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Marine Science Review – 412

Climate and climate change

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In this review:

A. Recent articles with abstracts

O/A denotes an open access article or journal

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Menon, S., Soberon, J., Li, X.G., and Peterson, A.T. **Preliminary global assessment of terrestrial biodiversity consequences of sea-level rise mediated by climate change.** *Biodiversity and Conservation* 19(6): 1599-1609, 2010.

Notes: Considerable attention has focused on the climatic effects of global climate change on biodiversity, but few analyses and no broad assessments have evaluated effects of sea-level rise on biodiversity. Taking advantage of new maps of marine intrusion under scenarios of 1 and 6 m sea-level rise, we calculated areal losses for all terrestrial ecoregions globally, with areal losses for particular ecoregions ranging from nil to complete. Marine intrusion is a global phenomenon, but its effects are most prominent in Southeast Asia and nearby islands, eastern North America, northeastern South America, and western Alaska. Making assumptions regarding faunal responses to reduced distributional areas of species endemic to ecoregions, we estimated likely numbers of extinctions caused by sea-level rise, and found that marine-intrusion-caused extinctions of narrow endemics are likely to be most prominent in northeastern South America, although anticipated extinctions in smaller numbers are scattered worldwide. This assessment serves as a complement to recent estimates of losses owing to changing climatic conditions, considering a dimension of biodiversity consequences of climate change that has not previously been taken into account.

Van de Waal, D.B., Verschoor, A.M., Verspagen, J.M.H., Van Donk, E., and Huisman, J. **Climate-driven changes in the ecological stoichiometry of aquatic ecosystems.** *Frontiers in Ecology and the Environment* 8(3): 145-152, 2010.

Notes: Advances in ecological stoichiometry, a rapidly expanding research field investigating the elemental composition of organisms and their environment, have shed new light on the impacts of climate change on freshwater and marine ecosystems. Current changes in the Earth's climate alter the availability of carbon and nutrients in lakes and oceans. In particular, atmospheric CO_2 concentrations will rise to unprecedented levels by the end of this century, while global warming will enhance stratification of aquatic ecosystems and may thereby diminish the supply of nutrients into the surface layer. These processes enrich phytoplankton with carbon, but suppress nutrient availability. Phytoplankton with a high carbon-to-nutrient content provide poor-quality food for most zooplankton species, which may shift the species composition of zooplankton and higher trophic levels to less nutrient-demanding species. As a consequence, climate-driven changes in plankton stoichiometry may alter the structure and functioning of entire aquatic food webs.

Wernberg, T., Thomsen, M.S., Tuya, F., Kendrick, G.A., Staehr, P.A., and Toohey, B.D. **Decreasing resilience of kelp beds along a latitudinal temperature gradient: potential implications for a warmer future.** *Ecology Letters* 13(6): 685-694, 2010.

Notes: Successful mitigation of negative effects of global warming will depend on understanding the link between physiological and ecological responses of key species. We show that while metabolic adjustment may assist Australasian kelp beds to persist and maintain abundance in warmer waters, it also reduces the physiological responsiveness of kelps to perturbation, and suppresses canopy recovery from disturbances by reducing the ecological performance of kelp recruits. This provides a warning not to rely solely on inventories of distribution and abundance to evaluate ecosystem function. The erosion of resilience is mediated by a shift in adult-juvenile interactions from competitive under cool to facilitative under warm conditions, supporting the prediction that positive interactions may become increasingly important in a warmer future. Kelp beds may remain intact but with a lower threshold for where additional impacts (e.g., extreme storms or reduced water quality) will lead to persistent loss of habitat and ecological function.

Lejeusne, C., Chevaldonne, P., Pergent-Martini, C., Boudouresque, C.F., and Perez, T. **Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea.** *Trends in Ecology and Evolution* 25(4): 250-260, 2010.

Notes: Little doubt is left that climate change is underway, strongly affecting the Earth's biodiversity. Some of the greatest challenges ahead concern the marine realm, but it is unclear to what extent changes will affect marine ecosystems. The Mediterranean Sea could give us some of the answers. Data recovered from its shores and depths have shown that sea temperatures are steadily increasing, extreme climatic events and related disease outbreaks are becoming more frequent, faunas are shifting, and invasive species are spreading. This miniature ocean can serve as a giant mesocosm of the world's oceans, with various sources of disturbances interacting synergistically and therefore providing an insight into a major unknown: how resilient are marine ecosystems, and how will their current functioning be modified?

Vargas-Yanez, M., Moya, F., Garcia-Martinez, M.C., Tel, E., Zunino, P., Plaza, F., Salat, J., Pascual, J., Lopez-Jurado, J.L., and Serra, M. **Climate change in the Western Mediterranean Sea 1900-2008.** *Journal of Marine Systems* 82(3): 171-176, 2010.

Notes: The deep waters in the Western Mediterranean (>600 m) are the result of mixing between the two water masses above it (Atlantic Water, 0-200 m and Levantine Intermediate Water, 200-600 m) and heat and buoyancy losses in late winter. Deep waters in the Western Mediterranean have undergone a continuous warming during the second half of the twentieth century and initially it was hypothesized that this had been caused by the warming of the contributing water masses, very likely linked to global warming. Nevertheless, no clear signals of warming have been detected in the intermediate layers and no warming trends were detected in the upper layer before the 1980s. This fact suggested that the cause of deep water warming could be linked to river damming and the consequent salinity increase, instead of to an increase of the heat absorbed by the upper ocean, as in other parts of the world ocean. In this work we use the data base MEDATLAS and data from more recent monitoring programs to construct the longest temperature and salinity time series ever analysed in the Western Mediterranean (1900 to 2008). These time series show that both the upper and intermediate layers have warmed throughout the twentieth century. Long term and decadal variability in the upper layer correlate with surface air temperature in the northern hemisphere and heat absorbed by the upper North Atlantic Ocean, suggesting that the time series analysed in this work reflect the present heat absorption of the oceans in the context of global warming. The present data set highlights the importance of monitoring programs and provides a proxy for the study of climate change.

Zahn, M. and von Storch, H. **Decreased frequency of North Atlantic polar lows associated with future climate warming.** *Nature* 467(7313): 309-312, 2010.

Notes: Every winter, the high-latitude oceans are struck by severe storms that are considerably smaller than the weather-dominating synoptic depressions. Accompanied by strong winds and heavy precipitation, these often explosively developing mesoscale cyclones – termed polar lows – constitute a threat to offshore activities such as shipping or oil and gas exploitation. Yet owing to their small scale, polar lows are poorly represented in the observational and global reanalysis data often used for climatological investigations of atmospheric features and cannot be assessed in coarse-resolution global simulations of possible future climates. Here we show that in a future anthropogenically warmed climate, the frequency of polar lows is projected to decline. We used a series of regional climate model simulations to downscale a set of global climate change scenarios from the Intergovernmental Panel of Climate Change. In this process, we first simulated the formation of polar low systems in the North Atlantic and then counted the individual cases. A previous study using NCEP/NCAR re-analysis data revealed that polar low frequency from 1948 to 2005 did not systematically change. Now, in projections for the end of the twenty-first century, we found a significantly lower number of polar lows and a northward shift of their mean genesis region in response to elevated atmospheric greenhouse gas concentration. This change can be related to changes in the North Atlantic sea surface temperature and mid-troposphere temperature; the latter is found to rise faster than the former so that the resulting stability is increased, hindering the formation or intensification of polar lows. Our results provide a rare example of a climate change effect in which a type of extreme weather is likely to decrease, rather than increase.

Peng, T.H. and Wanninkhof, R. **Increase in anthropogenic CO_2 in the Atlantic Ocean in the last two decades.** *Deep Sea Research Part I: Oceanographic Research Papers* 57(6): 755-770, 2010.

Notes: Data from the first systematic survey of inorganic carbon parameters on a global scale, the GEOSECS program, are compared with those collected during WOCE/JGOFS to study the changes in carbon and other geochemical properties, and anthropogenic CO_2 increase in the Atlantic Ocean from the 1970s to the early 1990s. This first data-based estimate of CO_2 increase over this period was accomplished by adjusting the GEOSECS data set to be consistent with recent high-quality carbon data. Multiple Linear Regression (MLR) and extended Multiple Linear Regression (eMLR) analyses to these carbon data are applied by regressing DIC with potential temperature, salinity, AOU, silica, and PO4 in three latitudinal regions for the western and eastern basins in the Atlantic Ocean. The results from MLR (and eMLR provided in parentheses) indicate that the mean anthropogenic CO_2 uptake rate in the western basin is 0.70 (0.53) mol m^{-2} yr^{-1} for the region north of 15ºN; 0.53 (0.36) mol m^{-2} yr^{-1} for the equatorial region between 15ºN and 15ºS; and 0.83 (0.35) mol m^{-2} yr^{-1} in the South Atlantic south of 15ºS. For the eastern basin an estimate of 0.57 (0.45) mol m^{-2} yr^{-1} is obtained for the equatorial region, and 0.28 (0.34) mol m^{-2} yr^{-1} for the South Atlantic south of 15ºS. The results of using eMLR are systematically lower than those from MLR method in the western basin. The anthropogenic CO_2 increase is also estimated in the upper thermocline from salinity normalized DIC after correction for AOU along the isopycnal surfaces. For these depths the results are consistent with the CO_2 uptake rates derived from both MLR and eMLR methods.

Kawano, T., Doi, T., Uchida, H., Kouketsu, S., Fukasawa, M., Kawai, Y., and Katsumata, K. **Heat content change in the Pacific Ocean between the 1990s and 2000s.** *Deep Sea Research Part II: Topical Studies in Oceanography* 57(13-14): 1141-1151, 2010.

Notes: We studied the change in heat content in the Pacific Ocean using data from repeat hydrographic surveys. The most recent trans-Pacific surveys along 47ºN and 179ºE conducted in 2007 reveal that circumpolar deep water has warmed along 179ºE as suggested by previous studies and also that the deep water was warmer along 47ºN even since 1999. Simple estimates show that the heat content increased in the layer deeper than 4000 m over almost the entire Pacific Ocean. The increase in heat content below 3000 m was about 5% of the ocean-wide increase. Heat content changes in the deep layer are not uniform and a vertical profile of heat content change has a minimum at a depth around

3000 m. The non-uniform distribution of heat content change in the mid- to bottom layer demonstrates the existence of overturn circulation and may indicate that this circulation is changing.

Metzl, N. et al. **Recent acceleration of the sea surface fCO_2 growth rate in the North Atlantic subpolar gyre (1993-2008) revealed by winter observations.** *Global Biogeochemical Cycles* 24(40): art. GB4004, 2010.

Notes: Recent studies based on ocean and atmospheric carbon dioxide (CO_2) observations, suggesting that the ocean carbon uptake has been reduced, may help explain the increase in the fraction of anthropogenic CO_2 emissions that remain in the atmosphere. Is it a response to climate change or a signal of ocean natural variability or both? Regional process analyses are needed to follow the ocean carbon uptake and to enable better attributions of the observed changes. Here, we describe the evolution of the surface ocean CO_2 fugacity (fCO_2^{oc}) over the period 1993-2008 in the North Atlantic subpolar gyre (NASPG). This analysis is based primarily on observations of dissolved inorganic carbon (DIC) and total alkalinity (TA) conducted at different seasons in the NASPG between Iceland and Canada. The fCO_2^{oc} trends based on DIC and TA data are also compared with direct fCO_2 measurements obtained between 2003 and 2007 in the same region. During winters 1993-2003, the fCO_2^{oc} growth rate was 3.7 (±0.6) μatm yr^{-1}, higher than in the atmosphere, 1.8 (±0.1) μatm yr^{-1}. This translates to a reduction of the ocean carbon uptake primarily explained by sea surface warming, up to 0.24 (±0.04) °C yr^{-1}. This warming is a consequence of advection of warm water northward from the North Atlantic into the Irminger basin, which occurred as the North Atlantic Oscillation (NAO) index moved into a negative phase in winter 1995/1996. In winter 2001-2008, the fCO_2^{oc} rise was particularly fast, between 5.8 (±1.1) and 7.2 (±1.3) μatm yr^{-1} depending on the region, more than twice the atmospheric growth rate of 2.1 (±0.2) μatm yr^{-1}, and in the winter of 2007-2008 the area was supersaturated with CO_2. As opposed to the 1990s, this appears to be almost entirely due to changes in seawater carbonate chemistry, the combination of increasing DIC and decreasing of TA. The rapid fCO_2^{oc} increase was not only driven by regional uptake of anthropogenic CO_2 but was also likely controlled by a recent increase in convective processes-vertical mixing in the NASPG and cannot be directly associated with NAO variability. The fCO_2^{oc} increase observed in 2001-2008 leads to a significant drop in pH of -0.069 (±0.007) $decade^{-1}$.

McNeil, B.I., Tagliabue, A., and Sweeney, C. **A multi-decadal delay in the onset of corrosive 'acidified' waters in the Ross Sea of Antarctica due to strong air-sea CO_2 disequilibrium.** *Geophysical Research Letters* 37(19): art. L19607, 2010.

Notes: Antarctic coastal waters have an abundance of marine organisms that secrete the mineral aragonite for growth and survival. Increasing oceanic anthropogenic CO_2 uptake will push these waters to a point whereby aragonite will start to geochemically corrode, with direct consequences for the Antarctic ecosystem. Here we combine surface CO_2 data in the Ross Sea, Antarctica with a regional ocean/sea-ice model to better pinpoint the timing of corrosive conditions. Our analysis suggests sea-ice cover and deep-water entrainment during winter results in 65% lower storage of anthropogenic CO_2 in comparison to atmospheric CO_2 equilibrium. This means that instead of corrosive 'acidified' waters beginning as early as the winter of 2015, anthropogenic CO_2 disequilibrium delays its onset by up to 30 years, giving this Antarctic marine ecosystem a several decade reprieve to corrosive conditions. Our results demonstrate a broader importance of understanding natural oceanic carbon cycle variability for the onset of corrosive conditions.

Mcleod, E., Hinkel, J., Vafeidis, A.T., Nicholls, R.J., Harvey, N., and Salm, R. **Sea-level rise vulnerability in the countries of the Coral Triangle.** *Sustainability Science* 5(2): 207-222, 2010.

Notes: Sea-level rise is a major threat facing the Coral Triangle countries in the twenty-first century. Assessments of vulnerability and adaptation that consider the interactions among natural and social systems are critical to identifying habitats and communities vulnerable to sea-level rise and for supporting the development of adaptation strategies. This paper presents such an assessment using the DIVA model and identifies vulnerable coastal regions and habitats in Coral Triangle countries at national and sub-national levels (administrative provinces). The following four main sea-level rise impacts are assessed in ecological, social and economic terms over the twenty-first century: (1) coastal wetland change, (2) increased coastal flooding, (3) increased coastal erosion, and (4) saltwater intrusion into estuaries and deltas. The results suggest that sea-level rise will significantly affect coastal regions and habitats in the Coral Triangle countries, but the impacts will differ across the region in terms of people flooded annually, coastal wetland change and loss, and damage and adaptation costs. Indonesia is projected to be most affected by coastal flooding, with nearly 5.9 million people expected to experience flooding annually in 2100 assuming no adaptation. However, if adaptation is considered, this number is significantly reduced. By the end of the century, coastal wetland loss is most significant for Indonesia in terms of total area lost, but the Solomon Islands are projected to experience the greatest relative loss of coastal wetlands. Damage costs associated with sea-level rise are highest in the Philippines (US $6.5 billion/year) and lowest in the Solomon Islands (US $70,000/year). Adaptation is estimated to reduce damage costs significantly, in particular for the Philippines, Indonesia, and Malaysia (between 68 and 99%). These results suggest that the impacts of sea-level rise are likely to be widespread in the region and adaptation measures must be broadly applied.

Sarmento, H., Montoya, J.M., Vazquez-Dominguez, E., Vaque, D., and Gasol, J.M. **Warming effects on marine microbial food web processes: how far can we go when it comes to predictions?** *Philosophical Transactions of the Royal Society of London [B]* 365(1549): 2137-2149, 2010.

Notes: Previsions of a warmer ocean as a consequence of climatic change point to a 2-6 ºC temperature rise during this century in surface oceanic waters. Heterotrophic bacteria occupy the central position of the marine microbial food web, and their metabolic activity and interactions with other compartments within the web are regulated by temperature. In particular, key ecosystem processes like bacterial production (BP), respiration (BR), growth efficiency and bacterial-grazer trophic interactions are likely to change in a warmer ocean. Different approaches can be used to predict these changes. Here we combine evidence of the effects of temperature on these processes and interactions coming from laboratory experiments, space-for-time substitutions, long-term data from microbial observatories and theoretical predictions. Some of the evidence we gathered shows opposite trends to warming depending on the spatio-temporal scale of observation, and the complexity of the system under study. In particular, we show that warming (i) increases BR, (ii) increases bacterial losses to their grazers, and thus bacterial-grazer biomass flux within the microbial food web, (iii) increases BP if enough resources are available (as labile organic matter derived from phytoplankton excretion or lysis), and (iv) increases bacterial losses to grazing at lower rates than BP, and hence decreasing the proportion of production removed by grazers. As a consequence, bacterial abundance would also increase and reinforce the already dominant role of microbes in the carbon cycle of a warmer ocean.

Peck, L.S., Barnes, D.K.A., Cook, A.J., Fleming, A.H., and Clarke, A. **Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica.** *Global Change Biology* 16(9): 2614-2623, 2010.

Notes: Feedbacks on climate change so far identified are predominantly positive, enhancing the rate of change. Loss of sea-ice, increase in desert areas, water vapour increase, loss of tropical rain forest and the restriction of significant areas of marine productivity to higher latitude (thus smaller geographical zones) all lead to an enhancement of the rate of change. The other major feedback identified, changes in cloud radiation, will produce either a positive feedback, if high level clouds are produced, or a negative feedback if low level clouds are produced. Few significant negative feedbacks have been identified, let alone quantified. Here, we show that the loss of ice shelves and retreat of coastal glaciers around the Antarctic Peninsula in the last 50 years has exposed at least 2.4×10^4 km^2 of new open water. We estimate that these new areas of open water have allowed new phytoplankton blooms containing a total standing stock of ~5.0×10^5 tonnes of carbon to be produced. New marine zooplankton and seabed communities have also been produced, which we estimate contain ~4.1×10^5 tonnes of carbon. This previously unquantified carbon sink acts as a negative feedback to climate change. New annual productivity, as opposed to standing stock, amounts to 3.5×10^6 tonnes yr^{-1} of carbon, of which 6.9×10^5 tonnes yr-1 deposits to the seabed. By comparison the total aboveground biomasses of lowland American tropical rainforest is 160 - 435 tonnes ha^{-1}. Around 50% of this is carbon. On this basis the carbon held in new biomass described here is roughly equivalent to 6000-17 000 ha of tropical rainforest. As ice loss increases in polar regions this feedback will become stronger, and eventually, over thousands to hundreds of thousands of years, over 50 Mtonnes of new carbon could be fixed annually in new coastal phytoplankton blooms and over 10 Mtonnes yr^{-1} locked in biological standing stock around Antarctica.

Soreide, J.E., Leu, E., Berge, J., Graeve, M., and Falk-Petersen, S. **Timing of blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic.** *Global Change Biology* 16(11): 3154-3163, 2010.

Notes: The Arctic bloom consists of two distinct categories of primary producers, ice algae growing within and on the underside of the sea ice, and phytoplankton growing in open waters. Long chain omega-3 fatty acids, a subgroup of polyunsaturated fatty acids (PUFAs) produced exclusively by these algae, are essential to all marine organisms for successful reproduction, growth, and development. During an extensive field study in the Arctic shelf seas, we followed the seasonal biomass development of ice algae and phytoplankton and their food quality in terms of their relative PUFA content. The first PUFA-peak occurred in late April during solid ice cover at the onset of the ice algal bloom, and the second PUFA-peak occurred in early July just after the ice break-up at the onset of the phytoplankton bloom. The reproduction and growth of the key Arctic grazer *Calanus glacialis* perfectly coincided with these two bloom events. Females of *C. glacialis* utilized the high-quality ice algal bloom to fuel early maturation and reproduction, whereas the resulting offspring had access to ample high-quality food during the phytoplankton bloom 2 months later. Reduction in sea ice thickness and coverage area will alter the current primary production regime due to earlier ice break-up and onset of the phytoplankton bloom. A potential mismatch between the two primary production peaks of high-quality food and the reproductive cycle of key Arctic grazers may have negative consequences for the entire lipid-driven Arctic marine ecosystem.

Liu, J.P. and Curry, J.A. **Accelerated warming of the Southern Ocean and its impacts on the hydrological cycle and sea ice.** *Proceedings of the National Academy of Sciences [USA]* 107(34): 14987-14992, 2010.

Notes: The observed sea surface temperature in the Southern Ocean shows a substantial warming trend for the second half of the 20th century. Associated with the warming, there has been an enhanced atmospheric hydrological cycle in the Southern Ocean that results in an increase of the Antarctic sea ice for the past three decades through the reduced upward ocean heat transport and increased snowfall. The simulated sea surface temperature variability from two global coupled climate models for the second half of the 20th century is dominated by natural internal variability associated with the Antarctic Oscillation, suggesting that the models' internal variability is too strong, leading to a response to anthropogenic forcing that is too weak. With increased loading of greenhouse gases in the atmosphere through the 21st century, the models show an accelerated warming in the Southern Ocean, and indicate that anthropogenic forcing exceeds natural internal variability. The increased heating from below (ocean) and above (atmosphere) and increased liquid precipitation associated with the enhanced hydrological cycle results in a projected decline of the Antarctic sea ice.

Talmage, S.C. and Gobler, C.J. **Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish.** *Proceedings of the National Academy of Sciences [USA]* 107(40): 17246-17251, 2010.

Notes: The combustion of fossil fuels has enriched levels of CO_2 in the world's oceans and decreased ocean pH. Although the continuation of these processes may alter the growth, survival, and diversity of marine organisms that synthesize $CaCO_3$ shells, the effects of ocean acidification since the dawn of the industrial revolution are not clear. Here we present experiments that examined the effects of the ocean's past, present, and future (21st and 22nd centuries) CO_2 concentrations on the growth, survival, and condition of larvae of two species of commercially and ecologically valuable bivalve shellfish (*Mercenaria mercenaria* and *Argopecten irradians*). Larvae grown under near preindustrial CO_2 concentrations (250 ppm) displayed significantly faster growth and metamorphosis as well as higher survival and lipid accumulation rates compared with individuals reared under modern day CO_2 levels. Bivalves grown under near preindustrial CO_2 levels displayed thicker, more robust shells than individuals grown at present CO_2 concentrations, whereas bivalves exposed to CO_2 levels expected later this century had shells that were malformed and eroded. These results suggest that the ocean acidification that has occurred during the past two centuries may be inhibiting the development and survival of larval shellfish and contributing to global declines of some bivalve populations.

Wood, H.L., Spicer, J.I., Lowe, D.M., and Widdicombe, S. **Interaction of ocean acidification and temperature; the high cost of survival in the brittlestar *Ophiura ophiura*.** *Marine Biology* 157(9): 2001-2013, 2010.

Notes: This study has demonstrated an interaction between the effect of increased ocean acidity and temperature (40 days exposure) on a number of key physiological parameters in the ophiuroid brittlestar, *Ophiura ophiura*. Metabolic upregulation is seen in the low pH treatments when combined with low temperature. However, this is far outweighed by the response to elevated temperature (+4.5 ºC). In the high temperature/low pH treatments treatments (where calcite is undersaturated) there appears to be an energetic trade-off likely in order to maintain net calcification where dissolution of calcium carbonate may occur. This energy deficit results in a ~30% reduction in the rate of arm regeneration at pH 7.3 which is predicted to be reached by the year 2300. This understanding of how *O. ophiura* responds to ocean acidification, taking into account an interactive effect of temperature, suggests that fitness and survival may indirectly be reduced through slower recovery from arm damage.

Byrne, M., Soars, N.A., Ho, M.A., Wong, E., McElroy, D., Selvakumaraswamy, P., Dworjanyn, S.A., and Davis, A.R. **Fertilization in a suite of coastal marine invertebrates from SE Australia is robust to near-future ocean warming and acidification.** *Marine Biology* 157(9): 2061-2069, 2010.

Notes: Climate change driven ocean acidification and hypercapnia may have a negative impact on fertilization in marine organisms because of the narcotic effect these stressors exert on sperm. In contrast, warmer, less viscous water may have a positive influence on sperm swimming speed and so ocean warming may enhance fertilization. To address questions on future vulnerabilities we examined the interactive effects of near-future ocean warming and ocean acidification/ hypercapnia on fertilization in intertidal and shallow subtidal echinoids (*Heliocidaris erythrogramma*, *H. tuberculata*, *Tripneustes gratilla*, *Centrostephanus rodgersii*), an asteroid (*Patiriella regularis*) and an abalone (*Haliotis coccoradiata*). Batches of eggs from multiple females were fertilized by sperm from multiple males in all combinations of three temperature and three pH/pCO_2 treatments. Experiments were placed in the setting of projected near-future conditions for southeast Australia, an ocean change hot spot. There was no significant effect of warming and acidification on the percentage of fertilization. These results indicate that fertilization in these species is robust to temperature and pH/pCO_2 fluctuation. This may reflect adaptation to the marked fluctuation in temperature and pH that characterises their shallow water coastal habitats. Efforts to identify potential impacts of ocean change to the life histories of coastal marine invertebrates are best to focus on more vulnerable embryonic and larval stages because of their long time in the water column where seawater chemistry and temperature have a major impact on development.

Dupont, S., Dorey, N., and Thorndyke, M. **What meta-analysis can tell us about vulnerability of marine biodiversity to ocean acidification?** *Estuarine, Coastal and Shelf Science* 89(2): 182-185, 2010.

Notes: Ocean acidification has been proposed as a major threat for marine biodiversity. Hendriks et al. [Hendriks, I.E., Duarte, C.M., Alvarez, M., 2010. Vulnerability of marine biodiversity to ocean acidification: a meta-analysis. *Estuarine, Coastal and Shelf Science*, doi:10.1016/j.ecss.2009.11. 022.] proposed an alternative view and suggested, based on a meta-analysis, that marine biota may be far more resistant to ocean acidification than hitherto believed. However, such a meta-analytical approach can mask more subtle features, for example differing sensitivities during the life-cycle of an organism. Using a similar metric on an echinoderm database, we show that key bottlenecks present in the life-cycle (e.g. larvae being more vulnerable than adults) and responsible for driving the whole species response may be hidden in a global meta-analysis. Our data illustrate that any ecological meta-analysis should be hypothesis driven, taking into account the complexity of biological systems, including all life-cycle stages and key biological processes. Available data allow us to conclude that near-future ocean acidification can/will have dramatic negative impact on some marine species, including echinoderms, with likely consequences at the ecosystem level.

Hendriks, I.E. and Duarte, C.M. **Ocean acidification: Separating evidence from judgment – A reply to Dupont et al.** *Estuarine, Coastal and Shelf Science* 89(2): 186-190, 2010.

Notes: Recently ocean acidification as a major threat for marine species has moved from a consensus statement into a much discussed and even challenged conception. A simple meta-analysis of Hendriks et al. (2010) showed that based on results of pooled experimental evidence, marine biota may turn out to be more resistant than hitherto believed. Dupont et al. (in press) indicate the importance of evaluating the most vulnerable stages in the life cycle of organisms instead of only adult stages. Here we evaluate additional material, composed of experimental evidence of the effect of ocean acidification on marine organisms during adult, larval, and juvenile stages, and show that the observed effects are within the range predicted by Hendriks et al. (2010). Species-specific differences and a wide variance in the reaction of organisms might obscure patterns of differences between life stages. Future research should be aimed to clarify underlying mechanisms to define the effect ocean acidification will have on marine biodiversity. Conveying scientific evidence along with an open acknowledgment of uncertainties to help separate evidence from judgment should not harm the need to act to mitigate ocean acidification and should pave the road for robust progress in our understanding of how ocean acidification impacts biota of the ocean.

Perez, F.F., Vazquez-Rodriguez, M., Mercier, H., Velo, A., Lherminier, P., and Rios, A.F. **Trends of anthropogenic CO_2 storage in North Atlantic water masses.** *Biogeosciences* 7(5): 1789-1807, 2010. **O/A**

Notes: A high-quality inorganic carbon system database, spanning over three decades (1981-2006) and comprising of 13 cruises, has allowed the applying of the φC°*T* method and coming up with estimates of the anthropogenic CO_2 (C_{ant}) stored in the main water masses of the North Atlantic. In the studied region, strong convective processes convey surface properties, like C_{ant}, into deeper ocean layers and grants this region an added oceanographic interest from the point of view of air-sea CO_2 exchanges. Generally, a tendency for decreasing C_{ant} storage rates towards the deep layers has been observed. In the Iberian Basin, the North Atlantic Deep Water has low C_{ant} concentrations and negligible storage rates, while the North Atlantic Central Water in the upper layers shows the largest C_{ant} values and the largest annual increase of its average concentration (1.13 ± 0.14 µmol kg^{-1} yr^{-1}). This unmatched rate of change in the C_{ant} concentration of the warm upper limb of the Meridional Overturning Circulation decreases towards the Irminger basin (0.68 ± 0.06 µmol kg^{-1} yr^{-1}) due to the lowering of the buffering capacity. The mid and deep waters in the Irminger Sea show rather similar C_{ant} concentration rates of increase (between 0.33 and 0.45 µmol kg^{-1} yr^{-1}), whereas in the Iceland basin these layers seem to have been less affected by C_{ant}. Overall, the C_{ant} storage rates in the North Atlantic subpolar gyre during the first half of the 1990s, when a high North Atlantic Oscillation (NAO) phase was dominant, are ~48% higher than during the 1997-2006 low NAO phase that followed. This result suggests that a net decrease in the strength of the North Atlantic sink of atmospheric CO_2 has taken place during the present decade. The changes in deep-water ventilation are the main driving processes causing this weakening of the North Atlantic CO_2 sink.

Piontek, J., Lunau, M., Handel, N., Borchard, C., Wurst, M., and Engel, A. **Acidification increases microbial polysaccharide degradation in the ocean.** *Biogeosciences* 7(5): 1615-1624, 2010. **O/A**

Notes: With the accumulation of anthropogenic carbon dioxide (CO2), a proceeding decline in seawater pH has been induced that is referred to as ocean acidification. The ocean's capacity for CO2 storage is strongly affected by biological processes, whose feedback potential is difficult to evaluate. The main source of CO2 in the ocean is the decomposition and subsequent respiration of organic molecules by heterotrophic bacteria. However, very little is known about potential effects of ocean acidification on bacterial degradation activity. This study reveals that the degradation of polysaccharides, a major component of marine organic matter, by bacterial extracellular enzymes was significantly accelerated during experimental simulation of ocean acidification. Results were obtained from pH perturbation experiments, where rates of extracellular alpha- and beta-glucosidase were measured and the loss of neutral and acidic sugars from phytoplankton-derived polysaccharides was determined. Our study suggests that a faster bacterial turnover of polysaccharides at lowered ocean pH has the potential to reduce carbon export and to enhance the respiratory CO2 production in the future ocean.

Bates, N.R., Amat, A., and Andersson, A.J. **Feedbacks and responses of coral calcification on the Bermuda reef system to seasonal changes in biological processes and ocean acidification.** *Biogeosciences* 7(8): 2509-2530, 2010. **O/A**

Notes: Despite the potential impact of ocean acidification on ecosystems such as coral reefs, surprisingly, there is very limited field data on the relationships between calcification and seawater carbonate chemistry. In this study, contemporaneous in situ datasets of seawater carbonate chemistry and calcification rates from the high-latitude coral reef of Bermuda over annual timescales provide a framework for investigating the present and future potential impact of rising carbon dioxide (CO_2) levels and ocean acidification on coral reef ecosystems in their natural environment. A strong correlation was found between the in situ rates of calcification for the major framework building coral species *Diploria labyrinthiformis* and the seasonal variability of [CO_3^{2-}] and aragonite saturation state $\Omega_{aragonite}$, rather than other environmental factors such as light and temperature. These field observations provide sufficient data to hypothesize that there is a seasonal 'Carbonate Chemistry Coral Reef Ecosystem Feedback' (CREF hypothesis) between the primary components of the reef ecosystem (i.e., scleractinian hard corals and macroalgae) and seawater carbonate chemistry. In early summer, strong net autotrophy from benthic components of the reef system enhance [CO_3^{2-}] and $\Omega_{aragonite}$ conditions, and rates of coral calcification due to the photosynthetic uptake of CO_2. In late summer, rates of coral calcification are suppressed by release of CO_2 from reef metabolism during a period of strong net heterotrophy. It is likely that this seasonal CREF mechanism is present in other tropical reefs although attenuated compared to high-latitude reefs such as Bermuda. Due to lower annual mean surface seawater [CO_3^{2-}] and $\Omega_{aragonite}$ in Bermuda compared to tropical regions, we anticipate that Bermuda corals will experience seasonal periods of zero net calcification within the next decade at [CO_3^{2-}] and $\Omega_{aragonite}$ thresholds of ~184 μmoles kg^{-1} and 2.65. However, net autotrophy of the reef during winter and spring (as part of the CREF hypothesis) may delay the onset of zero NEC or decalcification going forward by enhancing [CO_3^{2-}] and $\Omega_{aragonite}$. The Bermuda coral reef is one of the first responders to the negative impacts of ocean acidification, and we estimate that calcification rates for *D. labyrinthiformis* have declined by >50% compared to pre-industrial times.

Nicholls, R.J. and Cazenave, A. **Sea-level rise and its impact on coastal zones.** *Science* 328(5985): 1517-1520, 2010.

Notes: Global sea levels have risen through the 20th century. These rises will almost certainly accelerate through the 21st century and beyond because of global warming, but their magnitude remains uncertain. Key uncertainties include the possible role of the Greenland and West Antarctic ice sheets and the amplitude of regional changes in sea level. In many areas, nonclimatic components of relative sea-level change (mainly subsidence) can also be locally appreciable. Although the impacts of sea-level rise are potentially large, the application and success of adaptation are large uncertainties that require more assessment and consideration.

Schofield, O., Ducklow, H.W., Martinson, D.G., Meredith, M.P., Moline, M.A., and Fraser, W.R. **How do polar marine ecosystems respond to rapid climate change?** *Science* 328(5985): 1520-1523, 2010.

Notes: Climate change will alter marine ecosystems; however, the complexity of the food webs, combined with chronic undersampling, constrains efforts to predict their future and to optimally manage and protect marine resources. Sustained observations at the West Antarctic Peninsula show that in this region, rapid environmental change has coincided with shifts in the food web, from its base up to apex predators. New strategies will be required to gain further insight into how the marine climate system has influenced such changes and how it will do so in the future. Robotic networks, satellites, ships, and instruments mounted on animals and ice will collect data needed to improve numerical models that can then be used to study the future of polar ecosystems as climate change progresses.

Hoegh-Guldberg, O. and Bruno, J.F. **The impact of climate change on the world's marine ecosystems.** *Science* 328(5985): 1523-1528, 2010.

Notes: Marine ecosystems are centrally important to the biology of the planet, yet a comprehensive understanding of how anthropogenic climate change is affecting them has been poorly developed. Recent studies indicate that rapidly rising greenhouse gas concentrations are driving ocean systems toward conditions not seen for millions of years, with an associated risk of fundamental and irreversible ecological transformation. The impacts of anthropogenic climate change so far include decreased ocean productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and a greater incidence of disease. Although there is considerable uncertainty about the spatial and temporal details, climate change is clearly and fundamentally altering ocean ecosystems. Further change will continue to create enormous challenges and costs for societies worldwide, particularly those in developing countries.

Comeau, S., Jeffree, R., Teyssié, J.-L., and Gattuso, J.-P. **Response of the Arctic pteropod *Limacina helicina* to projected future environmental conditions.** *PLoS ONE* 5(6): art. e11362, 2010. **O/A**

Notes: Thecosome pteropods (pelagic mollusks) can play a key role in the food web of various marine ecosystems. They are a food source for zooplankton or higher predators such as fishes, whales and birds that is particularly important in high latitude areas. Since they harbor a highly soluble aragonitic shell, they could be very sensitive to ocean acidification driven by the increase of anthropogenic CO_2 emissions. The effect of changes in the seawater chemistry was investigated on *Limacina helicina*, a key species of Arctic pelagic ecosystems. Individuals were kept in the laboratory under controlled pCO_2 levels of 280, 380, 550, 760 and 1020 μatm and at control (0 °C) and elevated (4 °C) temperatures. The respiration rate was unaffected by pCO_2 at control temperature, but significantly increased as a function of the pCO_2 level at elevated temperature. pCO_2 had no effect on the gut clearance rate at either temperature. Precipitation of $CaCO_3$, measured as the incorporation of ^{45}Ca, significantly declined as a function of pCO_2 at both temperatures. The decrease in calcium carbonate precipitation was highly correlated to the aragonite saturation state. Even though this study demonstrates that pteropods are able to precipitate calcium carbonate at low aragonite saturation state, the results support the current concern for the future of Arctic pteropods, as the production of their shell appears to be very sensitive to decreased pH. A decline of pteropod populations would likely cause dramatic changes to various pelagic ecosystems.

Sheppard Brennand, H., Soars, N., Dworjanyn, S.A., Davis, A.R., and Byrne, M. **Impact of ocean warming and ocean acidification on larval development and calcification in the sea urchin *Tripneustes gratilla*.** *PLoS ONE* 5(6): art. e11372, 2010. **O/A**

Notes: *Background* As the oceans simultaneously warm, acidify and increase in pCO_2, prospects for marine biota are of concern. Calcifying species may find it difficult to produce their skeleton because ocean acidification decreases calcium carbonate saturation and accompanying hypercapnia suppresses metabolism. However, this may be buffered by enhanced growth and metabolism due to warming. *Methodology/Principal Findings* We examined the interactive effects of near-future ocean warming and increased acidification/pCO_2 on larval development in the tropical sea urchin *Tripneustes gratilla*. Larvae were reared in multifactorial experiments in flow-through conditions in all combinations of three temperature and three pH/pCO_2 treatments. Experiments were placed in the setting of projected near future conditions for SE Australia, a global change hot spot. Increased acidity/pCO_2 and decreased carbonate mineral saturation significantly reduced larval growth resulting in decreased skeletal length. Increased temperature (+3 °C) stimulated growth, producing significantly bigger larvae across all pH/*p*CO_2 treatments up to a thermal threshold (+6°C). Increased acidity (-0.3-0.5 pH units) and hypercapnia significantly reduced larval calcification. A +3 °C warming diminished the negative effects of acidification and hypercapnia on larval growth. *Conclusions and Significance* This study of the effects of ocean warming and CO_2 driven acidification on development and calcification of marine invertebrate larvae reared in experimental conditions from the outset of development (fertilization) shows the positive and negative effects of these stressors. In simultaneous exposure to stressors the dwarfing effects of acidification were dominant. Reduction in size of sea urchin larvae in a high *p*CO_2 ocean would likely impair their performance with negative consequent effects for benthic adult populations.

Irie, T., Bessho, K., Findlay, H.S., and Calosi, P. **Increasing costs due to ocean acidification drives phytoplankton to be more heavily calcified: Optimal growth strategy of coccolithophores.** *PLoS ONE* 5(10): art. e13436, 2010. **O/A**

Notes: Ocean acidification is potentially one of the greatest threats to marine ecosystems and global carbon cycling. Amongst calcifying organisms, coccolithophores have received special attention because their calcite precipitation plays a significant role in alkalinity flux to the deep ocean (i.e., inorganic carbon pump). Currently, empirical effort is devoted to evaluating the plastic responses to acidification, but evolutionary considerations are missing from this approach. We thus constructed an optimality model to evaluate the evolutionary response of coccolithophorid life history, assuming that their exoskeleton (coccolith) serves to reduce the instantaneous mortality rates. Our model predicted that natural selection favors constructing more heavily calcified exoskeleton in response to increased acidification-driven costs. This counter-intuitive response occurs because the fitness benefit of choosing a better-defended, slower growth strategy in more acidic conditions, outweighs that of accelerating the cell cycle, as this occurs by producing less calcified exoskeleton. Contrary to the widely held belief, the evolutionarily optimized population can precipitate larger amounts of $CaCO_3$ during the bloom in more acidified seawater, depending on parameter values. These findings suggest that ocean acidification may enhance the calcification rates of marine organisms as an adaptive response, possibly accompanied by higher carbon fixation ability. Our theory also provides a compelling explanation for the multispecific fossil time-series record from ~200 years ago to present, in which mean coccolith size has increased along with rising atmospheric CO_2 concentration.

Raupach, M.R. and Canadell, J.G. **Carbon and the Anthropocene.** *Current Opinion in Environmental Sustainability* 2(4): 210-218, 2010. **O/A**

Notes: Life on earth has created vast stores of detrital carbon - the remnants of carbon-based organisms after they have died. These carbon stores range from dead leaves and wood to the fossil carbon in coal, oil and gas. They contain large amounts of usable chemical energy. When the ancestors of modern humans learned to access this energy by mastering fire, they discovered a 'new trick' which led to massive evolutionary advantages for the human species. In the technological explosion of the last two centuries, industrial-scale use of energy flows from fossil carbon has not only transformed human societies and ecosystems, but also caused exponentially increasing accumulation of the released carbon in atmospheric, land and ocean carbon reservoirs. These changes have altered the carbon cycle and other cycles of matter and energy in the earth system, leading to the term 'Anthropocene' for the current epoch. In this epoch humankind is encountering finite-planet vulnerabilities for the first time, as a consequence of the dominance of its home planet bequeathed by the use of energy flows from detrital carbon. Signs of these vulnerabilities can be seen in the contemporary carbon cycle and emerging carbon-climate feedbacks. Interactions between humans, climate, the carbon cycle and other natural cycles are certain to become more profound over the next century and beyond.

Le Quéré, C. **Trends in the land and ocean carbon uptake.** *Current Opinion in Environmental Sustainability* 2(4): 219-224, 2010. **O/A**

Notes: Only about 45% of the total CO_2 emitted from fossil fuel burning and land use change stayed in the atmosphere on average during the past few decades. The remaining CO_2 was taken up by the carbon reservoirs (the 'CO_2 sinks') in the ocean and on land. The sinks are sensitive to climate and elevated CO_2 levels. Their efficiency in removing CO_2 emissions from the atmosphere is expected to decrease in the future under increasing atmospheric CO_2 because of their response to elevated CO_2 levels, warming and other climate changes. Recent evidence from observations and models suggests that the efficiency of the sinks could have already decreased in the past few decades, but the uncertainties are very large. There is an urgent need for reducing these uncertainties by better monitoring the CO_2 emissions and sinks, and by improving our understanding of the sinks dynamics.

McGuire, A.D., Macdonald, R.W., Schuur, E.A.G., Harden, J.W., Kuhry, P., Hayes, D.J., Christensen, T.R., and Heimann, M. **The carbon budget of the northern cryosphere region.** *Current Opinion in Environmental Sustainability* 2(4): 231-236, 2010. **O/A**

Notes: The northern cryosphere is undergoing substantial warming of permafrost and loss of sea ice. Release of stored carbon to the atmosphere in response to this change has the potential to affect the global climate system. Studies indicate that the northern cryosphere has been not only a substantial sink for atmospheric CO_2 in recent decades, but also an important source of CH4 because of emissions from wetlands and lakes. Analyses suggest that the sensitivity of the carbon cycle of the region over the 21st Century is potentially large, but highly uncertain because numerous pathways of response will be affected by warming. Further research should focus on sensitive elements of the carbon cycle such as the consequences of increased fire disturbance, permafrost degradation, and sea ice loss in the northern cryosphere region.

Friedlingstein, P. and Prentice, I.C. **Carbon-climate feedbacks: a review of model and observation based estimates.** *Current Opinion in Environmental Sustainability* 2(4): 251-257, 2010. **O/A**

Notes: A growing number of studies investigated the feedback between the carbon cycle and the climate system. Modeling studies evolved from analysis based on simple land or ocean carbon cycle models to comprehensive Earth System Models accounting for state-of-the-art climate models coupled to land and ocean biogeochemical models. So far, there is a general agreement that climate change negatively affects the oceanic uptake of carbon. On land there was a similar agreement until recently where new studies showed that warming could reduce nitrogen limitation to growth, reducing the amplitude, or even changing the sign of, the land feedback. In parallel, alternative approaches used the observational record of atmospheric CO_2 and temperature, on time scales ranging from interannual to millennial, to estimate the climate-carbon cycle feedback. These studies confirmed that at the global scale, warming leads to a release of CO_2 from the land/ocean system to the atmosphere. Whether these observations can strongly constrain the magnitude of the feedback under future climate change is still under investigation.

Matear, R.J., Wang, Y.P., and Lenton, A. **Land and ocean nutrient and carbon cycle interactions.** *Current Opinion in Environmental Sustainability* 2(4): 258-263, 2010. **O/A**

Notes: The biosphere's uptake and storage of carbon have the potential to either slow or amplify global warming providing a carbon-climate feedback to global warming. The interactions between carbon (C) and the nutrient cycles, especially nitrogen (N) and phosphorus (P), are important to the biosphere's storage of carbon. The century-scale carbon-climate feedback of the land is projected to be an order of magnitude greater than the ocean; however, the land's importance may have been overestimated as they are based on models that neglect nutrient limitation. The omission of N limitation reduces the negative carbon-climate feedback by up to 30%, and further, we postulate as N-deposition and N-fixation increase, P limitation will become important in limiting the future land carbon-climate feedback. Process-based C, N and P land models are needed to realistically project this century carbon-climate feedback. In the ocean, the carbon and nutrient cycles are tightly coupled as a result of low living biomass relative to its annual turnover. With rapid recycling of carbon and nutrients, the ocean carbon-climate feedback is weak at the century time-scale. The land and ocean C, N and P cycle models (earth system models) are needed for both improvement of projections of climate change and more realistic investigation of the impact of climate change on land and ocean ecosystems. An earth system modelling approach can also help to assess the impact of different processes on carbon and nutrient cycling, and identify where improved process-understanding is needed.
