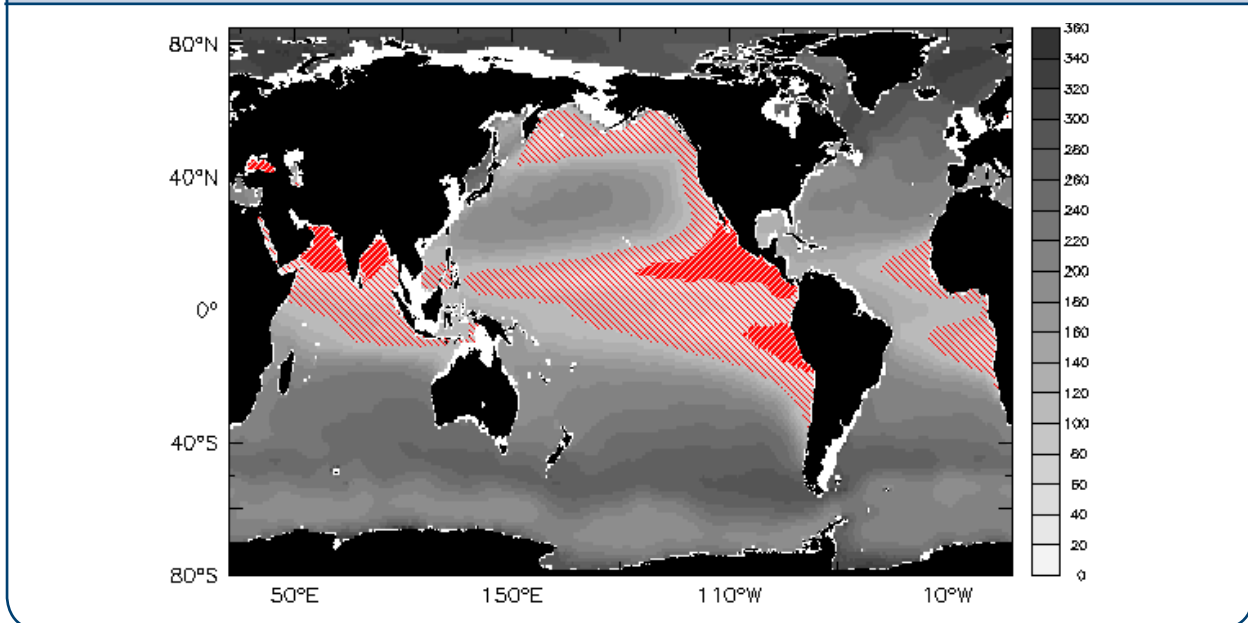
crustacean species, larvae are less tolerant of hypoxia than adults, and thus expansion of hypoxic waters may create or enlarge dispersal barriers. Rapidly growing larval fish are especially susceptible to stress from hypoxic conditions as they shift from oxygenation by diffusion to active ventilation of gills. Among adults, reproducing females might also be more *likely* to experience O_2 limitations, as gonads have elevated O_2 demand (Portner and Farrell 2008).

In most marine systems hypoxia alters physiological and metabolic rate processes, organism abundance, lifestyles, composition, complexity, diversity, and size structure (Childress and Siebel 1998; Levin 2003) resulting in mortality of benthic fauna, fish kills, habitat loss, and overall physiological stress. In the future it is expected to observe overall reduced biodiversity associated with avoidance, mortality, or lowered growth and reproductive rates of hypoxia-sensitive species. OMZ expansion may also cause jelly plankton to become more prevalent in the water column. In addition, increasing jellyfish populations may promote hypoxia by preying on zooplankton, leaving unconsumed phytoplankton to sink and degrade.

Hypoxia also influences biogeochemical cycles of elements, with perturbations to the global nitrogen cycle being the greatest current concern. Expansion of OMZ's is expected to lead to increased production of nitrous oxide (N_2O), an ozone-destroying greenhouse gas with global warming potential significantly higher than that of CO_2 (Ravishankara et al. 2009). Because of the paucity of direct measurements of N_2O production and consumption in the ocean, current rate estimates and predictions of how the N_2O budget will respond to future changes in oceanic O_2 concentration remain uncertain. However, the strongest oceanic sources of N_2O to the atmosphere are the suboxic (0 to 20 µmol l⁻¹) waters overlying the OMZs, based on measurements and models of supersaturated N_2O concentrations (Suntharalingam and Sarmiento 2000). Overall, the OMZs produce about half of all oceanic N_2O emissions (Codispoti 2010), which represents at least 20 per cent of total global emissions estimated at approximately 5.8 (+- 2) Tg N/y (Nevison et al. 2003). Concentration of dissolved N_2O is high in the tropical and northern Pacific and relatively low, although still supersaturated, in the Atlantic and Southern oceans. Subsurface N_2O in OMZs is generally supersaturated with respect to the atmosphere in the eastern tropical Pacific (ETP) and Arabian Sea. N_2O concentrations peak in the upper 500 m of the water column in the ETP, where typical maximum concentrations are 60–70 nM. In comparison, the concentration of N_2O is only 25–30 nM at equivalent depths in the tropical Atlantic, and 10–15 nM in the Southern Ocean (Nevison et al. 2003).

All this mounting evidence suggests that expanding OMZ's are a strong threat to the natural ocean ecosystem, undermining its health and indirectly negatively affecting human wellbeing. Therefore, the key indicator for ocean deoxygenation in this assessment is mapping of the predicted extent of OMZ's. Both projections of deoxygenation state in the future ocean and projected rate of deoxygenation change (trend quantification) are important indicators of change presented here to allow realistic considerations of mitigation and adaptation interventions.

Findings

Consistent with other studies (Matear et al. 2003; Bopp et al. 2002; Oschlies et al. 2008), CMIP5 projections show an overall decline in oceanic dissolved O_2 concentration of 2 to 4 per cent in the 2090s relative to the 1990s depending on the complexity of the model and global warming scenario chosen (Figure 4.35). For the so-called "business-as-usual" scenario RCP 8.5, the model mean change in the 2090s for global ocean O_2 content amounts to -3.45 (+-0.44) per cent (Bopp et al. 2013). Models support the prediction that further global warming will exacerbate hypoxia conditions mainly through reduced O_2 solubility in warmer water. All models also show a substantial additional O_2 loss resulting from enhanced upper ocean stratification and reduced winter ventilation of the water column, particularly in higher latitudes. As an additional complication, the negative trends in the O_2 content correlate not only with temperature, but also with levels of CO_2 connecting aerobic stress and calcification challenges (Hofmann and Schellnhuber 2009).

Figure 4.35. Global ocean model-mean O_2 concentration change (per cent) relative to mean concentration in the 1990s (hence 0 per cent change in the 1990s). The black line shows historical simulations tuned with available observations. Coloured lines represent four RCP scenarios: RCP 2.6 – blue, RCP 4.5 – green, RCP 6.0 – lavender and RCP 8.5 – red. Shading indicates one inter-model standard deviation.
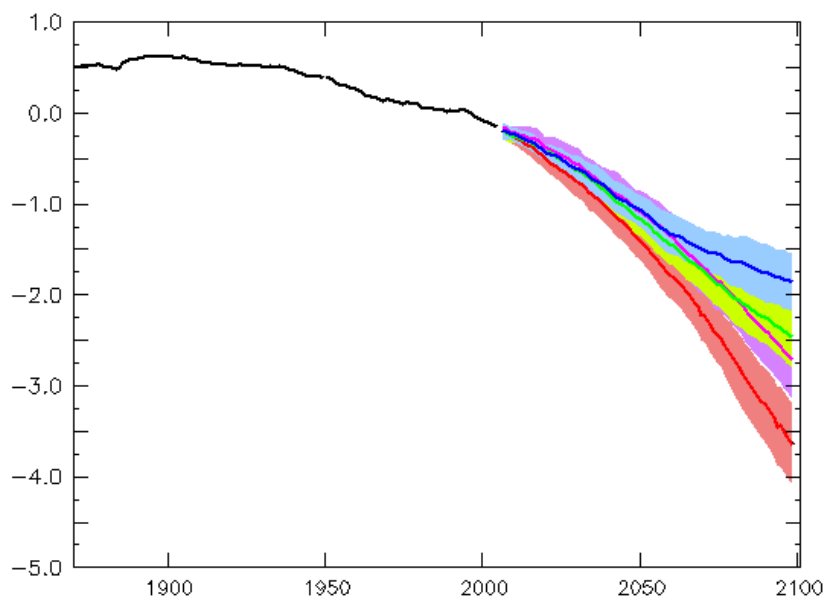
As a consequence, CMIP5 models project an increase in a volume of the mid-depth O_2 minimum under global warming conditions. We use two thresholds (O_2<80 µmol kg^{-1} in Figure 4.36 and O_2<20 µmol kg^{-1} in Figure 4.37) to characterize time evolution of water volumes of low- O_2 waters. Suboxic waters are defined with a threshold of 20 µmol kg^{-1}, whereas hypoxic waters are defined here with a threshold of 80 µmol kg^{-1}. Figures 4.4.3-4 present the relative evolution of these two volumes as simulated by the CMIP5 models over 1870 to 2100 for all the RCP scenarios. By 2100, all models project an increase in the volume of hypoxic waters, ranging from +1 per cent to +9 per cent for individual models.

This response is more consistent than that of the previous generation of earth system models, for which changes varied from −26 to +16 per cent over 1870 to 2099 under the SRES-A2 scenario (Cocco et al. 2013). For lower O_2 levels (Figure 4.37), there is still much less agreement among the CMIP5 models. For suboxic waters, individual models project an expansion of up to 30 per cent or even a slight contraction of 4 per cent. These results for low-O_2 waters agree with those of Cocco et al. (2013), with large model–data and model–model discrepancies and simulated responses varying in sign for the evolution of these volumes under climate change.

Figure 4.36. Model-mean time series of water masses with O_2 content ‹80 µmol kg⁻¹ over 1870-2100 using historical simulations (black line) and four RCP scenarios. Shading indicates one inter-model standard deviation. Colours represent RCP scenarios: RCP 2.6 – blue, RCP 4.5 – green, RCP 6.0 – lavender and RCP 8.5 – red. Values are plotted relative to the 1990s mean.

Figure 4.37. Model-mean time series of water masses with O_2 content ‹20 µmol kg⁻¹ over 1870-2100 using historical simulations (black line) and four RCP scenarios. Shading indicates one inter-model standard deviation. Colours represent RCP scenarios: RCP 2.6 – blue, RCP 4.5 – green, RCP 6.0 – lavender and RCP 8.5 – red. Values are plotted relative to the 1990s mean.
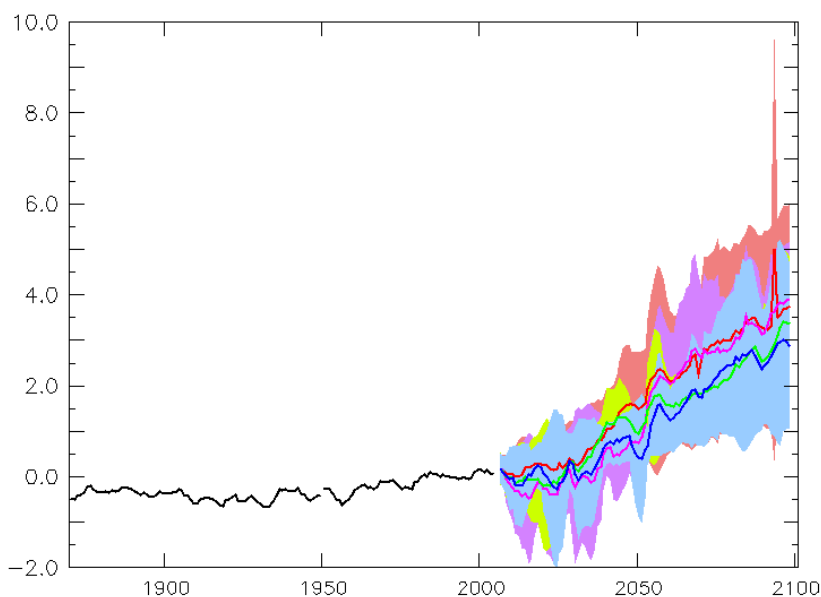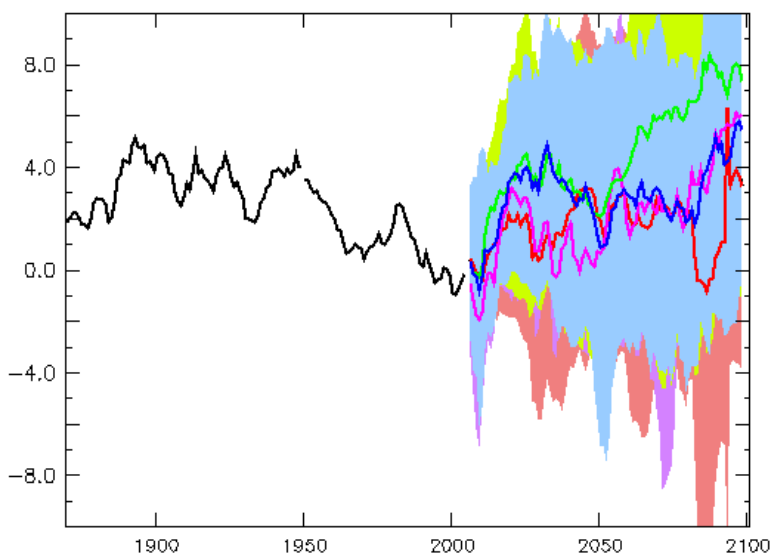
In Figure 4.38 we show projected spatial and temporal changes in subsurface (200 m to 600 m depth) O_2 distribution for the two selected scenarios (RCP 8.5 in left column and RCP 4.5 in right column). All panels show maps of differences. Top row shows changes between the 1990s and 2030s for both scenarios and bottom row shows changes between the 1990s and 2090s, also for both scenarios. Negative values mean deoxygenation. Projected changes are also not uniform across models. Black dots marks regions with high projection robustness across models defined when at least 80 per cent of models agree on the sign of the mean change. The complex patterns of spatial changes are very similar across the two scenarios for both periods and reflect the influence of changes in several processes like ventilation, vertical mixing or remineralization on O_2 levels.

Figure 4.38. Change in subsurface (averaged for 200-600 m depth) O_2 concentration in the 2030s relative to the 1990s (top panels) and in the 2090s relative to the 1990s (bottom panels), for two RCP scenarios, RCP 8.5 on the left and RCP 4.5 on the right. Negative values mean deoxygenation. Black dots marks regions with high projection robustness across models. Red stripes indicate current OMZs as in Figure 4.34.
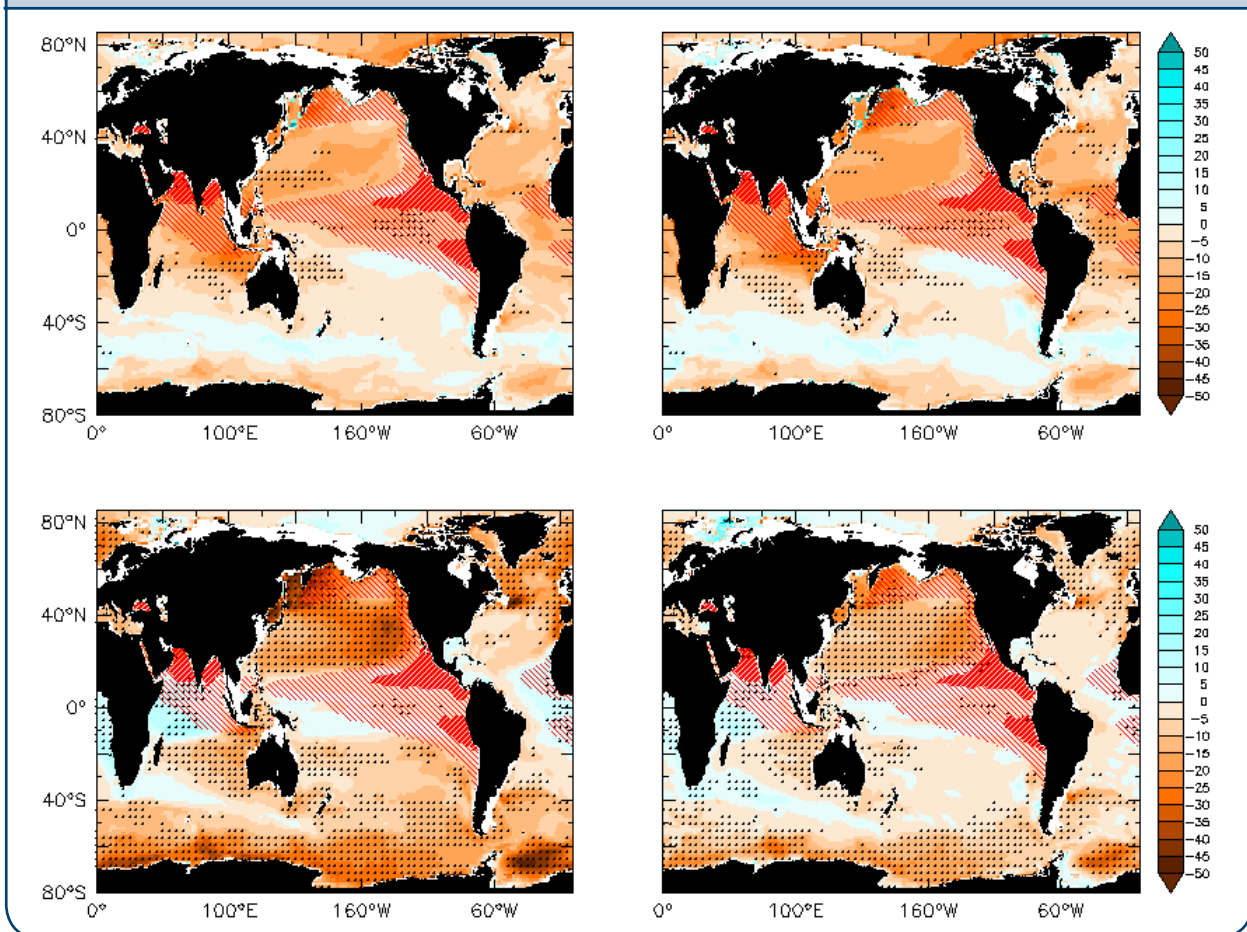
The North Pacific, the North Atlantic, the Southern Ocean, the subtropical South Pacific and South Indian oceans all undergo deoxygenation, with O_2 decreases of as much as −50 μmol kg^{-1} in the North Pacific for the RCP 8.5 scenario. In contrast, the tropical Atlantic and the tropical Indian show increasing O_2 concentrations in response to climate change, in both scenarios. The equatorial Pacific displays a weak east–west dipole, with increasing O_2 in the east and decreasing O_2 in the west. Apart from changes in the equatorial Pacific, these regional changes in subsurface O_2 are consistent across models under the RCP 8.5 scenario for the 2090s as indicated by black dots in Figure 4.38, and they are quite similar to those from a recent intermodel comparison of the previous generation of Earth system models (Cocco et al. 2013).

Over the mid-latitudes, patterns of projected changes in subsurface O_2 are broadly consistent with observations collected over the past several decades (Helm et al. 2011; Stendardo and Gruber 2012; Takatani et al. 2012). Yet there is no such model–data agreement over most of the tropical oceans Red stripes indicate a negative O_2 concentration trend based on observations and a blue background indicates a positive O_2 concentration trend projected by the models. Observed time series suggest a vertical expansion of the low-O_2 zones in the eastern tropical Atlantic and the equatorial Pacific during the past 50 years (Stramma et al. 2008), conversely with models that simulate increasing O_2 levels with global warming over the historical period (Andrews et al. 2013).

These results indicate a strong need for better understanding of "model-usable" physical and biogeochemical processes driving O_2-related changes at the global and regional scales. Currently, most of the data-model discrepancies are explained primarily by the fact that a number of biogeochemical ocean carbon cycle feedbacks that could also impact future trends of ocean deoxygenation are not yet included in most marine biogeochemical models (including CMIP5 models). For example, model experiments which include one of the feedbacks (namely pCO_2- sensitive C:N drawdown in primary production) suggested by some medium-scale in-situ experiments of limited duration (Riebesell et al. 2007), project future increases of up to 50 per cent in the volume of the suboxic waters by 2100 (Oschlies et al. 2008; Tagliabue et al. 2011). In addition, future marine hypoxia could be amplified by changes in the $CaCO_3$ to organic matter 'rain ratio' in response to rising seawater pCO_2 (Hofmann and Schellnhuber, 2009). CMIP5 estimates also do not take into account processes that are specific to the coastal ocean and may amplify deoxygenation.

Discussion and Conclusions

There is high agreement among CMIP5 models that O_2 concentrations will continue to decrease in most parts of the ocean due to the effect of temperature on O_2 solubility, ocean ventilation, and ocean stratification and microbial respiration rates (Andrews et al. 2013). Negative implications for nutrient and carbon cycling and ocean productivity are *very likely* (Bopp et al. 2013). The North Pacific and Atlantic oceans as well as the Southern Ocean will be the most affected by deoxygenation by the end of the century. Projections for tropical regions have *high* uncertainties and call for much caution when concluding from CMIP5 results.

Global trend quantification remains a very challenging task. Projected O_2 changes in the subsurface layer (200-600 m) show a complex pattern with both increasing and decreasing trends reflecting the subtle balance of different competing factors such as circulation, production, remineralization, and temperature changes (Cocco et al. 2013). Projected changes in the total volume of hypoxic and suboxic waters remain relatively uncertain in the current generation of earth system models. The outcomes of the global changes are *very likely* to be influenced by regional differences such as wind stress (Vecchi and Soden 2007), coastal processes, and the supply of organic matter (Snyder et al. 2003). Global earth system models such as those used in CMIP5 only start to be run at detailed-enough resolution to be able to resolve regional variability and answer questions on regional ecosystem or species level very accurately.

Biological consequences of reduced O_2 concentrations are *likely* to be most notable for the 200–400 m layer, as these waters impinge on the euphotic zone and the outer continental shelf, where these O_2-depleted waters may be upwelled into productive eastern boundary currents (Chhak and Di Lorenzi, 2007). According to an ever-growing body of literature, OMZs expanding vertically and laterally will cause habitat and abundance losses for intolerant taxa with a high O_2 demand such as fishes including top predators (Prince et al. 2010; Stramma et al. 2010; Koslow et al. 2011; Stramma et al. 2012). Expanding OMZs will probably further constrain the distribution of key zooplankton and nekton species (Ekau et al. 2010). Dissolved O_2, among other factors, plays an important role in shaping large alternating fluctuations of sardine and anchovy abundances, particularly off Peru. Where OMZs intersect the continental shelves, groundfishes (McClatchie et al. 2010) and large benthic invertebrates like crabs display high mortalities (Chan et al. 2008). Susceptibility of early life stages to hypoxia in both pelagic and benthic ecosystems (Ekau et al. 2010) threatens population survival. The upwelled OMZ waters may interact with natural or eutrophication-induced hypoxic zones on the inner shelves; this occurs for example off Peru and Chile, Namibia and the western Indian margin. In the eastern Pacific these O_2-poor upwelled waters are corrosive and under-saturated with respect to

aragonite, exacerbating the stress imposed on the exposed ecosystems (Feely et al. 2008). In regions where O_2 levels decline and OMZs expand, tolerant taxa, such as anaerobic bacteria (Ulloa et al. 2012), gelatinous zooplankton (medusae, ctenophores), selected fishes (gobies, hake), and possibly selected cephalopods (Gilly et al. 2006; Bazzino et al. 2010), will respond with range expansions or population growth. A community change toward hypoxia-tolerant fauna will occur in mid-water (IPCC 2013). The diversity of macro-organisms will decrease and, finally, higher marine organisms will disappear and heterotrophic micro-organisms will dominate (IPCC 2013). In isolated water bodies like the Black Sea, warming will lead to the expansion of anoxia and hydrogen sulfide (H_2S) poisoning, reduce pelagic and bottom faunal distributions, and shape trophic relations, energy flows, and productivity (Daskalov 2003; Fashchuk 2011). All these ecosystem-related feedbacks need to be incorporated into the earth system models through better description of related physical and biogeochemical processes.

Similarly, the ability of climate models to represent O_2 concentration observations has been questioned in recent studies. Stramma et al. (2012) performed a series of model simulations over the historical period and compared the simulated subsurface O_2 trends with observations. They showed that the model was unable to reproduce the spatial patterns of observed changes. Andrews et al. (2013) compared output of two earth system models to observations over the historical period. They reported that both models fail to reproduce the pattern of O_2 loss recorded by observations in low-latitude OMZs. A more thorough analysis of the mechanisms responsible for the model–data discrepancies as well as the mechanisms driving the simulated future changes is necessary. Gnanadesikan et al. (2012) performed such an analysis with simulations carried out with a previous version of the GFDL Earth system model (GFDL-ESM2.1) under the SRES-A2 scenario. They show that the volume of suboxic waters does not increase under global warming in the tropical Pacific. A detailed analysis of the different terms contributing to the O_2 budget showed that an increase in O_2 in very low O_2 waters is associated with an enhanced supply of O_2 through lateral diffusion and increased ventilation along the Chilean coast. These results cast doubt on the ability of the present generation of models to project changes in O_2 accurately at the regional level, especially for low-O_2 waters, and stress the need for more model–data comparisons over the historical period alongside a better understanding of reasons for model biases.

Recommendations

Representation of ecosystems in earth system models such as these presented here is an evolving science. CMIP 5 models represent only a small set of the processes controlling the ecosystem and biogeochemical function. While the models are each constructed in mathematically defensible forms, they are all different in the underlying assumptions. Rather than representing discrete biological forms, they represent ecosystems as a biological continuum with infinite biodiversity in some ways (for example: the role of temperature), and an artificial rigidity in others (for example: fixed half-saturation constants). First strong recommendation would be to focus on improving the next generation of earth system models in this regard.

A related long-term recommendation would be to vastly enhance the resolution in order to represent the mesoscale phenomena such as coastal upwelling and eddies. Only models with resolution fine-enough to represent mesoscale physical and biogeochemical processes will be able to predict ecosystem changes related to anthropogenic pressures.

Finally, the existence of potential synergistic effects between the four different stressors (deoxygenetaion, warming, changes in primary productivity (NPP) and ocean acidification) strongly emphasizes the need to study them together (Boyd et al. 2008). Bopp et al. (2013) shows the temporal model-mean evolution of global surface pH, global O_2 content and global NPP vs. global sea surface warming for each of the RCPs over the 21st century. For RCP 8.5, all these relationships appear linear, implying a constant fraction of acidification, deoxygenation, and NPP reduction per degree of warming. For the other RCP scenarios, relationships are similar for surface pH vs. Sea Surface Temperature (SST) and for NPP vs. SST, but the relationship breaks down for O_2 content versus SST. That is, deoxygenation continues long after SSTs have stabilized. A recommendation would be to significantly enhance observational capacity for all four stressors. Developing a better understanding of the role of processes related to temperature (warming vs stratification), rising biological demand (especially in coastal regions) and acidification in determining O_2

concentrations will enable a more coherent understanding of the changes and potential risks to marine ecosystems. Linkages between changes occurring in the surface ocean and those associated with the deep layers are particularly important in light of a need to understand how rapidly changes are occurring and the implications for the metabolic activity and O_2 content of deep ocean habitats. Both, sensor technology and appropriate platforms exist, but need to be utilized in a much wider geographical context as opposed to the current very limited coverage offered by a couple of hundred profiling floats equipped with biogeochemical sensors. Strong emphasis has to be put on observing system simulation experiments so that the resources are distributed in the most efficient manner in terms of geographic coverage, temporal distribution and combinations of parameters observed.

Given the importance of OMZs to the physical, chemical, and biological characteristics of the ocean, it is extremely important that these systems receive greater focus, especially with regards to their response to ocean warming and acidification. Significant reduction in the uncertainty of model projections is needed for informed regional management interventions and policy implementation. Increasing our observational capacity to gain better understanding of the very dynamic relationships between the major stressors will in turn enhance our ability to model these systems more realistically and with less uncertainty.

4.3.3   Notes on Methods

For this report simulations were obtained with the latest generation of so-called earth system models collated under the Coupled Model Intercomparison Project Phase 5 (CMIP 5[25]) (Taylor et al. 2012). The models simulate future climate states and dynamics based on four greenhouse-gas concentration trajectories adopted by the IPCC for its Fifth Assessment Report. Scenarios are referred to as RCPs (Representative Concentration Pathways) and describe four possible climate futures, depending on how much greenhouse gases are going to be emitted in the years to come (RCP2.6, RCP 4.5, RCP 6.5 and RCP 8.5). In this Chapter, simulations were focused on two scenarios: RCP 4.5 in which emissions peak around 2040, then decline and RCP 8.5 in which emissions continue to rise throughout the 21st century.

Standard CMIP5 output from the Program for Climate Model Diagnosis and inter-comparison (now replaced by the Earth System Grid Federation portal[26]) was provided by the different modeling groups. Ten models were used to compute simulations discussed in this report based on the availability of all variables necessary to discuss the future dynamics of O_2 concentrations in the global ocean. In this report, models were used, for which the simulated volumes of hypoxic and suboxic waters over 1990–1999 fall within + 100 per cent and – 50 per cent of the observed volumes, as estimated from the WOA 2009 database (Bianchi et al. 2012). Each model includes representations of the general circulation and physics of the atmosphere and the ocean, as well as biogeochemical components, including a representation of the ocean carbon cycle and the lowest trophic level of marine ecosystems (Bopp et al. 2013). However, the models differ in many respects like architecture, with a set of components to the degree of complexity. Thus attributing the causes of differences between models to particular processes is difficult (Bopp et al. 2013) and as it is not the subject of this report, will not be discussed. Results presented in this report are the model-mean with inter-model standard deviation as an uncertainty estimate.

The projected evolution of ocean deoxygenation for the 2030s and 2090s for both RCPs were mapped and discussed as differences between projections for these decades and data-based climatology of O_2 distributions obtained from WOA 2009 for the 1990s (shown in Figure 4.34). Further, the projected evolution of global mean O_2 content of the ocean for all four RCPs was presented. Finally, the projected changes in the volumes of water with O_2 levels lower than 80 µmol kg^{-1} and lower than 20 µmol kg^{-1} were discussed.

Models are invaluable tools for studying system dynamics, generalizing discrete observations and predicting future states. Model analyses and predictions are therefore used in this assessment, however their limitations in simulating regional and local concentrations are not insignificant and therefore this data-based assessment was presented for matters un-resolvable by the current generation of earth system models.

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25   http://cmip-pcmdi.llnl.gov/cmip5/index.html?submenuheader=0
26   http://pcmdi9.llnl.gov

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