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Trends in marine climate change research in the Nordic region since the first IPCC report

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Abstract Oceans are exposed to anthropogenic climate change shifting marine systems toward potential instabilities. The physical, biological and social implications of such shifts can be assessed within individual scientific disciplines, but can only be fully understood by combining knowledge and expertise across disciplines. For climate change related problems these research directions have been well-established since the publication of the first IPCC report in 1990, however it is not well-documented to what extent these

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directions are reflected in published research. Focusing on the Nordic region, we evaluated the development of climate change related marine science by quantifying trends in number of publications, disciplinarity, and scientific focus of 1362 research articles published between 1990 and 2011. Our analysis showed a faster increase in publications within climate change related marine science than in general marine science indicating a growing prioritisation of research with a climate change focus. The composition of scientific disciplines producing climate change related publications, which initially was dominated by physical sciences, shifted toward a distribution with almost even representation of physical and biological sciences with social sciences constituting a minor constant proportion. These trends suggest that the predominantly model-based directions of the IPCC have favoured the more quantitatively oriented natural sciences rather than the qualitative traditions of social sciences. In addition, despite being an often declared prerequisite to successful climate science, we found surprisingly limited progress in implementing interdisciplinary research indicating that further initiatives nurturing scientific interactions are required.

1 Introduction

Oceans are a key component in climate systems and provide physical as well as biological resources and services on which human communities depend. Thus, assessing the physical, biological, and social causes and consequences of anthropogenic climate change to oceans requires research efforts from different scientific disciplines separately as well through interdisciplinary initiatives (Bjurström and Polk 2011a).

In climate studies, research from different scientific disciplines is often intertwined. Climate projections, a cornerstone of the IPCC reports (Bjurström and Polk 2011b), rely on detailed computer models that integrate physical processes of ocean and atmosphere under various emission scenarios determined from societal trends. In climate projection models oceans act as CO_2 buffers and heat absorbers (Doney et al. 2012), in turn affecting sea level, wind speed, and precipitation. Changed ocean conditions feed back to coastal societies, which are directly threatened through potential sea level rise and severe weather (IPCC 1990; Hoegh-Guldberg and Bruno 2010). Moreover, changing ocean temperatures indirectly affect socioeconomic systems through a biological pathway such as ecosystem services (Brander 2007) altered by temperature induced changes in distributions of exploited species (Burrows et al. 2011). Finally, decision makers respond with mitigation and adaptation policies that may alter anthropogenic drivers of climate change. These systemic couplings highlight the necessity of interdisciplinary collaboration when assessing causes and consequences of marine climate change (Shaman et al. 2013).

The understanding that interdisciplinarity is a prerequisite when addressing general climate issues is well established (Changnon 1992), and studies advocating interdisciplinarity in climate research are numerous (Reid et al. 2010; Shaman et al. 2013). However, though

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Grieneisen and Zhang (2011) found that, since the publication of the first IPCC report, the trend in general climate change science is an exponential increase in the number of publications, a detailed quantification of the development of marine climate science is absent.

Here we analyse how marine climate change research has evolved in the Nordic region during the two recent decades (1990–2011) as a response to an increased societal need for understanding climate change. Here, the Nordic region is defined as the waters surrounding the Nordic countries: the Norwegian, Barents, Greenland, Iceland, Baltic and North seas including the connecting waters (map in Supplementary Fig. S1). Given the strong academic, social and political systems of the region and that it is the best studied region within marine ecological research regarding climate change (Poloczanska et al. 2013), our study area is an ideal case for indicating trends in marine climate change research also beyond the Nordic region (Paasche et al. 2015).

Our approach is to quantify trends in marine climate change research at three levels: 1) by, similar to Larsen and von Ins (2010), identifying trends in the number of published peer reviewed research articles within marine science with a climate change focus; 2) by quantifying trends in the composition of major scientific branches and in the degree of interdisciplinary research within marine climate change research; 3) by identifying differences and overlap between the major scientific branches in their focus on different environmental variables related to climate change to increase the understanding of the observed scientific composition and interactions.

2 Methods

2.1 Literature collection

To gather relevant peer reviewed scientific literature focusing on climate change in relation to marine systems in the Nordic region (Supplementary Fig. S1) we closely followed the systematic review guidelines of Pullin and Stewart (2006). As search engine we used the Aquatic Sciences and Fisheries Abstracts (ASFA, http://search.proquest.com/asfa) bibliographic database. ASFA was chosen because of its particular emphasis on literature within aquatic sciences and its broad scientific scope including natural and social scientific disciplines.

To search the ASFA database we developed two character strings composed of search terms determined to obtain publications focusing primarily on 1) climate change within natural sciences (biology, ecology, climatology, oceanography), and 2) climate change within social sciences (sociology and economics). Both search strings contained climate change keywords such as “global warming”, “climate change”, “environmental variability”, etc. and various combinations thereof (Supplementary Methods S1.2). The natural sciences string explicitly searched for publications within the Nordic region, whereas the social sciences string searched without a geographic constraint. This approach was taken to avoid excluding generic studies without a specific regional focus, which were assumed to be more common within social sciences. To obtain marine related research, we included broad search terms such as “marine”, “ocean”, and “sea” with wildcards. The search strings were further refined iteratively by adding exclusive terms to improve the specificity of the search and avoid studies concerning fresh and waste water environments as well as climate change on geological time scales. The search was performed within peer-reviewed articles published in scholarly journals thus excluding grey literature. Results from the two search strings were merged and duplicates removed. We only focused on studies published from 1990 (the year of the first IPCC report) until 2011. Publications were extracted in the third quarter of 2012 inhibiting the inclusion of data from 2012 in the analyses.

The search resulted in 2806 scientific publications. The full text of each publication was screened and excluded if it did not focus on current anthropogenic climate change, i.e. publications focusing on climate change on geological time scales were excluded. Moreover, publications were excluded if they specifically focused on areas outside the Nordic region.

For each of the relevant remaining publications ($N = 1362$) we assigned specific disciplines to publications containing science that overlapped with the discipline definitions (Table 1). We chose broad categories for the scientific branches: physical sciences (chemical and physical oceanography and climatology), biological sciences (biology and ecology), and social sciences (sociology and economics). By construction all publications study aspects of climate change, however this does not automatically define them as a climatology study because their scientific content does not necessarily overlap with the definition of climatology. For example, a publication studying temperature effects on the spatial distribution of cod overlaps with the definition of the biological discipline but not with the climatological discipline. On the other hand, a publication explicitly modelling climate variations and coupling this with a model for the spatial distribution of cod would overlap with both biology and climatology and therefore be considered interdisciplinary.

For each publication we furthermore noted which environmental variables it focused on in the section explaining scientific method. The environmental variables were chosen from

Table 1 Definitions used to categorise publications into disciplines

Branch	Discipline	Definition
Physical	Oceanography	The study of the physical aspects of the ocean, the movements of the sea, and the variability of these factors in relationship to the atmosphere and the ocean bottom.
	Climatology	The study of climate, specifically of weather condition trends, over a defined period of time, past, present or future. In analysing long-term climatic developments, climatology is distinct from meteorology, which is associated with short-term weather system studies.
Biological	Biology	The study of life, and living organisms, including their structure, function, growth, origin, evolution, distribution, and taxonomy.
	Ecology	The study of interactions among living organisms and their environment.
Social	Economics	The study of processes that govern the production, distribution and consumption of goods and services.
	Sociology	The study of social behavior, its origins, development, organisation, and institutions.
Interdisciplinary	–	A publication falling within more than one of the above defined branches is defined as interdisciplinary. Interdisciplinary publications are thus not explicitly categorised, but arise automatically from the categorisation of the other disciplines.

a list of thirteen categories (Table 2) determined prior to categorization. Articles not mentioning environmental variables from this list either studied unlisted variables or focused on marine climate change in general without emphasising specific variables. A simple categorization protocol was formulated (Supplementary Methods S1.3). The ability of different individuals to follow this protocol and produce homogeneous data was checked via a pilot study where eleven individuals categorized the same 60 publications (Supplementary Methods S1.3). Convincing agreement between categorisers was found (Figure S2).

2.2 Quantitative trends analysis

To quantify trends in marine climate change research since 1990 we fitted a Poisson generalized linear model (GLM) with a log link function to the annual number of peer-reviewed publications within marine climate change in the Nordic region, $N_{cc}(t)$, where t is time in years. We also fitted a Poisson GLM to the annual number of peer-reviewed publications within general marine research in the Nordic region, $N_{gm}(t)$, to test the hypothesis of a difference in publication rate (β) of general marine science versus marine science with a climate change focus. $N_{gm}(t)$ was obtained by eliminating climate change related words in the search strings. Formally, the Poisson GLM is written as

$$N_*(t) \sim \text{Poisson}[\lambda(t)], \tag{1}$$

$$\log[\lambda(t)] = \alpha + \beta t, \tag{2}$$

where $N_*(t)$ represents either $N_{cc}(t)$ or $N_{gm}(t)$, $\lambda(t)$ is the mean parameter of the Poisson distribution, α is the intercept parameter and β is the slope interpreted as the temporal rate of publication, which is the parameter of primary interest in terms of identifying trends in scientific publication.

To check if different scientific branches reacted differently to increased climate change awareness, we investigated the trend in the distribution of publications among physical, biological, and social sciences. We controlled for the general increase in number of publications observed for all branches by comparing proportions calculated within each year as opposed to comparing absolute numbers within each year. To facilitate the comparison,

Table 2 List of environmental variables used in the categorisation

Environmental variable
Climatic index
CO_2 (carbon dioxide)
O_2 (oxygen)
Other greenhouse gases (GHG)
pH (acidity)
Precipitation
Salinity
Sea ice cover
Sea level rise
Heat flux
Temperature
Turbidity
Wind

Climatic index refers to studies focusing on e.g. the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation (AMO), or similar. "Other greenhouse gases" refers to publications focusing on gases other than CO_2 and O_2, e.g. O_3, CH_4, etc. Heat flux refers to studies focusing on e.g. solar radiation, heat loss or similar binomial GLMs with a logit link function were fitted to the proportion of extracted publications within each of the three broad scientific branches. We also counted, for each year, the number of interdisciplinary publications, i.e. publications that were assigned more than one scientific branch. We then fitted a binomial GLM to the proportion of these interdisciplinary studies to uncover possible tendencies in scientific collaboration across branches. Formally, the binomial GLM is written as

$$N_{branch}(t) \sim \text{Binomial}[N_{CC}(t), p_{branch}(t)], \quad (3)$$

$$\text{logit}[p_{branch}(t)] = \alpha + \beta t, \quad (4)$$

where $N_{branch}(t)$ represents the number of publications within a branch (physical, biological, and social) or number of interdisciplinary publications, and $p_{branch}(t)$ is the expected proportion of disciplinary/interdisciplinary publications within N_{CC}. Again, α is the intercept and β is the slope.

To uncover overlaps and differences in climate science between scientific branches, we quantified how the focus on different environmental variables within each branch evolved since 1990. We did this by calculating the proportion of publications that, within a branch and within a temporal interval (bin), studied a given environmental variable. The social sciences branch was determining for bin widths because it had the fewest publications and therefore the smallest sample size (Supplementary Table S1). Bins widths were therefore selected to contain at least 20 social publications each with the most even resulting distribution over time producing six temporal bins (1990–1998, 1999–2004, 2005–2008, 2009, 2010, 2011). The choice of setting bin-sizes to contain a minimum of 20 social publication is a trade-off between having enough bins to provide sufficient resolution of the temporal dimension versus having sufficient information in each bin to provide a basis for inference. The inference drawn from the GLMs should be relatively insensitive to the exact choice of the determining number of social publications, as the uncertainties associated with sample sizes are propagated through the model and reflected in the resulting p-value. Within each scientific branch we also calculated the proportion of publications that studied climate change more generally, i.e. where no specific variables were studied, and the proportion of publications that focused on increasing complexity and potential interactions of environmental variables, i.e. that studied more than one variable. Finally, to quantify the diversity in scientific focus within each branch, we calculated the Shannon-Wiener diversity of environmental variables within each of the six aforementioned temporal bins. Linear regressions with a t-distributed error were fitted to the calculated diversity for each scientific branch. Significant slopes of the linear regressions were tested using a likelihood ratio test by comparing a model including a slope parameter to a model without slope parameter (further details in Supplementary methods S1.5).

3 Results

3.1 Trends in number of publications

The number of publications within marine science focusing on climate change increased exponentially with a doubling time of 4.8 years (Fig. 1). In contrast, general marine science took almost twice as long to double its annual number of publications with a 9.4 year doubling time (Wald test, $z = 13.3$, $P < 10^{-16}$).

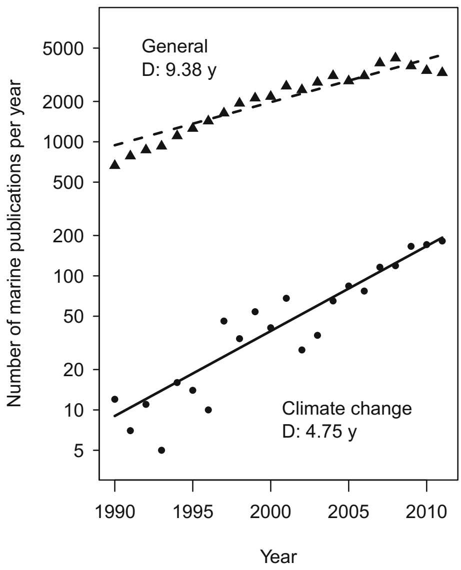

Fig. 1 Trends in number of marine science publications per year in the Nordic region. Both general marine science and marine publications focusing on climate change followed an exponential growth pattern. *D* is the estimated doubling time of the absolute number of papers per year

3.2 Trends in scientific branches

Of the marine related publications focusing on climate change, physical sciences represented a large proportion, which declined significantly over the study period (Wald test, $z = -4.42$, $P < 0.0001$), from an estimated 82 % to 59 % (Fig. 2). In contrast, the number of publications within biological sciences increased significantly (Wald test, $z = 5.66$, $P < 10^{-7}$) over the two decades from an estimated proportion of 15 % to 44 % (Fig. 2). Social sciences represented a relatively small proportion, 11 % [9, 12] (95 % confidence interval indicated in square brackets), of climate change papers with no significant trend (Wald test, $z = 0.28$, $P = 0.78$, Fig. 2). We found vague evidence (significant at the 10 % level, but not at the 5 % level) of an increasing trend in the proportion of interdisciplinary publications (Wald test, $z = 1.69$, $P = 0.090$, Fig. 2). The mean proportion of interdisciplinary publications when eliminating the insignificant slope parameter was 12 % [10, 13].

3.3 Trends in environmental variables

Overall, no significant positive or negative trends were found in proportion of publications studying specific environmental variables within any of the three branches (Tab. S2).

3.3.1 Physical sciences

Within physical sciences most environmental variables showed only minor variability in proportion with the exception of "climatic index" (Fig. 3, Fig. S1.3). On average, 8 % [6, 10] of the physical publications did not include an environmental variable whereas 55 % [51, 58] studied more than one environmental variable. In addition, the diversity of variables studied showed no significant trend (likelihood ratio test, $\chi_1 = 0.025$, $P = 0.88$) with an effective number of variables of 9.1 [8.8, 9.4] (Fig. 4).

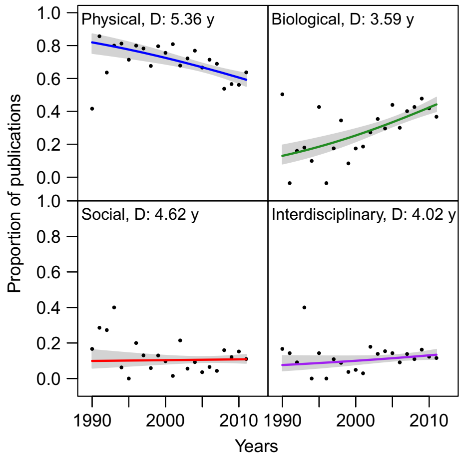

Fig. 2 Trends in proportions of disciplinary and interdisciplinary research within marine climate change literature in the Nordic region. Proportions (*lines*) with 95 % confidence envelopes (*shaded areas*) fitted to observed annual proportions (*circles*) using binomial generalized linear models. *D* is the estimated doubling time of the absolute number of publications per year. Significant trends in proportion were observed for physical and biological sciences while social and interdisciplinary were non-significant. Note that the sum of the physical, biological, and social proportions can exceed 1 within a year because of publications assigned to multiple scientific branches

3.3.2 Biological sciences

Within biological sciences "temperature" was represented in a substantial proportion of the publications (63 % [60, 67]) as compared to the other environmental variables (Fig. 3, Tab. S3). Furthermore, "climatic index" and "salinity" represented intermediate level proportions (18 % and 15 % respectively) while the remaining variables received limited attention (proportion below 9 %, Tab. S3). On average 21 % [18, 25] of the biological publications did not include an environmental variable. These publications were more generic in the form of interdisciplinary studies on marine resource management (e.g. Grafton 2010), expert surveys (e.g. Lyytimäki and Hildén 2011), and reviews without a variable-specific climate change focus (e.g. MacNeil et al. 2012). The average proportion of biological publications studying more than one environmental variable was 35 % [31, 40] indicating considerable representation of publications concerned with higher climate complexity and effect interactions. The estimated effective number of environmental variables studied was constant (likelihood ratio test, $\chi_1 = 0.51$, $P = 0.48$) at 6.5 [6.0, 7.1], which is a significantly lower diversity than estimated for physical sciences (Fig. 4).

3.3.3 Social sciences

Within social sciences "temperature" and "sea level rise" were the most studied environmental variables (Tab. S3) with proportions of 24 % [18, 32] and 23 % [17, 30] respectively. Thus, "temperature" was significantly lower in proportion compared to natural sciences, while "sea level rise" was significantly higher (Fig. 3). In addition to these variables, "CO_2" also received moderate attention (11 % [7, 17]) while the remaining variables were largely ignored with proportions of 5 % or less (Tab. S3). On average, 49 % [41, 57] of social publications did not focus on specific environmental variables, while 18 % [12, 25] studied

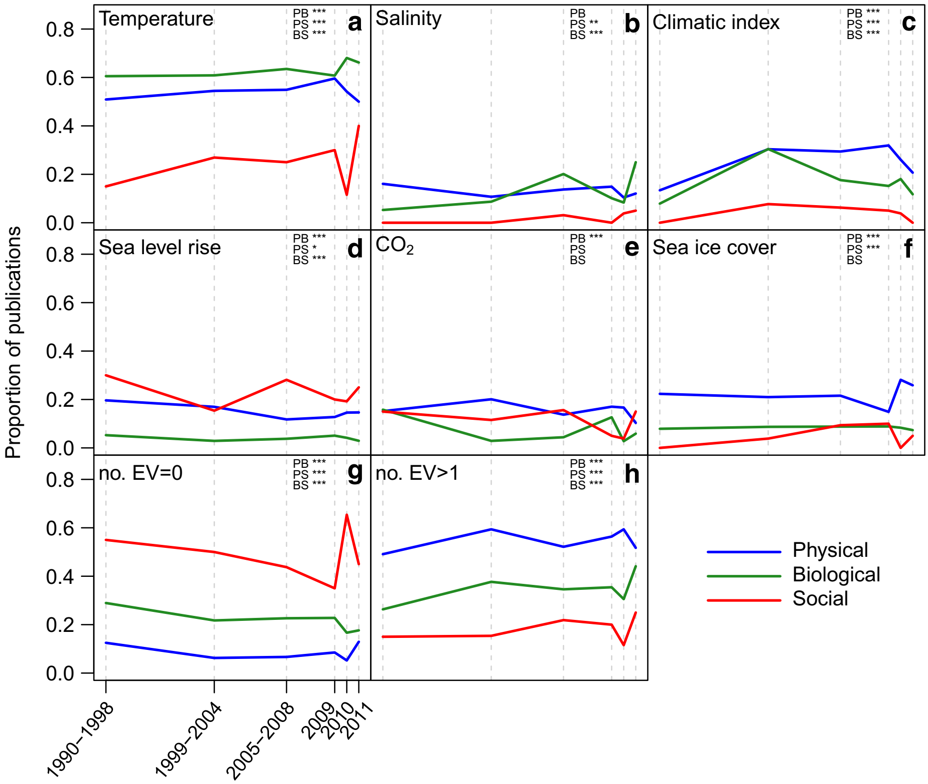

Fig. 3 Trends in scientific focus of marine climate change literature in the Nordic region. **a**–**f**, proportion of publications studying different environmental variables. **g**, proportion of publications studying climate change more generally, i.e. where no specific variables were studied. **h**, proportion of publications focusing on increasing complexity and potential interactions of environmental variables, i.e. studying more than one variable. All panels have identical axes as in **g**. Significance levels ($***$, $P < 0.001$; $**$, $P < 0.01$; $*$, $P < 0.05$) of tests of equal intercept between branches (zero slope) are listed in top right corners with PB: physical versus biological, PS: physical versus social, BS: biological versus social

more than one environmental variable. These proportions indicate a focus on more general aspects of climate change as compared to natural sciences. A significant trend in the diversity of environmental variables was observed (likelihood ratio test, $\chi_1 = 4.26$, $P = 0.039$) increasing from 4.2 to 7.6 (Fig. 4).

4 Discussion

The Nordic region contains strong academic, social, and political systems, governing communities that depend on surrounding waters for resources such as food, energy, transport and recreation. Furthermore, as a result of long scientific traditions of sampling and exploring, the Nordic region has become the best studied region within marine ecological research regarding climate change (Poloczanska et al. 2013). Our study region therefore makes an ideal case for indicating trends in other regions with similar strong cultural, economical or geographical ties to oceans such as the Northwest Atlantic and the North Pacific (Paasche

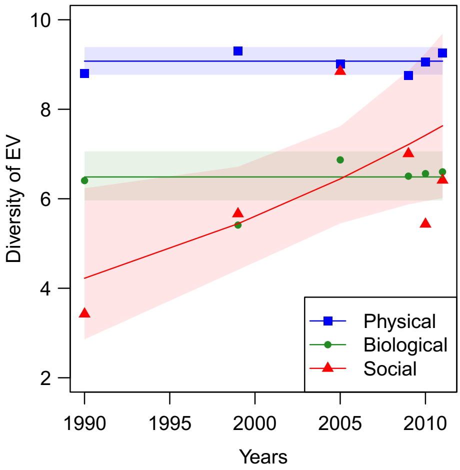

Fig. 4 Trends in estimated diversities of environmental variables studied in marine climate change literature in the Nordic region. Log-linear regressions (*lines*) of observed diversities (*symbols*) with 95 % bootstrapped confidence envelopes (*shaded areas*). Diversity of environmental variables is defined as effective number of variables per scientific branch. Physical and biological branches showed no significant trend, while social sciences showed a significantly increasing trend in diversity

et al. 2015). Additionally, our results may be ahead of the curve relative to developing regions with similar properties where anthropogenic exploitation is increasing. Thus, the findings presented here are likely to be an indicator of current and future trends in marine climate change research also beyond the Nordic region.

The methodological approach of this study bears close resemblance to the systematic review framework of Pullin and Stewart (2006), which aims to generate reproducible results through a strict review protocol. Still, a subjective component is unavoidable: Because our dataset of categorisations were gathered by human experts a component of variability can be expected in each categorisation. Intuitively, unsupervised categorisation following an algorithm would tend to have high precision (low variability) with low accuracy (high bias), whereas supervised categorisation by many individuals (in our case 23) should tend to have lower precision with higher accuracy. We therefore expect our data to be unbiased with a minor "noise"-component as illustrated by the pilot study (Supplementary Methods S1.3). It is not possible to directly quantify the influence of the noise on the results, however our large sample size ($N = 1362$ publications) and generally small P-values obtained indicates that the results are robust toward minor unmodelled variability in the data.

Using GLMs we found a substantial increase in the number of publications on marine climate change research, indicating the emergence of a scientific niche soon after the publication of the first IPCC report in 1990. Our results show that the annual number of marine climate change publications in the Nordic region increased at an elevated rate relative to those within general marine research in the region (Fig. 1). This result is supported by Brander et al. (2013) who found a doubling time of marine climate impact publications of 5.3 years. A plausible explanation for this rise in number of publications is the growing awareness of the societal risks inherent to climate change together with an increasing confidence of scientists that recent climate change is driven by human activities (IPCC 1990, 2013). Together, these factors have triggered political systems and funding bodies alike to strengthen financial support of climate change related science (Grieneisen and Zhang 2011), leading to rising publication numbers (Fig. 1).

By categorizing marine related climate change publications into branches, we observed a significant negative trend in the proportion of studies within the physical sciences (Fig. 2). This is likely because climate change as a concept originated within the physical disciplines prior to 1990. By 1990 research into the physical aspects of marine climate change were already in an advanced state and therefore less affected by the recent increased focus on climate change than social and biological research (Bjurström and Polk 2011b; Mooney et al. 2013). Moreover, a constant diversity of environmental variables within the physical disciplines (Fig. 4) further supports the hypothesis that a sound theoretical foundation was established within physical climate science by 1990.

The proportion of studies focusing on biological aspects increased significantly to more than 40 % (Fig. 2). This increased interest in "climate change biology" has also been noted by other authors who claim it to have reached the status of a scientific discipline (Hannah 2010). In contrast, social studies remained at a constant, and relatively minor, proportion throughout the study period (Fig. 2). Rather than suggesting that nature supersedes society in importance, a more plausible explanation is that the complexity and associated structural uncertainties of modelling the interface of social mechanisms with physico-biological systems precludes rigorous statistical inference (Oppenheimer et al. 2008).

Other potential causes for the observed trends in biological and social sciences include: Opposed to social science it is likely that increased funding of biological experiments have increased the scientific production (Mooney et al. 2013); the availability of long-term biometric data series from scientific surveys (Richardson and Schoeman 2004), the equivalent of which have only more recently begun in social sciences; or a general predisposition toward estimation of climate change effects on natural resources with minor emphasis on explicit modelling of associated social aspects (Beaugrand et al. 2002; Perry et al. 2005). While we cannot make definite conclusions as to the causal relationships suggested above, the predominantly model-based direction of the IPCC appears to have favoured the more quantitatively oriented natural sciences rather than the qualitative traditions of social sciences (Demeritt 2001). Elucidating the underlying reasons for the observed research trends requires an analysis incorporating exogenous information e.g. on the temporal evolution of strategies and incentives of stakeholders and political systems. Such an analysis, however, is outside the scope of the current study.

Interdisciplinary research efforts are required to assess direct and associated implications of climate change to ocean conditions, marine ecosystems, and societies that depend on these resources. Our results showed that progress in implementing interdisciplinary climate change research has been limited in the period 1990–2011 (Fig. 2). A fundamental prerequisite for interdisciplinary research is an overlap in the scientific focus and interest. As a proxy for scientific focus we used the emphasis of environmental variables by each scientific discipline. Overall we found significant differences in the scientific focus between physical, biological and social sciences (Fig. 3). Biological publications focused on environmental variables whose physiological effect may be tested experimentally and extrapolated using physical models. Additionally, the strong focus on climatic indices can likely be ascribed to their common role as climate proxies in correlation studies on larger spatial scales (Perry and Ommer 2003). In contrast, social sciences considered these variables less important with the exception of CO_2, and instead studied temperature and sea level rise as well as more generic and variable-unspecific aspects of climate change (Fig. 3). The general lacking emphasis of specific environmental variables and lower importance of temperature suggest a division in social science studies that focus on reviews or indirect linkages via ecosystem models versus directly quantifiable effects on human communities of variables such as sea level rise, which are likely more easily assessed (e.g. Hallegatte et al. 2011). The high proportion of generic social studies could relate to an increased focus on societal failures leading to climate change. This is supported by Boonstra et al. (2015), who found that natural scientists primarily focus on impacts of climate change and thus differ from social scientists who, to a higher degree, also consider causes of climate change e.g. through bad governance and other societal failures.

In addition to deviations in scientific focus between branches, the limited progress in interdisciplinary efforts could be explained by the notorious difficulty in formulating and directing international and interdisciplinary research programs (Mooney et al. 2013). At the practical level, differing branches may deviate in scale of interest, e.g. decadal oscillations matter in predicting longer term fish population dynamics however to a social system discussing next year's catch such oscillations are of lesser importance (Perry and Ommer 2003). Furthermore, in the absence of interdisciplinary training, differences in scientific method and language often lead to inefficient communication among disciplines thus diminishing the likelihood of successful interdisciplinary research (Petts et al. 2008; Haapasaari et al. 2012).

Facing a lack of progress in interdisciplinary publications it is natural to ask: What lessons can then be learned from the publications that successfully implemented interdisciplinary research? The publications contained in our database indicated that interdisciplinary science arises in areas where there is a clear interface between scientific branches. For example, direct interactions between the physical and social disciplines were often based in the management of coastal zones and assessment of potential societal implications of sea-level rise (e.g. Vellinga and Klein 1993; Van Vuren et al. 2004), biological and social disciplines interacted in assessing climate change implications for sea food availability (e.g. Pitcher 2008; Rice and Garcia 2011), and interactions between biological and physical disciplines typically studied the response and adaptation of marine species to projected climatic conditions (e.g. Greene and Pershing 2000; Huse and Ellingsen 2008).

The interdisciplinary publications revealed that modelling was the dominant scientific method. This indicates that the formalism of models provides a framework for structuring and facilitating disciplinary interaction (e.g. Huse and Ellingsen 2008; Merino et al. 2010). Models developed separately within scientific branches can be coupled to form larger interdisciplinary models (Lange 2008). Such integration across systems enables assessment of consequences of exogenous effects and the associated necessary adaptation within scientific branches that would have been impossible without interdisciplinarity. Through advancements in technology and numerical computation, modelling based studies appear to become critical building blocks of future successful interdisciplinary research between the physical, biological, and social sciences.

Models can, however, not address all interdisciplinary questions. An alternative interdisciplinary approach is to use a discipline-specific method in a different discipline. An example of this is Shackley et al. (1999) who used a social science method (survey) to investigate the controversy around "flux adjustments" in Atmosphere-Ocean General Circulation Models and their uncertain effect on outputs. Combining methodological expertise from social science with highly specialised climate knowledge makes the results of this study accessible to both social and climate disciplines thus setting the study apart from similar studies conducted within each individual discipline.

Modelling and observational studies are examples of interdisciplinary science that tackle a specific and concrete problem. In our literature database such interdisciplinary approaches were further supplemented by the outlook of reviews, syntheses, and meta-analyses (Nicholls and Cazenave 2010; Hare et al. 2011) and reports of large international projects such as the BALANCE project (Lange 2008), and the Global Ocean Ecosystem Dynamics project (GLOBEC, Perry and Barange 2009). Such synthesis efforts aggregate the most important disciplinary and interdisciplinary findings and make conclusions that are more accessible to managers, policy makers and the public.

Looking ahead, the positive trend in number of marine climate change publications combined with the diversification of social sciences' scientific focus (Fig. 4) increase the scientific overlap between branches thus providing better opportunities for interdisciplinary science. The projections of IPCC (2013) indicate a likely future where the impacts of climate change on our oceans will become more extreme. The physical, biological and social implications of such impacts can only be fully understood by exchanging knowledge and expertise among these branches. To achieve this, further initiatives explicitly nurturing interactions between scientific branches, e.g. by interdisciplinary training of early-career scientists, should be prioritised by funding agencies and policy makers.

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