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Marine Science Review – 327

Climate and climate change

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In this review:

O/A denotes an open access article or journal

A. Recent articles – no abstract

Greene, C.H., Monger, B.C., and McGarry, L.P. **Some like it cold.** *Science* 324(5928): 733-734, 2009.

Ivins, E.R. **Ice sheet stability and sea level.** *Science* 324(5929): 888-889, 2009.

Monastersky, R. **A burden beyond bearing.** *Nature* 458(7242): 1091-1094, 2009.

Jones, N. **Sucking it up.** *Nature* 458(7242): 1094-1097, 2009.

Morton, O. **Great white hope.** *Nature* 458(7242): 1097-1100, 2009.

Parry, M., Lowe, J., and Hanson, C. **Overshoot, adapt and recover.** *Nature* 458(7242): 1102-1103, 2009.

Schneider, S. **The worst-case scenario.** *Nature* 458(7242): 1104-1105, 2009.

Schmidt, G. and Archer, D. **Climate change: Too much of a bad thing.** *Nature* 458(7242): 1117-1118, 2009.

B. Recent publications available online

Parry, M., Arnell, N., Berry, P., Dodman, D., Fankhauser, S., Hope, C., Kovats, S., Nicholls, R., Satterthwaite, D., Tiffin, R., and Wheeler, T. 2009. ***Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates.*** International Institute for Environment and Development and Grantham Institute for Climate Change, London. 111pp.

Available at: http://www.iied.org/pubs/pdfs/11501IIED.pdf

Notes: This report takes another look at the costs of adapting to climate change. The estimates for 2030 used by the UN Framework Convention on Climate Change are likely to be substantial under-estimates. The report's authors look at the estimates from a range of perspectives, and conclude that:

- the current cost assessments do not include some key sectors, such as ecosystems, energy, manufacturing, retailing, and tourism;

- some of the sectors included have been only partially covered in cost estimates;

- the additional costs of adaptation have sometimes been calculated as 'climate mark-ups' against low levels of assumed investment.

In some parts of the world, low levels of investment have led to an adaptation deficit, and this deficit will need to be made good by full funding of development, without which the funding for adaptation will be insufficient. Residual damages also need to be evaluated and reported because not all damages from climate change can be avoided. There is an urgent need for more detailed assessments of these costs, including case studies of costs of adaptation in specific places and sectors. This report aims to demonstrate the need for the further and transparent refinement of cost estimates for responding to climate change.

Sommerkorn, M. and Hassol, S.J. (eds). 2009. ***Arctic Climate Feedbacks: Global Implications.*** WWF International Arctic Programme, Oslo. 97pp.

Available at: http://assets.panda.org/downloads/wwf_arctic_feedbacks_report.pdf

This report concludes that numerous Arctic climate feedbacks will make global climate change more severe than indicated by other recent projections, including those of the Intergovernmental Panel on Climate Change's 2007 assessment. These feedbacks include: severe flooding, affecting one quarter of the world's population; substantial increases in greenhouse gas emissions from massive carbon pools; and extreme global weather changes, faster than predicted. Key findings of this assessment include:

- Amplification of global warming in the Arctic will have fundamental impacts on Northern Hemisphere weather and climate.

- The global ocean circulation system will change under the strong influence of arctic warming.

- The loss of ice from the Greenland Ice Sheet has increased and will contribute substantially to global sea level rise.

- Arctic marine systems currently provide a substantial carbon sink but the continuation of this service depends critically on arctic climate change impacts on ice, freshwater inputs, and ocean acidification.

- Arctic terrestrial ecosystems will continue to take up carbon, but warming and changes in surface hydrology will cause a far greater release of carbon.

- The degradation of arctic sub-sea permafrost is already releasing methane from the massive, frozen, undersea carbon pool and more is expected with further warming.

McMullen, C.P. and Jabbour, J. 2009. ***Climate Change Science Compendium 2009.*** United Nations Environment Programme, Nairobi. 69pp.

Available at: http://www.unep.org/compendium2009/

Notes: The Climate Change Science Compendium is a review of some 400 major scientific contributions to our understanding of Earth Systems and climate that have been released through peer-reviewed literature or from research institutions over the last three years, since the close of research for consideration by the IPCC Fourth Assessment Report. The Compendium is not a consensus document or an update of any other process. Instead, it is a presentation of some exciting scientific findings, interpretations, ideas, and conclusions that have emerged among scientists. Focusing on work that brings new insights to aspects of Earth System Science at various scales, it discusses findings from the International Polar Year and from new technologies that enhance our abilities to see the Earth's Systems in new ways. Evidence of unexpected rates of change in Arctic sea ice extent, ocean acidification, and species loss emphasizes the urgency needed to develop management strategies for addressing climate change.

C. Recent articles with abstracts

Marland, G., Hamal, K., and Jonas, M. **How uncertain are estimates of CO2 emissions?** *Journal of Industrial Ecology* 13(1): 4-7, 2009. O/A

Notes: Can satellite or other remotely sensed data provide independent estimates – or even confirmation of existing estimates – for emissions from power plants, highways, projects, cities, countries, or groups of countries? The answer for now is no; estimates of emissions from fossil fuels are actually one of the best constrained pieces of data in analyzing the global carbon cycle.

Orr, F.M. **CO_2 capture and storage: are we ready?** *Energy and Environmental Science* 2(5): 449-458, 2009.

Notes: Options for capture and storage of CO_2 that would otherwise be released into the atmosphere by combustion of fossil fuels are considered. This paper assesses whether CO_2 can be captured, whether sufficient potential capacity exists for storage in geologic formations, describes physical mechanisms that can prevent escape of the CO_2 from the subsurface, delineates methods for monitoring the movement of CO_2 in the subsurface and for detecting leaks, and describes field experience with CO_2 injection. While much remains to be learned about the design of specific storage projects, the current state of knowledge of carbon capture and storage is sufficient to permit testing at the scale of large power plants.

Widdicombe, S., Dashfield, S.L., McNeill, C.L., Needham, H.R., Beesley, A., McEvoy, A., Oxnevad, S., Clarke, K.R., and Berge, J.A. **Effects of CO_2 induced seawater acidification on infaunal diversity and sediment nutrient fluxes.** *Marine Ecology Progress Series* 379: 59-75, 2009.

Notes: A mesocosm experiment was conducted to quantify the effects of short- (2 wk) and long-term (20 wk) exposure to acidified seawater on the structure and diversity of macrofaunal and nematode assemblages in 2 different sediment types. The impact of acidified seawater on sediment nutrient fluxes was also determined. Using carbon dioxide (CO_2) gas, seawater was acidified to pH 7.3 (mimicking ocean acidification), 6.5 or 5.6 (mimicking leakage from a sub-seabed CO_2 store site). Control treatments were maintained in natural seawater [pH approximate to 8.0). Exposure to acidified seawater significantly altered community structure and reduced diversity for both macrofaunal and nematode assemblages. However, the impact on nematodes was less severe than that on macrofauna. While the communities in both sediment types were significantly affected by changes in seawater pH, impacts on sandy sediment fauna were greater than those on muddy sediment fauna. Sandy sediments also showed the greatest effects with respect to nutrient fluxes. In sand, the efflux of nitrite, nitrate and silicate decreased in response to increased acidification while the efflux of ammonium increased. In mud, acidification increased the efflux of ammonium but had no effect on the other nutrients. We conclude that both leakage from carbon storage and ocean acidification could cause significant changes in the structure and diversity of coastal sediment communities. Lowered seawater pH could also affect nutrient cycling directly by altering bacterial communities and indirectly through impacts on the abundance and activity of key bioturbators.

Budikova, D. **Role of Arctic sea ice in global atmospheric circulation: A review.** *Global and Planetary Change* 68(3): 149-163, 2009.

Notes: Formed by the freezing of sea water, sea ice defines the character of the marine Arctic. The principal purpose of this review is to synthesize the published efforts that document the potential impact of Arctic sea ice on remote climates. The emphasis is on atmospheric processes and the resulting modifications in surface conditions such as air temperature, precipitation patterns, and storm track behavior at interannual timescales across the middle and low latitudes of the Northern hemisphere during cool months. Addressed also are the theoretical, methodological, and logistical challenges facing the current observational and modeling studies that aim to improve our awareness of the role that Arctic sea ice plays in the definition of global climate. Moving towards an improved understanding of the role that polar sea ice plays in shaping the global climate is a

subject of timely importance as the Arctic environment is currently undergoing rapid change with little slowing down forecasted for the future.

Turner, J. and Overland, J. **Contrasting climate change in the two polar regions.** *Polar Research* 28(2): 146-164, 2009.

Notes: The two polar regions have experienced remarkably different climatic changes in recent decades. The Arctic has seen a marked reduction in sea-ice extent throughout the year, with a peak during the autumn. A new record minimum extent occurred in 2007, which was 40% below the long-term climatological mean. In contrast, the extent of Antarctic sea ice has increased, with the greatest growth being in the autumn. There has been a large-scale warming across much of the Arctic, with a resultant loss of permafrost and a reduction in snow cover. The bulk of the Antarctic has experienced little change in surface temperature over the last 50 years, although a slight cooling has been evident around the coast of East Antarctica since about 1980, and recent research has pointed to a warming across West Antarctica. The exception is the Antarctic Peninsula, where there has been a winter (summer) season warming on the western (eastern) side. Many of the different changes observed between the two polar regions can be attributed to topographic factors and land/sea distribution. The location of the Arctic Ocean at high latitude, with the consequently high level of solar radiation received in summer, allows the ice-albedo feedback mechanism to operate effectively. The Antarctic ozone hole has had a profound effect on the circulations of the high latitude ocean and atmosphere, isolating the continent and increasing the westerly winds over the Southern Ocean, especially during the summer and winter.

Beaugrand, G., Luczak, C., and Edwards, M. **Rapid biogeographical plankton shifts in the North Atlantic Ocean.** *Global Change Biology* 15(7): 1790-1803, 2009.

Notes: Large-scale biogeographical changes in the biodiversity of a key zooplankton group (calanoid copepods) were detected in the north-eastern part of the North Atlantic Ocean and its adjacent seas over the period 1960-1999. These findings provided key empirical evidence for climate change impacts on marine ecosystems at the regional to oceanic scale. Since 1999, global temperatures have continued to rise in the region. Here, we extend the analysis to the period 1958-2005 using all calanoid copepod species assemblages (nine species assemblages based on an analysis including a total of 108 calanoid species or taxa) and show that this phenomenon has been reinforced in all regions. Our study reveals that the biodiversity of calanoid copepods are responding quickly to sea surface temperature (SST) rise by moving geographically northward at a rapid rate up to about 23.16 km yr^{-1}. Our analysis suggests that nearly half of the increase in sea temperature in the northeast Atlantic and adjacent seas is related to global temperature rises (46.35% of the total variance of temperature) while changes in both natural modes of atmospheric and oceanic circulation explain 26.45% of the total variance of temperature. Although some SST isotherms have moved northwards by an average rate of up to 21.75 km yr^{-1} (e.g. the North Sea), their movement cannot fully quantify all species assemblage shifts. Furthermore, the observed rates of biogeographical movements are far greater than those observed in the terrestrial realm. Here, we discuss the processes that may explain such a discrepancy and suggest that the differences are mainly explained by the fluid nature of the pelagic domain, the life cycle of the zooplankton and the lesser anthropogenic influence (e.g. exploitation, habitat fragmentation) on these organisms. We also hypothesize that despite changes in the path and intensity of the oceanic currents that may modify quickly and greatly pelagic zooplankton species, these organisms may reflect better the current impact of climate warming on ecosystems as terrestrial organisms are likely to significantly lag the current impact of climate change.

Sedlacek, L., Thistle, D., Carman, K.R., Fleeger, J.W., and Barry, J.P. **Effects of carbon dioxide on deep-sea harpacticoids revisited.** *Deep Sea Research Part I: Oceanographic Research Papers* 56(6): 1018-1025, 2009.

Notes: As part of the evaluation of the environmental impact of sequestering carbon dioxide in the deep ocean, we exposed the sediment-dwelling fauna at a station in Monterey Submarine Canyon (36.378ºN, 122.676ºW, 3262 m) to carbon dioxide-rich seawater and found that most of the harpacticoid copepods were killed. In an expanded, follow-on experiment on the continental rise nearby (36.709ºN, 123.523ºW, 3607 m), not only did harpacticoids survive exposure to carbon dioxide-rich seawater, but we found no evidence from seven additional metrics that the harpacticoids had been affected. We infer that during the second experiment the harpacticoids were not exposed to a stressful dose. During the second experiment, carbon

dioxide-rich seawater appears to have been produced more slowly than in the first, probably because of differences in the near-bottom flow regimes. We conclude that local physical circumstances can substantially influence the results of experiments of this type and will complicate the evaluation of the environmental consequences of deep-ocean carbon dioxide sequestration.

Higgins, M.E. and Cassano, J.J. **Impacts of reduced sea ice on winter Arctic atmospheric circulation, precipitation, and temperature.** *Journal of Geophysical Research* 114(D16): art. D16107, 2009.

Notes: Changes predicted by the Community Atmospheric Model version 3 (CAM3) in winter Arctic atmospheric circulation, precipitation, and temperature due to projected reductions in sea ice are investigated from a synoptic climatology perspective using the self-organizing map (SOM) technique. A decrease in 1000 hPa geopotential height (Z1000) over Alaska and northern North America is found to be a result of an increase in frequency of patterns with low pressure over much of the Arctic basin. Over Alaska in particular, a deepening of Aleutian lows is also found to contribute to lower Z1000 in this region. With reduced sea ice, Z1000 increases over Siberia and is found to be the result of increases in the frequency of strong high-pressure ridges. Increases over the Greenland and Norwegian Seas are found to be the result of decreases in frequency of strong Icelandic low cyclones. Large increases in precipitation across the Arctic are found to be primarily due to thermodynamic changes, such as increased moisture in the atmosphere, rather than changes in the frequency of cyclones. Temperature changes for the winter season are found to be due almost equally to diabatic heating and changes in temperature advection.

Dessens, O., Zeng, G., Warwick, N., and Pyle, J. **Short-lived bromine compounds in the lower stratosphere; impact of climate change on ozone.** *Atmospheric Science Letters* 10(3): 201-206, 2009.

Notes: We consider how future changes in the circulation of the troposphere might change the delivery of short-lived brominated species to the stratosphere and study the impact of this change on stratospheric ozone. Changes in stratospheric bromine are potentially significant, amounting, under an extreme scenario of all short-lived species having a tropical source, to an increase of perhaps 10% above current levels. This must be set against the slow removal of anthropogenic halogens from the stratosphere. These changes lead to modest, but non-negligible decreases in ozone in the lower stratosphere, reaching about 8% at the tropopause, where changes in ozone have important climate consequences.

Bonsal, B.R. and Kochtubajda, B. **An assessment of present and future climate in the Mackenzie Delta and the near-shore Beaufort Sea region of Canada.** *International Journal of Climatology* 29(12): 1780-1795, 2009.

Notes: Climate change is projected to significantly alter physical, biological, and socio-economic systems, particularly in high latitudes. The Mackenzie Delta and near-shore Beaufort Sea region of Canada is one such area that has already experienced considerable changes in climate and associated impacts. It has also been identified as highly sensitive due to recent oil and gas exploration and extraction. All Global Climate Models (GCMs) are projecting further changes to the Arctic climate, however, regional-scale variations are not well documented. Using seven international GCMs, this study quantifies 18 future (2010-2039) temperature and precipitation projections over the Beaufort region on annual and seasonal scales. Several observed gridded temperature and precipitation datasets are also compared.Observed climate comparisons reveal substantial variability, especially for precipitation. All future projections demonstrate temperature and for the most part, precipitation increases, however, there is a considerable range on both temporal and spatial scales. For temperature, autumn has the greatest change (+1.4 to +3.3 °C), followed by winter (+1.2 to +2.6 °C), spring (+0.8 to +2.4 °C), and summer (+0.2 to +1.6 °C). Spatially, the ocean warms more than the land during the cold season, and the eastern Beaufort is warmer than the western region. Future precipitation shows annual increases averaging between 4.8 and 10.7%. Unlike temperature, seasonal precipitation changes do not vary greatly although slight decreases are projected in some scenarios. Recent (1991-2005) temperature changes at Inuvik, Northwest Territories, indicate that Beaufort-region warming is occurring faster than projected by the majority of GCMs. However, precipitation has not experienced these rapid changes. In terms of extremes, climate-change projections revealed a substantial shift in the temperature distribution toward fewer very cold months and several more warm months. Extremely high monthly precipitation amounts are also projected to increase. This study can be considered an important step towards addressing future climate-change impact assessments in Arctic regions.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., and Allen, M.R. **Greenhouse-gas emission targets for limiting global warming to 2 ºC.** *Nature* 458(7242): 1158-1162, 2009.

Notes: More than 100 countries have adopted a global warming limit of 2 ºC or below (relative to pre-industrial levels) as a guiding principle for mitigation efforts to reduce climate change risks, impacts and damages. However, the greenhouse gas (GHG) emissions corresponding to a specified maximum warming are poorly known owing to uncertainties in the carbon cycle and the climate response. Here we provide a comprehensive probabilistic analysis aimed at quantifying GHG emission budgets for the 2000-50 period that would limit warming throughout the twenty-first century to below 2 ºC, based on a combination of published distributions of climate system properties and observational constraints. We show that, for the chosen class of emission scenarios, both cumulative emissions up to 2050 and emission levels in 2050 are robust indicators of the probability that twenty-first century warming will not exceed 2 ºC relative to pre-industrial temperatures. Limiting cumulative CO_2 emissions over 2000-50 to 1,000 Gt CO_2 yields a 25% probability of warming exceeding 2 ºC – and a limit of 1,440 Gt CO_2 yields a 50% probability – given a representative estimate of the distribution of climate system properties. As known 2000-06 CO_2 emissions were similar to 234 Gt CO_2, less than half the proven economically recoverable oil, gas and coal reserves can still be emitted up to 2050 to achieve such a goal. Recent G8 Communiques envisage halved global GHG emissions by 2050, for which we estimate a 12-45% probability of exceeding 2 ºC – assuming 1990 as emission base year and a range of published climate sensitivity distributions. Emissions levels in 2020 are a less robust indicator, but for the scenarios considered, the probability of exceeding 2 ºC rises to 53-87% if global GHG emissions are still more than 25% above 2000 levels in 2020.

Allen, M.R., Frame, D.J., Huntingford, C., Jones, C.D., Lowe, J.A., Meinshausen, M., and Meinshausen, N. **Warming caused by cumulative carbon emissions towards the trillionth tonne.** *Nature* 458(7242): 1163-1166, 2009.

Notes: Global efforts to mitigate climate change are guided by projections of future temperatures. But the eventual equilibrium global mean temperature associated with a given stabilization level of atmospheric greenhouse gas concentrations remains uncertain, complicating the setting of stabilization targets to avoid potentially dangerous levels of global warming. Similar problems apply to the carbon cycle: observations currently provide only a weak constraint on the response to future emissions. Here we use ensemble simulations of simple climate-carbon-cycle models constrained by observations and projections from more comprehensive models to simulate the temperature response to a broad range of carbon dioxide emission pathways. We find that the peak warming caused by a given cumulative carbon dioxide emission is better constrained than the warming response to a stabilization scenario. Furthermore, the relationship between cumulative emissions and peak warming is remarkably insensitive to the emission pathway (timing of emissions or peak emission rate). Hence policy targets based on limiting cumulative emissions of carbon dioxide are likely to be more robust to scientific uncertainty than emission-rate or concentration targets. Total anthropogenic emissions of one trillion tonnes of carbon (3.67 trillion tonnes of CO_2), about half of which has already been emitted since industrialization began, results in a most likely peak carbon-dioxide-induced warming of 2 ºC above pre-industrial temperatures, with a 5-95% confidence interval of 1.3-3.9 ºC.

Koeller, P., Fuentes-Yaco, C., Platt, T., Sathyendranath, S., Richards, A., Ouellet, P., Orr, D., Skuladottir, U., Wieland, K., Savard, L., and Aschan, M. **Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean.** *Science* 324(5928): 791-793, 2009.

Notes: Climate change could lead to mismatches between the reproductive cycles of marine organisms and their planktonic food. We tested this hypothesis by comparing shrimp (*Pandalus borealis*) egg hatching times and satellite-derived phytoplankton bloom dynamics throughout the North Atlantic. At large spatial and long temporal (10 years or longer) scales, hatching was correlated with the timing of the spring phytoplankton bloom. Annual egg development and hatching times were determined locally by bottom water temperature. We conclude that different populations of *P. borealis* have adapted to local temperatures and bloom timing, matching egg hatching to food availability under average conditions. This strategy is vulnerable to interannual oceanographic variability and long-term climatic changes.

Bamber, J.L., Riva, R.E.M., Vermeersen, B.L.A., and LeBrocq, A.M. **Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet.** *Science* 324(5929): 901-903, 2009.

Notes: Theory has suggested that the West Antarctic Ice Sheet may be inherently unstable. Recent observations lend weight to this hypothesis. We reassess the potential contribution to eustatic and regional sea level from a rapid collapse of the ice sheet and find that previous assessments have substantially overestimated its likely primary contribution. We obtain a value for the global, eustatic sea-level rise contribution of about 3.3 meters, with important regional variations. The maximum increase is concentrated along the Pacific and Atlantic seaboard of the United States, where the value is about 25% greater than the global mean, even for the case of a partial collapse.

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de Nooijer, L.J., Toyofuku, T., and Kitazato, H. **Foraminifera promote calcification by elevating their intracellular pH.** *Proceedings of the National Academy of Sciences [USA]* 106(36): 15374-15378, 2009.

Notes: Surface seawaters are supersaturated with respect to calcite, but high concentrations of magnesium prevent spontaneous nucleation and growth of crystals. Foraminifera are the most widespread group of calcifying organisms and generally produce calcite with a low Mg content, indicating that they actively remove Mg^{2+} from vacuolized seawater before calcite precipitation. However, one order of foraminifera has evolved a calcification pathway, by which it produces calcite with a very high Mg content, suggesting that these species do not alter the Mg/Ca ratio of vacuolized seawater considerably. The cellular mechanism that makes it possible to precipitate calcite at high Mg concentrations, however, has remained unknown. Here we demonstrate that they are able to elevate the pH at the site of calcification by at least one unit above seawater pH and, thereby, overcome precipitation-inhibition at ambient Mg concentrations. A similar result was obtained for species that precipitate calcite with a low Mg concentration, suggesting that elevating the pH at the site of calcification is a widespread strategy among foraminifera to promote calcite precipitation. Since the common ancestor of these two groups dates back to the Cambrian, our results would imply that this physiological mechanism has evolved over half a billion years ago. Since foraminifera rely on elevating the intracellular pH for their calcification, our results show that ongoing ocean acidification can result in a decrease of calcite production by these abundant calcifyers.

Swanson, K.L., Sugihara, G., and Tsonis, A.A. **Long-term natural variability and 20th century climate change.** *Proceedings of the National Academy of Sciences [USA]* 106(38): 16120-16123, 2009.

Notes: Global mean temperature at the Earth's surface responds both to externally imposed forcings, such as those arising from anthropogenic greenhouse gases, as well as to natural modes of variability internal to the climate system. Variability associated with these latter processes, generally referred to as natural long-term climate variability, arises primarily from changes in oceanic circulation. Here we present a technique that objectively identifies the component of inter-decadal global mean surface temperature attributable to natural long-term climate variability. Removal of that hidden variability from the actual observed global mean surface temperature record delineates the externally forced climate signal, which is monotonic, accelerating warming during the 20th century.

Zickfeld, K., Eby, M., Matthews, H.D., and Weaver, A.J. **Setting cumulative emissions targets to reduce the risk of dangerous climate change.** *Proceedings of the National Academy of Sciences [USA]* 106(38): 16129-16134, 2009.

Notes: Avoiding "dangerous anthropogenic interference with the climate system" requires stabilization of atmospheric greenhouse gas concentrations and substantial reductions in anthropogenic emissions. Here, we present an inverse approach to coupled climate-carbon cycle modeling, which allows us to estimate the probability that any given level of carbon dioxide (CO_2) emissions will exceed specified long-term global mean temperature targets for "dangerous anthropogenic interference," taking into consideration uncertainties in climate sensitivity and the carbon cycle response to climate change. We show that to stabilize global mean temperature increase at 2 °C above preindustrial levels with a probability of at least 0.66, cumulative CO_2 emissions from 2000 to 2500 must not exceed a median estimate of 590 petagrams of carbon (PgC) (range, 200 to 950 PgC). If the 2 °C temperature stabilization target is to be met with a probability of at least 0.9, median total allowable CO_2 emissions are 170 PgC (range, -220 to 700 PgC). Furthermore, these estimates of cumulative CO_2 emissions, compatible with a specified

temperature stabilization target, are independent of the path taken to stabilization. Our analysis therefore supports an international policy framework aimed at avoiding dangerous anthropogenic interference formulated on the basis of total allowable greenhouse gas emissions.

Dutreuil, S., Bopp, L., and Tagliabue, A. **Impact of enhanced vertical mixing on marine biogeochemistry: lessons for geo-engineering and natural variability.** *Biogeosciences* 6(5): 901-912, 2009. **O/A**

Notes: Artificially enhanced vertical mixing has been suggested as a means by which to fertilize the biological pump with subsurface nutrients and thus increase the oceanic CO_2 sink. We use an ocean general circulation and biogeochemistry model (OGCBM) to examine the impact of artificially enhanced vertical mixing on biological productivity and atmospheric CO_2, as well as the climatically significant gases nitrous oxide (N_2O) and dimethyl sulphide (DMS) during simulations between 2000 and 2020. Overall, we find a large increase in the amount of organic carbon exported from surface waters, but an overall increase in atmospheric CO_2 concentrations by 2020. We quantified the individual effect of changes in dissolved inorganic carbon (DIC), alkalinity and biological production on the change in *p*CO(2) at characteristic sites and found the increased vertical supply of carbon rich subsurface water to be primarily responsible for the enhanced CO_2 outgassing, although increased alkalinity and, to a lesser degree, biological production can compensate in some regions. While ocean-atmosphere fluxes of DMS do increase slightly, which might reduce radiative forcing, the oceanic N_2O source also expands. Our study has implications for understanding how natural variability in vertical mixing in different ocean regions (such as that observed recently in the Southern Ocean) can impact the ocean CO_2 sink via changes in DIC, alkalinity and carbon export.

Hauton, C., Tyrrell, T., and Williams, J. **The subtle effects of sea water acidification on the amphipod *Gammarus locusta*.** *Biogeosciences* 6(8): 1479-1489, 2009. **O/A**

Notes: We report an investigation of the effects of increases in *p*CO2 on the survival, growth and molecular physiology of the neritic amphipod *Gammarus locusta* which has a cosmopolitan distribution in estuaries. Amphipods were reared from juvenile to mature adult in laboratory microcosms at three different levels of pH in nominal range 8.1-7.6. Growth rate was estimated from weekly measures of body length. At sexual maturity the amphipods were sacrificed and assayed for changes in the expression of genes coding for a heat shock protein (*hsp70* gene) and the metabolic enzyme glyceraldehyde-3-phosphate dehydrogenase (*gapdh* gene). The data show that the growth and survival of this species is not significantly impacted by a decrease in sea water pH of up to 0.5 units. Quantitative real-time PCR analysis indicated that there was no significant effect of growth in acidified sea water on the sustained expression of the *hsp70* gene. There was a consistent and significant increase in the expression of the *gapdh* gene at a pH of ~7.5 which, when combined with observations from other workers, suggests that metabolic changes may occur in response to acidification. It is concluded that sensitive assays of tissue physiology and molecular biology should be routinely employed in future studies of the impacts of sea water acidification as subtle effects on the physiology and metabolism of coastal marine species may be overlooked in conventional gross "end-point" studies of organism growth or mortality.

Maier, C., Hegeman, J., Weinbauer, M.G., and Gattuso, J.-P. **Calcification of the cold-water coral *Lophelia pertusa*, under ambient and reduced pH.** *Biogeosciences* 6(8): 1671-1680, 2009. **O/A**

Notes: The cold-water coral *Lophelia pertusa* is one of the few species able to build reef-like structures and a 3-dimensional coral framework in the deep oceans. Furthermore, deep cold-water coral bioherms may be among the first marine ecosystems to be affected by ocean acidification. Colonies of *L. pertusa* were collected during a cruise in 2006 to cold-water coral bioherms of the Mingulay reef complex (Hebrides, North Atlantic). Shortly after sample collection onboard these corals were labelled with calcium-45. The same experimental approach was used to assess calcification rates and how those changed due to reduced pH during a cruise to the Skagerrak (North Sea) in 2007. The highest calcification rates were found in youngest polyps with up to 1% d^{-1} new skeletal growth and average rates of 0.11±0.02% d^{-1}±S.E.). Lowering pH by 0.15 and 0.3 units relative to the ambient level resulted in calcification being reduced by 30 and 56%. Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus skeletal growth of young and fast calcifying corallites suffered more from ocean acidification. Nevertheless, *L. pertusa* exhibited positive net calcification (as measured by ^{45}Ca incorporation) even at an aragonite saturation state (Ω_a) below 1.

Arnold, K.E., Findlay, H.S., Spicer, J.I., Daniels, C.L., and Boothroyd, D. **Effect of CO_2-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.).** *Biogeosciences* 6(8): 1747-1754, 2009. **O/A**

Notes: Oceanic uptake of anthropogenic CO_2 results in a reduction in pH termed "Ocean Acidification" (OA). Comparatively little attention has been given to the effect of OA on the early life history stages of marine animals. Consequently, we investigated the effect of culture in CO_2-acidified sea water (approx. 1200 ppm, i.e. average values predicted using IPCC 2007 A1F1 emissions scenarios for year 2100) on early larval stages of an economically important crustacean, the European lobster *Homarus gammarus*. Culture in CO_2-acidified sea water did not significantly affect carapace length of *H. gammarus*. However, there was a reduction in carapace mass during the final stage of larval development in CO_2-acidified sea water. This co-occurred with a reduction in exoskeletal mineral (calcium and magnesium) content of the carapace. As the control and high CO_2 treatments were not undersaturated with respect to any of the calcium carbonate polymorphs measured, the physiological alterations we record are most likely the result of acidosis or hypercapnia interfering with normal homeostatic function, and not a direct impact on the carbonate supply-side of calcification *per se*. Thus despite there being no observed effect on survival, carapace length, or zoeal progression, OA related (indirect) disruption of calcification and carapace mass might still adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function.

Andersson, A.J., Kuffner, I.B., Mackenzie, F.T., Jokiel, P.L., Rodgers, K.S., and Tan, A. **Net loss of $CaCO_3$ from a subtropical calcifying community due to seawater acidification: mesocosm-scale experimental evidence.** *Biogeosciences* 6(8): 1811-1823, 2009. **O/A**

Notes: Acidification of seawater owing to oceanic uptake of atmospheric CO_2 originating from human activities such as burning of fossil fuels and land-use changes has raised serious concerns regarding its adverse effects on corals and calcifying communities. Here we demonstrate a net loss of calcium carbonate ($CaCO_3$) material as a result of decreased calcification and increased carbonate dissolution from replicated subtropical coral reef communities (n=3) incubated in continuous-flow mesocosms subject to future seawater conditions. The calcifying community was dominated by the coral *Montipora capitata*. Daily average community calcification or Net Ecosystem Calcification (NEC=$CaCO_3$ production - dissolution) was positive at 3.3 mmol $CaCO_3$ m^{-2} h^{-1} under ambient seawater pCO_2 conditions as opposed to negative at -0.04 mmol $CaCO_3$ m^{-2} h^{-1} under seawater conditions of double the ambient pCO_2. These experimental results provide support for the conclusion that some net calcifying communities could become subject to net dissolution in response to anthropogenic ocean acidification within this century. Nevertheless, individual corals remained healthy, actively calcified (albeit slower than at present rates), and deposited significant amounts of $CaCO_3$ under the prevailing experimental seawater conditions of elevated pCO_2.

Kwok, R. and Rothrock, D.A. **Decline in Arctic sea ice thickness from submarine and ICESat records: 1958-2008.** *Geophysical Research Letters* 36(15): art. L15501, 2009.

Notes: The decline of sea ice thickness in the Arctic Ocean from ICESat (2003-2008) is placed in the context of estimates from 42 years of submarine records (1958-2000) described by Rothrock et al. (1999, 2008). While the earlier 1999 work provides a longer historical record of the regional changes, the latter offers a more refined analysis, over a sizable portion of the Arctic Ocean supported by a much stronger and richer data set. Within the data release area (DRA) of declassified submarine sonar measurements (covering ~38% of the Arctic Ocean), the overall mean winter thickness of 3.64 m in 1980 can be compared to a 1.89 m mean during the last winter of the ICESat record - an astonishing decrease of 1.75 m in thickness. Between 1975 and 2000, the steepest rate of decrease is -0.08 m/yr in 1990 compared to a slightly higher winter/summer rate of -0.10/-0.20 m/yr in the five-year ICESat record (2003-2008). Prior to 1997, ice extent in the DRA was >90% during the summer minimum. This can be contrasted to the gradual decrease in the early 2000s followed by an abrupt drop to <55% during the record setting minimum in 2007. This combined analysis shows a long-term trend of sea ice thinning over submarine and ICESat records that span five decades.

Westbrook, G.K. *et al.* **Escape of methane gas from the seabed along the West Spitsbergen continental margin.** *Geophysical Research Letters* 36(15): art. L15608, 2009.

Notes: More than 250 plumes of gas bubbles have been discovered emanating from the seabed of the West Spitsbergen continental margin, in a depth range of 150-400 m, at and above the present upper limit of the gas hydrate stability zone (GHSZ). Some of the plumes extend upward to within 50 m of the sea surface. The gas is predominantly methane. Warming of the northward-flowing West Spitsbergen current by 1°C over the last thirty years is likely to have increased the release of methane from the seabed by reducing the extent of the GHSZ, causing the liberation of methane from decomposing hydrate. If this process becomes widespread along Arctic continental margins, tens of Teragrams of methane per year could be released into the ocean.

Son, S.-W., Tandon, N.F., Polvani, L.M., and Waugh, D.W. **Ozone hole and Southern Hemisphere climate change.** *Geophysical Research Letters* 36(15): art. L15705, 2009.

Notes: Climate change in the Southern Hemisphere (SH) has been robustly documented in the last several years. It has altered the atmospheric circulation in a surprising number of ways: a rising global tropopause, a poleward intensification of the westerly jet, a poleward shift in storm tracks, a poleward expansion of the Hadley cell, and many others. While these changes have been extensively related with anthropogenic warming resulting from the increase in greenhouse gases, their potential link to stratospheric cooling resulting from ozone depletion has only recently been examined and a comprehensive picture is still lacking. Examining model output from the coupled climate models participating in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (AR4), and grouping them depending on the stratospheric ozone forcing used, we here show that stratospheric ozone affects the entire atmospheric circulation in the SH, from the polar regions to the subtropics, and from the stratosphere to the surface. Furthermore, model projections suggest that the anticipated ozone recovery, resulting from the implementation of the Montreal Protocol, will likely decelerate future climate change resulting from increased greenhouse gases, although it might accelerate surface warming over Antarctica.

Tanaka, K., Raddatz, T., O'Neill, B.C., and Reick, C.H. **Insufficient forcing uncertainty underestimates the risk of high climate sensitivity.** *Geophysical Research Letters* 36(16): art. L16709, 2009.

Notes: Uncertainty in climate sensitivity is a fundamental problem for projections of the future climate. Equilibrium climate sensitivity is defined as the asymptotic response of global-mean surface air temperature to a doubling of the atmospheric CO_2 concentration from the preindustrial level (~280 ppm). In spite of various efforts to estimate its value, climate sensitivity is still not well constrained. Here we show that the probability of high climate sensitivity is higher than previously thought because uncertainty in historical radiative forcing has not been sufficiently considered. The greater the uncertainty that is considered for radiative forcing, the more difficult it is to rule out high climate sensitivity, although low climate sensitivity (<2°C) remains unlikely. We call for further research on how best to represent forcing uncertainty.

Liu, S.C., Fu, C., Shiu, C.-J., Chen, J.-P., and Wu, F. **Temperature dependence of global precipitation extremes.** *Geophysical Research Letters* 36(17): art. L17702, 2009.

Notes: Data from the Global Precipitation Climatology Project (GPCP) covering the period 1979-2007 are examined for changes of precipitation extremes as a function of global mean temperature by using a new method which focuses on interannual differences rather than time series. We find that the top 10% bin of precipitation intensity increases by about 95% for each degree Kelvin (K) increase in global mean temperature, while 30%-60% bins decrease by about 20% K^{-1}. The global average precipitation intensity increases by about 23% K^{-1}, substantially greater than the increase of about 7% K^{-1} in atmospheric water-holding capacity estimated by the Clausius-Clapeyron equation. The large increase of precipitation intensity is qualitatively consistent with the hypothesis that the precipitation intensity should increase by more than 7% K^{-1} because of the additional latent heat released from the increased moisture. Our results also provide an independent evidence in support for significant increases in the number and/or size of strong global tropical cyclones. However an ensemble of 17 latest generation climate models estimates an increase of only about 2% K^{-1} in precipitation intensity, about one order of magnitude smaller than our value, suggesting that the risk of extreme precipitation events due to global warming is substantially greater than that estimated by the climate models.

Dlugokencky, E.J. *et al.* **Observational constraints on recent increases in the atmospheric CH_4 burden.** *Geophysical Research Letters* 36(18): art. L18803, 2009.

Notes: Measurements of atmospheric CH_4 from air samples collected weekly at 46 remote surface sites show that, after a decade of near-zero growth, globally averaged atmospheric methane increased during 2007 and 2008. During 2007, CH_4 increased by 8.3 ± 0.6 ppb. CH_4 mole fractions averaged over polar northern latitudes and the Southern Hemisphere increased more than other zonally averaged regions. In 2008, globally averaged CH_4 increased by 4.4 ± 0.6 ppb; the largest increase was in the tropics, while polar northern latitudes did not increase. Satellite and in situ CO observations suggest only a minor contribution to increased CH_4 from biomass burning. The most likely drivers of the CH_4 anomalies observed during 2007 and 2008 are anomalously high temperatures in the Arctic and greater than average precipitation in the tropics. Near-zero CH_4 growth in the Arctic during 2008 suggests we have not yet activated strong climate feedbacks from permafrost and CH_4 hydrates.
