Climate change: implications for ecotoxicological environmental impact assessment

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Word count: **6719**

Abstract:

As a consequence of increasing atmospheric CO_2 and its subsequent sequestration, the oceans are undergoing changes that have not been seen for millennia, including temperature increases, ocean acidification and localised alterations in salinity. The current methodologies for undertaking environmental impact assessments may not be suitable for use under near future (2100) conditions. This paper reviews and analyses what research has presently been undertaken to address these concerns. The authors find that little attention has previously been paid to chronic exposure conditions that accurately reflect the near future, but the few available studies show that the consequences of oceanic climate change will not only be significant for marine life, but also impact humans who depend on it. The authors suggest that future research targets understanding how climate change will impact the physiological health of a wide array of species, important both economically and ecologically, going beyond the often-chosen model species and standardised testing. This information is

necessary to accurately estimate the environmental risk of proposed engineering projects in changing environmental conditions.

Introduction:

Human civilisation has developed during an unusual period of environmental stability, the Holocene era. However, due to humanity's continued use of natural resources this has led to a large degree of perturbation of local and regional ecology, coupled with previously unseen levels of industrialisation. It is clear that humans have had an impact on a global scale and this has led to the beginning of the Anthropocene era (Zalasiewicz et al. 2008). Climate change is perhaps the most concerning example of humanity's impact upon the global ecosystem, with 2016 the first year that monthly atmospheric CO_2 levels are predicted to remain above the 400 ppm threshold throughout the full year, where a global temperature rise of 2ºC becomes "likely" to occur and global CO_2 cycles begin to enter into dangerous oscillations rather than the current steady state system (Meinshausen 2006; Meissner et al. 2008; Meinshausen et al. 2009; Betts et al. 2016; World Meteorological Organization 2016). Of course, anthropogenic climate change is a well-established scientific fact, if not a political one, although the full implications of this in the marine environment are still unclear and under debate (Hoegh-Guldberg and Bruno 2010; Doney et al. 2012).

The three largest "symptoms" of marine climate change are likely to be: temperature increases, fluctuations in salinity and an overall depression in pH (Brierley and Kingsford 2009), as demonstrated by the latest Intergovernmental Panel on Climate Change (IPCC) report (IPCC 2014). Indeed, it states that the upper 75m of the world's oceans have been warming, on average, at a rate of 0.11°C per decade since at least 1971, and 0.015°C per decade at 700m. The average pH has been depressed by 0.1 over the same period and it is predicted to decrease by another 0.4 units by 2100, accompanied by salinity changes occurring throughout the entire water column (IPCC 2014). With atmospheric CO_2 concentrations predicted to continue rising until at least 2040, the acidification or temperature increase of the oceans will not cease, or even slow, within the next 50 years (Hall-Spencer et al. 2008; Riebeek 2008; Hönisch et al. 2012).

Moving towards the near future, defined as 2100 within this article, there are numerous models available concerning the magnitude and rates of climate change, however, available studies have shown that these models, even the more extreme ones, may be underestimating the future rates of change (Forest et al. 2002; Rahmstorf et al. 2007; Horton et al. 2010; Gosling et al. 2011). Climate change will not affect all areas of the oceans equally, as the rate and magnitude of predicted changes will be heterogeneous due to ocean circulation, local and regional variability in wind patterns, and interactions with other natural or anthropogenic sources of local climate variability, such as the El Niño Southern Oscillation (ENSO) or terrestrial freshwater runoff (Wernberg et al. 2011; Hobday and Pecl 2014; Betts et al. 2016). Irrespective of the actual rate and magnitude of change, be it local, regional or global, these deviations from the norm are expected to have large-scale effects on marine biota and overall ecosystem health in the near future, and as such, will affect how these parameters are measured or assessed.

Assessing these potential impacts and mitigating any further damage to the marine environment by human activity are key to protecting the ocean’s future and society’s access to ecosystem services for their socio-economic benefit. Currently, effects of potential anthropogenic activities are predicted by means of an environmental impact assessment (EIA), defined as “the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made” (Senécal et al. 1999). EIAs have been incorporated into environmental legislation around the world, and are deeply integrated within EU & US regulations concerning sound environmental management. Assessment of environmental impacts within the EIA process have traditionally been conducted following a primarily ecological approach based on species abundance, presence/absence and diversity, alongside analytical techniques of chemical levels assessment and their potential effects on organisms. However, as will be discussed in this paper, these methods can fail to be sensitive enough to detect deleterious effects of contaminants and anthropogenic activities prior to the occurrence of large-scale population changes.

Biomarkers and climate change: current knowledge and future shortfalls

Biomarkers are defined as any naturally occurring molecule, gene or characteristic that can be used for the diagnosis of a particular pathological or physiological process or disease (Gestel and Brummelen 1996). They can be objectively and quantitatively measured and the results interpreted as a gauge of physical health, or provide evidence of exposure to a specific contaminant. When single biomarkers are studied in isolation, they rarely provide sufficient evidence or information to suitably assess a given hypothesis of exposure (Forbes, Palmqvist and Bach, 2006). Instead, a carefully considered panel of biomarkers should be utilised across multiple levels of biological organisation that can give rise to a biomarker profile, or “fingerprint”. These profiles can be directly correlated to specific substance or environmental exposures, and, with very careful consideration, scaled to population level impacts (Calow and Forbes 2003; Kidd et al. 2007; Schmolke et al. 2010). The use of sub-lethal biological responses as tools is well-established in ecotoxicology, with a range of advantages over traditional chemical/analytical or ecological approaches (Peakall 1992; Hook, Gallagher and Batley 2014). Biomarkers can provide proactive or precautionary predictive values for risk, as biochemical-level effects almost always occur before contaminants are found to affect whole populations (Galloway et al. 2004). An additional advantage is the ability to tailor a biomarker suite to assess the specific concerns of the contaminant or environment being studied.

As marine invertebrates, comprising around 95% of extant species in the oceans (Ruppert, Fox and Barnes 2004), are ectotherms, the impact of increasing temperature upon their physiology will likely be a compounding factor in species' response to climate change. Temperature directly influences cellular membrane permeability and fluidity (Papahadjopoulos et al. 1973; Cossins and Prosser 1978), meaning that ectotherms, in the predicted warmer oceans, will have lesser control over what can and cannot be excluded from a cell, which could have large effects upon contaminant behaviour once inside an organism (Schiedek et al. 2007; Noyes et al. 2009). In addition, increased membrane fluidity could affect key membrane-bound enzymes and processes, such as the cytochrome P450 monooxygenase system, key for monitoring exposure to organic contaminants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Bucheli and Fent, 1995). Whilst studies pertaining specifically to climate change scenarios have been limited thus far, many have been undertaken detailing the effects of seasonal temperature changes in commercially important species such as prawns, shrimp and crabs (Howard and Hacker 1990; Cailleaud et al. 2007; Vinagre et al. 2014), with fewer studies assessing how water temperature correlates to varying activities of certain enzymes in other, more ecologically relevant, invertebrates including urchins, sediment dwellers and copepods (Hogan 1970; Leiniö and Lehtonen 2005; Ferreira et al. 2016).

Similarly, salinity fluctuations have been found to alter the activity of antioxidant and detoxification systems in several invertebrates (Zanette et al. 2011; Tu et al. 2012), whilst studies of biomarkers of DNA damage have shown salinity to have no, or limited, impact in estuarine mussel species (Singh and Hartl 2012). Multiple studies have detailed how salinity fluctuations can affect growth and fecundity, however, once again, this has primarily been conducted with commercially important species in estuarine conditions, utilising extreme fluctuations in salinity and neglecting a wider range of more ecologically important species (Pfeifer, Schiedek and Dippner 2005; Cailleaud et al. 2007; Rodrigues et al. 2012). Whilst these studies have found significant alterations in enzymatic activities following changes in salinity, they were the result of short-term, shock loads of salinity levels upon organisms, not a slow and chronic increase over multiple generations that climate change is likely to bring.

One of the largest unknowns in relation to the biological impacts of climate change is that of ocean acidification. The observed rates of change in sea surface pH are dramatic: pH is being depressed at least 100 times faster than the Earth has experienced in millions of years (Caldeira and Wickett 2003; Raven et al. 2005). Whilst studies concerning ocean acidification are more numerous than salinity, they are the most variable of any concentrating on physiological impacts of climate change. For example, coccolithophore calcification and photosynthesis have been shown to both increase and decrease in response to elevated CO_2 (Buitenhuis, De Baar and Veldhuis 1999; Sciandra et al. 2003; Iglesias-Rodriguez et al. 2008). Similar findings have been reported with echinoderms, indicating that the impacts of ocean acidification are likely to be species specific (Langer et al. 2006; Dupont, Ortega-Martínez and Thorndyke 2010).

Whilst calcifying organisms will arguably be the most affected by acidification (Kuffner et al. 2008; Hennige et al. 2015; Ainsworth et al. 2016), the induction of hypercapnia, abnormally elevated CO_2 levels within the circulatory system, and its subsequent effects in non-calcifying organisms, remains a significant issue that little research has explored beyond small-scale perturbation studies. Similar to the issues with salinity, most acidification studies to date have concentrated on short-term, rapid perturbation experiments *in vivo* on single species in isolation in order to study the impacts of near-future ocean acidification (Miles et al. 2007; Hall-Spencer et al. 2008; Havenhand et al. 2008; Havenhand

and Schlegel 2009; Dupont, Ortega-Martínez and Thorndyke 2010; Stumpp et al. 2012; Ohki et al. 2013). Whilst numerous historical climate events and seasonal variations have provided the conditions necessary to study salinity and temperature fluctuations, other than natural carbon seeps, such as volcanic vents (Hall-Spencer et al. 2008), there are almost no opportunities to study the effects of pH reduction on whole ecosystems, or even individual organisms in the natural environment or to establish monitoring programs over multiple generations of organisms. It should also be noted that undertaking ocean acidification research in the laboratory is also not a trivial matter. Whilst altering temperature and salinity levels is relatively cheap and simple, the carbonate chemistry of water is remarkably complex and considerable forethought and careful experimental design is required in order for studies to have meaningful results (Riebesell et al. 2011). A review by Cornwall and Hurd (2016) found that 95% of ocean acidification studies between 1993 and 2014 did not design experiments suitably for the accurate detection of the biological impacts of climate change.

The authors have yet to find a single biomarker study simultaneously detailing ecologically relevant, rather than commercially important, species, realistic (2100 values in IPCC (2014)) climate change-induced physicochemical changes and longer term exposures to these conditions (over 1 month). The need to address these shortfalls is clear. There is currently a lack of knowledge, and understanding, of how climate change alone will alter the results of ecotoxicological tests. It may be that temperature, salinity and pH alterations have a synergistic effect upon organisms, something that can only be elucidated with targeted multiple stressor approaches. Whilst some previous studies have utilised this multiple stressor approach, others appear to have “jumped the gun” by introducing a known contaminant such as persistent pesticides or heavy metals into the assessed variables alongside climatic factors (DeLorenzo et al. 2009; Tu et al. 2012; Freitas et al. 2017). What is required before such research can have meaningful impacts, is the fundamental understanding and establishment of how climatic variables alone impact the baseline levels of classic and novel biomarkers. Sardi et al. (2016) and (Pires et al. 2015) provide good examples of the work necessary before pollutants should be included in climate change related biomarker research.

What is strikingly common amongst studies concerning the biological impacts of climate change is the frequent use of mortality, growth and reproductive rates as sole experimental endpoints, even in the few longer-term chronic exposure studies (Miles et al. 2007; Gooding, Harley and Tang 2009). Such endpoints are rather blunt and can miss underlying stress (immunological, neurological, metabolic or oxidative stress etc.), which, exaggerated by warmer sea temperatures, can make organisms more susceptible to microbial challenge, for example, leading to large scale mortalities. This has been previously observed in the American lobster, *Homarus americanus*, where water temperatures greater than 20ºC suppressed the immune system, resulting in favourable conditions for paramoebiasis, causing a rapid die-off of local populations (Cawthorn 2011). Results of future ecotoxicological studies must take considerations like this into account, where an otherwise minor suppression or alteration of a physiological process can result in population-scale effects that cannot be objectively predicted through *in vitro* experimental data alone. The authors recommend that a holistic approach be employed to avoid such scenarios, with cross-talk between ecologists, environmental scientists, ecotoxicologists and wider societal stakeholders being encouraged to make more accurate predictions of the impact of changes in climate that are forecasted to take place within the next century.

The issue with EIAs in a changing climate.

Climate change and the associated physicochemical changes in the marine environment will affect species on multiple organisational levels, from subcellular to population. However, due to the current way environmental impacts are assessed, these population level impacts are difficult, if not impossible to predict, without large, economically impractical studies being undertaken. The potential variables that need to be incorporated into the EIA process, including both design and environmental considerations are too numerous to list here. A review by researchers from the Organisation for Economic Co-operation and Development (OECD) into incorporating climate change considerations and adaptations into the design phase of EIAs found that the goal of incorporating climate change impacts and adaptation within environmental assessments remains, to a large extent, an aspirational goal (Agrawala et al. 2010). While a number of governments have signalled their intent to move in this direction, the OECD assessment could only find examples of projects that have adopted climate change impacts and adaptation as part of the EIA process in the Netherlands, Canada and Australia (Agrawala et al. 2010; European Commission 2013). Readers are directed towards the reports by Agrawala et al. (2010) and the European Commission (2013), for a detailed overview of how considerations for the impacts of climate change can be incorporated into environmental impact assessments of future projects, however, it should be noted that both of these reports primarily take biodiversity indices and associated ecological methods into account.

Incorporating biological and climatic considerations should be a priority for any future project destined for the marine environment for any significant length of time. Vulnerability assessments are increasingly applied as mainstream tools for supporting conservation decisions, and could potentially be used to inform the EIA process, though with some notable caveats (Small-Lorenz et al. (2013). The process uses available data on the biological traits of a given species, including dispersal ability, genetic variability and phenotypic plasticity, thus accounting for “adaptive capacity” (Beever et al. 2016), that is, the biological responses which could mitigate or reduce the sensitivity of a given population to climate change (Morrison et al. 2015). These models do provide a basic framework for assessing species-specific vulnerability, but have yet to be validated with laboratory experiments, and so should be treated purely as advisory until such research is completed. It should also be made clear that these vulnerability assessments often do not take migratory species, or those that have not been thoroughly studied (often due to a lack of impetus if species are not economically important) into account, as insufficient biological or historical data exist to complete an assessment at a species population level (Small-Lorenz et al. 2013).

These shortfalls could feasibly be a major drawback of these models, as whilst data for commonly used ecotoxicological biomarker species, such as bivalves, crabs, other invertebrates and selected fish species, are plentiful, such species may no longer be available for ecosystem health assessment in the future, as will be discussed below. This will mean that species selection when undertaking an EIA will be more key than ever for reaching the correct local policy and management decisions. These selections should be carefully evaluated on a case-by-case basis, due to the spatial heterogeneity of climate change and oceanic conditions, some species, or populations of the same species, will be more exposed than others (Hobday and Pecl 2014). If a species already exists at its tolerance limits, be it for temperature, pH, salinity or contaminant load, then migration will be the first option when conditions become untenable in the future. Species may well persist, especially if this avoidance behaviour is not possessed, but adaptations will have to manifest themselves for the organism to survive. As climate or other natural changes shift, all organisms initially respond based on behavioural and physical adaptations that have been shaped throughout their evolutionary history (Doney et al. 2012). However, when the rate of change is faster, larger in magnitude, or both, then any genetic plasticity in the population may not be sufficient for acclimatisation and adaptation to occur.

Population-level shifts will occur due to physiological intolerance to new environments (Mills et al. 2013), altered dispersal patterns (Rutgers University 2014), and changes in species interactions at various biotic and abiotic levels (Calow and Forbes 2003; Noyes et al. 2009; Doney et al. 2012). Together with local climate-driven invasion and extinction, these processes will result in altered community structure and diversity, including possible emergence of novel ecosystems (Doney et al. 2012). Some organisms, particularly those with well-developed osmoregulatory systems (e.g., migratory fish), already maintain or restore internal acid-base balance when confronted with a degree of change in ocean chemistry, whereas less physiologically flexible taxa (e.g., Echinodermata, specifically urchins) may be more vulnerable (reviewed in Dupont et al. 2010). Data from Rutgers University collected from the OceanAdapt program on lobster catch distribution of the Northeast United States between 1967 and 2014 clearly show that as the water temperatures farther south have increased, the lobsters have moved north in an effort to avoid the changes (Rutgers University 2014). Such migrations will certainly have large effects upon society's access to ecosystem services, affecting livelihoods, food distribution and even existing projects, such as tidal generators, that may not have been designed to tolerate such a large influx of organisms at levels that were not previously predicted. Due to the global scale of climate change, the options for migration may be limited to local or regional "microenvironments", as seen above with *H. americanus*, where depth and water temperature play a limiting role in defining species' primary distributions (Lawton and Lavalli 1995; Wahle et al. 2015).

Despite the clear benefits of utilising biomarkers in ecotoxicity testing, environmental regulators have been slow to incorporate biological endpoints into regulatory frameworks and management plans (Dallas and Jha 2015). The EU Water Framework Directive (WFD) requires "good ecological status", measured primarily through ecological methods, which provide an overview of present ecosystem health. However, these methods can easily neglect the early warning signs that many sub-lethal biological responses provide and indeed, potentially result in whole species being removed from a system before any broad ecological changes are recorded (Vasseur and Cossu-Leguille 2003). The EU Marine Strategy Framework Directive (MSFD) includes considerations of relevance in this context by stating that “concentrations of contaminants are at levels not giving rise to pollution effects”. Whilst this statement has enabled the use of biomarker studies much more than previous directives, the MFSD’s wording is still open to interpretation, dependent on many factors, from the level of biological organisation being evaluated to which EU member state or regulatory body is undertaking the assessment (Thain, Vethaak and Hylland 2008; Borja et al. 2010, 2011; Lyons et al. 2010; Van Hoey et al. 2010).

Conclusions

When coupled with traditional ecological approaches, biomarker studies can provide an invaluable tool to aid environmental scientists, ecologists and ecotoxicologists alike in informing policy and management decisions pertaining to the potential impacts of a proposed project. Experimental protocols will need to be adapted to account for site specific environmental variation, as standardised testing (OECD etc.) does not currently take this into consideration. Whilst biomarkers of exposure do contribute to current methodologies, little work has been undertaken in detailing the potential changes in biomarker baseline values that changing environmental conditions alone may cause. In order to accurately estimate risk associated to any long-standing development by humans, it must first be understood how climate change is going to affect the basal levels of organism physiology. This can be achieved through a series of carefully designed studies incorporating the three main effectors of climate change in the marine environment, an increase in water temperature coupled with depressed pH and fluctuations in salinity. Future studies must also ensure that appropriate exposure times are used, as climate change will not be a simple shock load on a system, but a chronic and gradual increase/decrease (or fluctuations in extremes) of key parameters, that will fundamentally alter the environment surrounding an organism.

As the physicochemical changes effected by climate change become more pronounced in the near future, researchers must comprehend how these changes will affect the baseline levels of key biomarkers used in ecotoxicological testing. A lack of knowledge of these baselines under altered environmental conditions could result in significant under- or overestimation of risks when interpreting biomarker results that, coupled with the current implementation of EIAs, could see future engineering projects severely mismanaged in terms of environmental impact. In addition, there is a crucial need for improved knowledge transfer between ecotoxicologists, environmental biologists, engineers, regulators and other stakeholders to ensure effective management of both current and future impacts upon the marine environment (Schwarzenbach et al. 2006; Cvitanovic et al. 2015; Dallas and Jha 2015).

Even with biomarker studies integrated into EIAs, neither ecological nor ecotoxicological methods currently take climate change and its future impacts into account. Owing to the potentially more hostile conditions that will arise, the marine taxa frequently utilised for ecotoxicological testing may no longer be available for environmental assessment due to migration, and so, far more consideration must be put into species selection. Species not possessing avoidance behaviour may well persist, but at a higher physiological “stress” level, which may lead to elevated baseline biomarker values potentially resulting in a misinterpretation or underestimation of risk and lead to the introduction of further anthropogenic stressors causing a “tipping point” within the system. The resulting ecosystem level impacts that occur when a species important to ecosystem stability is severely disrupted (Miller and Colodey 1983; Carpenter 1988; Jurgens et al. 2015) could be prevented with the research proposed in this article. Specific effort, in the form of carefully considered biomarker studies, should be put into closing this knowledge gap in the coming years to ensure that biologists may suitably inform policy makers so that society is prepared for the changes that will undoubtedly take place as the impact of climate change takes effect in the near future.

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