A Case for the Deep Ocean

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Encompassing 95% of the planet's habitable volume, the deep ocean plays a major role in climate regulation, and thus new pressures exerted on it and its components should be a major concern. The deep sea provides many ecosystem services, such as storing heat and anthropogenic carbon emitted into the atmosphere. These services are key to sequestrating CO_2 and CH_4 on longer time-scales, as well as in supporting nutrient cycling on which the entire foodweb (and so commercial activities such as fisheries) relies. Heat absorption and redistribution impacts human exploited-species ranges. Already absorbing many pollutants and waste, the deep ocean could also become a place for new activities such as mining. Setting up key mitigation and adaptation measures to climate change will require new knowledge, and implementation of a complete legal framework and management tools.

Covering over half of the planet, and comprising 95% of its habitable volume, the deep ocean (>200 m) merits dedicated attention in the context of climate change for several major reasons:

- The deep ocean has a predominant role in the sequestration of heat and carbon, with tight links to the upper ocean and atmosphere through vertical mixing, species migrations and particulate sinking, and a diverse range of ecosystems, making it critical to any analysis of ocean roles in climate mitigation and adaptation.
- The deep ocean provides a broad range of ecosystem services that are just beginning to be inventoried; greenhouse gas regulation, support to biodiversity (including genetic diversity), food supply and energy production.
- The deep ocean is increasingly impacted by human activities including contaminant inputs, overfishing, and disturbances from seafloor extractive activities. There is currently little understanding of how these direct impacts will interact with climate stressors.

WE NEED TO INCREASE OUR KNOWLEDGE TO BETTER PROTECT THE DEEP OCEAN

Key adaptations to climate change will require new knowledge, including the broadening of deep-water observation programs, to enable the design of marine protected areas encompassing vulnerable regions in deep waters, and to inform environmental management of industrial activities and development of new policies addressing deep national and international waters.

There is an unprecedented need to integrate the deep ocean into ocean science and policy. Knowledge of deep hydrology, hydrography, pelagic and seafloor ecology is critical to climate predictions and societal impact assessments (*e.g.*, Mora *et al.* 2013) because of the strength of connectivity between the oceans, atmosphere and the terrestrial realm. New international regulations (*e.g.* for mining) and treaties (*e.g.* for biodiversity), environmental management, and spatial planning also must incorporate climate and the role of deep processes.

KEY ELEMENTS TO UNDERSTAND THE FUTURE OF THE DEEP OCEAN

We draw attention to the following themes, which make the case for the significance of the deep ocean.

Ecosystem services of the deep ocean

Life in the deep ocean provides or regulates many valuable services that sustain the planet (Armstrong *et al.* 2012; Thurber *et al.* 2014); key among these are CO_2 and CH_4 sequestration, nutrient cycling, substrate, food and nursery grounds provisioning for fisheries by a variety of habitats. The deep ocean is the largest reservoir of carbon on Earth and constitutes the ultimate sink for most anthropogenic carbon. The biogenic deep-sea carbon component is poorly quantified, but chemosynthetic ecosystems with high carbon fixation rates and vertical transport by pelagic species may significantly contribute to 'blue carbon' sequestration (Marlow *et al.* 2014, Trueman *et al.* 2014, James *et al.* 2016).

Thermal energy budgets

The ocean absorbs 90% of the extra heat trapped by anthropogenic greenhouse gas emissions, with 30% of this being stored at depths >700 m (IPCC 5th assessment report) and is thus a more accurate indicator of planetary warming than surface global mean temperature (Victor and Kennel, 2015). In this stable and mainly cold environment (except in the Mediterranean Sea and at bathyal depths in tropical regions), thermal limits shape species distributions. The consequences of warming on deep ocean waters will profoundly influence ecosystems and their biodiversity. Examples of rapid changes in deep-sea benthic ecosystems have been documented in downwelling, upwelling and polar regions (*e.g.* Danovaro *et al.* 2004, Smith *et al.* 2012, Soltwedel *et al.* 2016), although discriminating natural cycles from climatic impacts in the deep sea will require unprecedented time series data (Smith *et al.* 2013).

Biogeochemical changes

The deep ocean supports major biogeochemical recycling functions; these are expected to undergo major changes. Declines in O_2, pH and aragonite saturation have been observed and are predicted to strongly impact intermediate water depths under future emission scenarios (Bopp *et al.* 2013). Deep-water oxygenation is tightly coupled to the overturning circulation and O_2 trends inform changes in global or basin-scale ocean circulation. As a regulator of the biogeochemical cycling of N, Fe, P, and S, O_2 is key to potential synergistic responses. N_2O production is expected to increase as oxygen declines (Codispoti, 2010), potentially linking O_2 decline and climate through a positive feedback, though large uncertainties remain (Martinez-Rey *et al.* 2015).

Cumulative impacts of changes

There are many climate change-related stressors affecting deep-sea ecosystem functions (Levin and Le Bris 2015). Deep-sea ecosystems may be particularly vulnerable to change due to their environmental stability or to tight links with surface productivity or hydrodynamic regime. Deep-sea diversity patterns are shaped by export production (Woolley *et al.* 2016) and CMIP5 models predict overall decreases in integrated primary productivity with climate change. Large reductions in the tropics and the North Atlantic (Bopp *et al.* 2013), suggest possible negative impacts for deep-sea diversity. We need to assess how and where these cumulative changes, including warming, ocean acidification, aragonite undersaturation, shifts in nutrient fluxes and deoxygenation, will challenge ecosystem stability and species capacity to adapt (Lunden *et al.* 2014, Gori *et al.* 2016). This involves gathering sufficient knowledge about cumulative impacts of multiple stressors to build accurate scenarios of vulnerability.

A need for deep observations

The sparse nature and typically small spatial resolution of deep-ocean observations, combined with overly large spatial resolution of models, results in knowledge gaps and uncertainties. This includes natural variability, the coupling of climate to biogeochemical cycles, and the responses of biodiversity hotspots (*e.g.*, seamounts and canyons). In addition, multicellular life in the deep pelagic realm is still largely unexplored, though this realm represents over 95% of the living space on the planet. Seafloor observatories and long-term time series have started providing insights into how deep-sea ecosystems respond to climate perturbations (Soltweddel *et al.* 2016; Smith *et al.* 2013). Long-term integrated ecological studies, covering a range of deep-sea systems and the most vulnerable hotspots, are needed to identify threats to critical ecosystem services and the potential feedbacks to the climate system and humans.

Synergies of direct human-induced stressors

Beyond the complexity of multiple climate stressors, deep-ocean ecosystems are facing an onslaught from pollutants, fishing, mining, energy extraction, and debris (Mengerink *et al.* 2014), with deep seabed mining now on the near-term horizon. New efforts to develop requirements for environmental impact assessments, environmental indicators, spatial planning and create marine protected areas in deep water will need to incorporate the interplay with climate change.

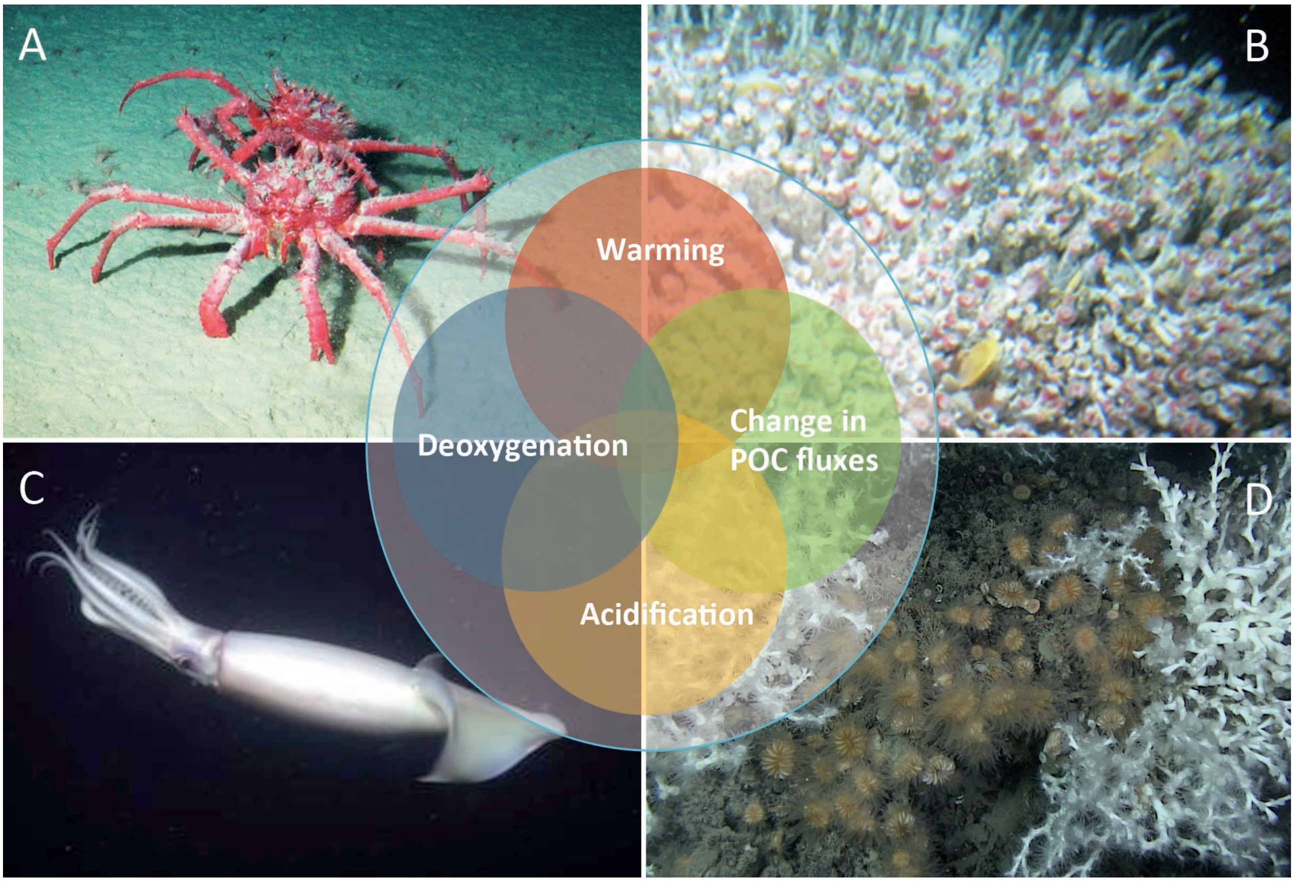

Figure from Levin and Le Bris 2015. Winners and losers from exposure to interacting climate stressors. (A) King crabs invading Palmer Deep in Antarctica enabled by warming (9). (B) Cold seep fauna may expand as warming promotes methane release from the seafloor (12), such as occurs at sites recently discovered along the Atlantic coast. (C) Hypoxia-tolerant Humboldt squid (*Dosidicus gigas*) have extended their distribution in concert with expanding oxygen minima along the East Pacific margin. (D) Cold-water coral reefs vulnerable to warming and acidification in Mediterranean canyons.

[Photo credits: (A) Image courtesy of K. Heirman and C. Smith, NSF LARISSA and Ghent University HOLANT projects. (B) Image courtesy of Deepwater Canyons 2013–Pathways to the Abyss, National Oceanic and Atmospheric Admin- istration (NOAA)–Office of Exploration and Research, Bureau of Ocean Energy Management, and U.S. Geological Survey. (C) Image courtesy of N. Le Bris, Laboratoire d'Ecogéochimie des Environnements Benthiques (LECOB), Fondation Total– UPMC. (D) Image courtesy of R. Starr, NOAA–Cordell Bank National Marine Sanctuary].

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