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Geographical imbalances and divides in the scientific production of climate change knowledge

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ABSTRACT

Studies on scientific production of climate change knowledge show a geographical bias against the developing and more vulnerable regions of the world. If there is limited knowledge exchange between regions, this may deepen global knowledge divides and, thus, potentially hamper adaptive capacities. Consequently, there is a need to further understand this bias, and, particularly, link it with the exchange of knowledge across borders. We use a world-wide geographical distribution of author affiliations in >15,000 scientific climate change publications to show that (1) research production mainly takes place in richer, institutionally well-developed countries with cooler climates and high climate footprints, and (2) the network of author affiliations is structured into distinct modules of countries with strong common research interests, but with little knowledge exchange between modules. These modules are determined mainly by geographical proximity, common climates, and similar political and economic characteristics. This indicates that political-economic, social and educational-scientific initiatives targeted to enhance local research production and collaborations across geographical-climate module borders may help diminish global knowledge divides. We argue that this could strengthen adaptive capacity in the most vulnerable regions of the world.

1. Introduction

The scientific community provides increasing evidence that climate change impacts are unevenly distributed across the globe. Many regions with a high risk of negative impacts from climate change are in the less developed and low adaptive capacity countries (IPCC, 2012; Richardson et al., 2009), but scientific research on climate change has a skewed focus on the more developed and less vulnerable regions of the world (Pasgaard and Strange, 2013; Rosenzweig et al., 2007). The distribution of scientific research may be driven by underlying economic, demographic, and institutional factors. For instance, spending on science and climate change research increases with the wealth and educational level of the country (Ho-Lem et al., 2011; Karlsson et al., 2007), and institutional governance characteristics influence the production of research in general (Karlsson et al., 2007; Moustakas and Karakassis, 2009; Pasgaard and Strange, 2013). Notably, a lack of governance and economic performance of a country may indirectly negatively affect its research output, including the production of scientific publications (Karlsson et al., 2007). This may result in a lack of a sufficient climate change knowledge base in developing and vulnerable regions, limit the understanding of the response of natural and managed systems to climate change (Rosenzweig et al., 2007), and therefore limit adaptive capacity (Karlsson et al., 2007; Kiparsky et al., 2006). In addition, exchange of knowledge among researchers appears critical for reducing global knowledge divides (Karlsson et al., 2007). Thus, to advance the discussion on how to address challenges associated with climate change, there is a need to better understand the geographical imbalances in climate change knowledge production and its exchange between nations and regions, including why it has emerged and persists.

Here we present a comprehensive bibliometric and network analysis of a decade of scientific climate change publications in

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order to identify gaps in production and exchange of knowledge across the world. Bibliometric analysis has been used in environmental science to study which authors, journals or countries contribute within a given field (Aksnes and Hessen, 2009; Fu et al., 2010; Kahn, 2011; Karlsson et al., 2007; Ma and Stern, 2006). Such studies have addressed the link between climate change research and certain knowledge domains (resilience, vulnerability and adaptation) (Janssen et al., 2006), as well as unequally distributed knowledge on adaptation strategies, as reflected by a lack of aquatic research published by developing countries on adaptation to climate change (van der Zaag et al., 2009). A few studies also analyzed published research within a given field in relation to geographic, social and economic characteristics of the corresponding author's affiliated country (Moustakas and Karakassis, 2009; Pasgaard and Strange, 2013). These studies suggest that the number of publications is linked with the economic activity of the publishing country, the consuming behavior and lifestyle of the citizens in the publishing country, and the relationship of the citizens with the particular environment and its resources (Moustakas and Karakassis, 2009).

However, as for other types of systems which may be interpreted as networks across geographical units, such as the world-wide air transportation network (Guimera et al., 2005) or bird distributions across islands (Dalsgaard et al., 2014), a more holistic network view would allow a deeper understanding of the geographical structure and exchange of scientific knowledge production. Specifically, modularity analysis provides an analytical tool to quantify sub-groups within networks (Dalsgaard et al., 2014; Yarime et al., 2010), such as geographical regions of strong collaboration between countries. This type of analysis require detailed data on co-authors in order to determine the extent to which authors are locally or externally based, and the extent to which multiple authorships involve shared research interests among academics in different countries. In the present study, we analyze a comprehensive dataset of >15.000 climate change publications (published between 1999 and 2010, see Supplementary information), in which all author affiliations of all individual publications are separated into one of a total of 197 countries.

We show that production of climate change knowledge is biased away from developing, more vulnerable regions of the world with warmer climates and low climate footprints, and that in these regions, relatively few authors are based in the country being studied. Furthermore, the global network of climate change publications is structured into modules of countries with a common research interest; these modules are associated mainly with geographical proximity, common climate, politics and trade, but unrelated to cultural and linguistic ties. We conclude that the geographical imbalance in scientific research production on climate change, and the modular structure of research interests, delimits the potential exchange of knowledge on climate change. Future initiatives of a political, economic, social and educational-scientific character may increase knowledge exchange beyond geographical and climatic boundaries, which, especially if targeted to promote collaborations across geographical-climate module borders, would help diminish global knowledge divides and strengthen adaptive capacity in the most vulnerable parts of the world.

2. Methods

2.1. Data collection and affiliation data

In order to analyze the global geographic distribution and production of climate change knowledge, three types of data were collected: case country publications, the number of publications concerning climate change for a specific country; first author publications, the number of publications by first authors based in a specific country; and co-authorships, the number of times an author country occurred in each publication. The overall methodological approach of searching and reviewing climate change publications follow guidelines for systematic reviews (Davies and Pullin, 2007; Pullin and Stewart, 2006) adapted to the purpose of this study (for detailed description of methods, see Supplementary information).

We investigate how knowledge production (measured by publications) and the flow of climate change knowledge among those who produce it vary with country-level demographical, geographical, economical, educational, institutional, and environmental variables. The count regression models and network analysis are presented in the subsequent sections.

These models included a range of variables designed to capture each of these aspects. We expect that countries that are most susceptible to climate change, such as countries with high mean annual temperatures (MAT) (Pasgaard and Strange, 2013) and low mean annual precipitation (MAP) are more likely to be studied and exchange knowledge. We use gridded data for MAT and MAP between 1960 and 1990 (Hijmans et al., 2005; WorldClim, 2015). To describe spatial proximity, we used the longitude and latitude of each country's capital as predictors. Small Island States are included as a dummy variable (AOSIS, 2015). We expect that small island states, which in general are considered more climatic sensitive than other locations, will be more studied (Pasgaard and Strange, 2013). However, the research effort on climate change could also be tied with the economic situation of the country (Ho-Lem et al., 2011). More wealthy countries with high gross national income (World Bank, 2015a) would be more likely to invest in climate change research. They may also represent high carbon dioxide emitters, and we would expect that countries that are large carbon dioxide emitters (EIA, 2015) may have an incentive to invest in climate change research compared to low emitters (Pasgaard and Strange, 2013). We used country data on the total carbon dioxide emission from energy consumption to test for such a relationship. We include data on country membership in the World Trade Organization (WTO, 2015), which may represent countries with wealthier inhabitants and a higher environmental carbon footprint. To test for this we use the share of exports of gross domestic product (World Bank, 2015b) as an indicator of the degree of openness towards the rest of the world (Neumayer, 2002). Other studies have demonstrated that a number of institutional governance characteristics could be determining (either directly or indirectly) research production (Ho-Lem et al., 2011; Moustakas and Karakassis, 2009). Other studies have demonstrated that research output may be indirectly negatively affected by a lack of governance and economic performance (Karlsson et al., 2007). Chowdhury (2004) found that democracy can have significant impact on state capacity to cope with corruption and crises. Hence, we hypothesize that countries with higher democracy scores (Center for Systemic Peace, 2015) may have higher adaptive capacity and a stronger focus on research into climate change impacts, adaptation and mitigation (Karlsson et al., 2007; Kiparsky et al., 2006; Pasgaard and Strange, 2013). Furthermore, the value of research may depend on press freedom and the likelihood of research being disseminated to the public. If civil freedom, as well as the ability of researchers, journals, newspapers and other media to communicate with the general public, is low then adaptive capacity could be weakened (Pahl-Wostl, 2009). We therefore tested if the number of publications and exchange of knowledge were positively related to the freedom of the press (RSF, 2015). The cultural background of countries may influence the willingness of individuals to cooperate (Gächter et al., 2010). We use religious and cultural values (World Values Survey, 2008) to test if countries of similar cultural backgrounds are

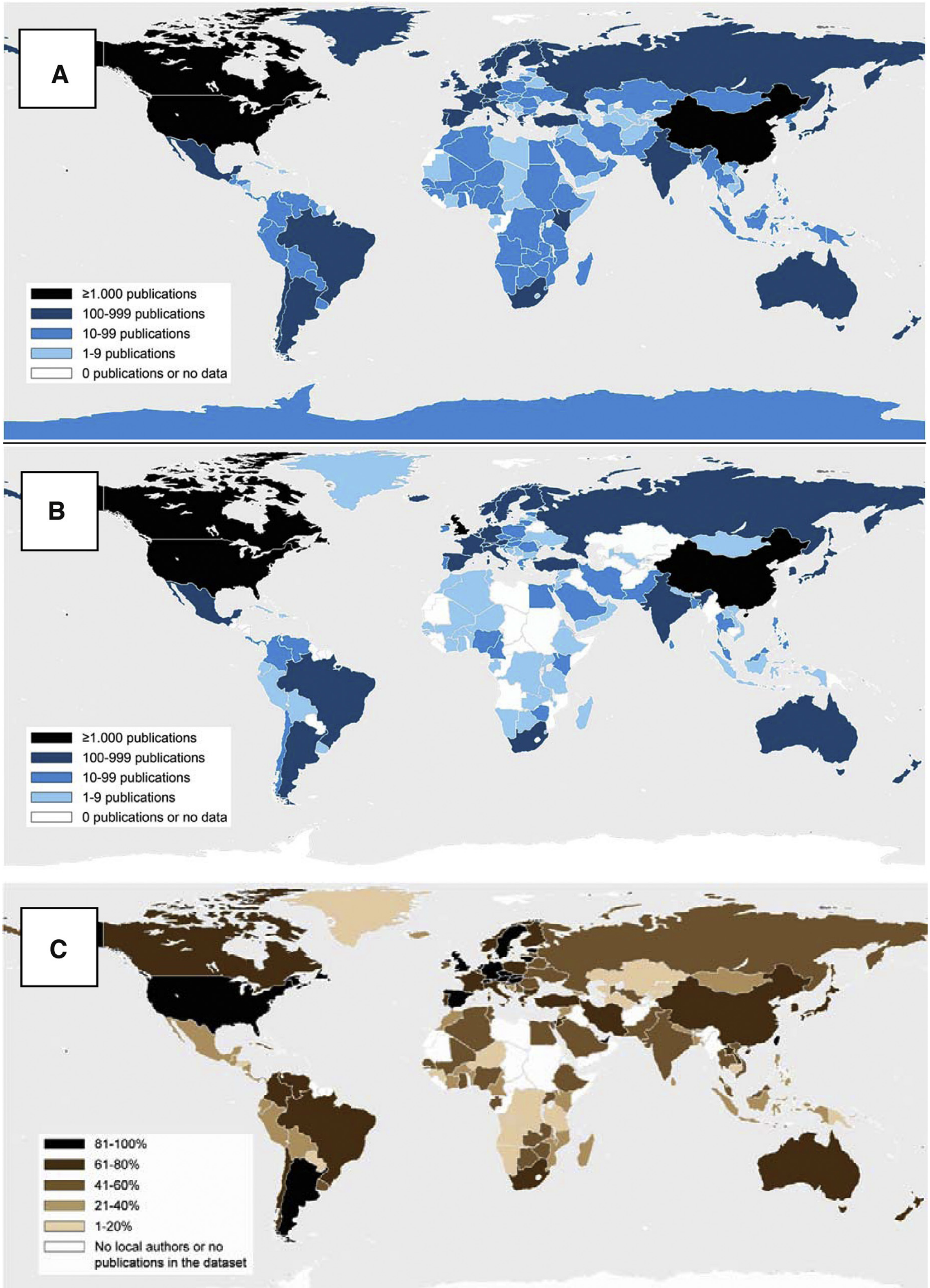

Fig. 1. Geographical distribution of scientific climate change publications.
(A) Geographical distribution of publications concerning climate change in a specific country (see also Ref. Pasgaard and Strange, 2013). (B) Production of climate change publications based on first author affiliations. Publications concerning climate change in developing regions are dominated by first authors based in developed countries and in the BRICS countries except Russia. C: Percentage of publications with contribution from at least one locally based author (67.5% of the total dataset). A large group of countries has few or no locally based authors; even for countries with as many as 19, 27 or 72 publications (Guinea-Bissau, Republic of Congo and North Korea, respectively).

cooperating more on climate change publications. Similarly, we use data on official language (Melitz and Toubal, 2014) to test if cooperation (Smith, 2010) and knowledge exchange is more widespread between countries sharing the same language.

Detailed descriptions of the search-review methodology and country-level demographical, geographical, economical, educational, institutional, and environmental variables are presented in Supplementary information.

2.2. Negative binomial count regression modeling

To model the relationship between the number of case country publications and the geographic, demographic, climatic, economic, and political variables, we used a count regression model with a negative binomial error distribution. We examined both a Poisson distribution and a negative binomial and calculated goodness-of-fit measures based on comparing the log likelihood values of the Poisson and negative binomial models (Cameron and Trivedi, 1998). The dispersion factor as well as the log likelihood test indicated that the negative binomial model fit better than Poisson model. The count regression was estimated applying SAS 9.4.

2.3. Network and classification tree analyses

The flow of climate change knowledge among those who produce it may take place across both national and regional borders, forming a global network of collaborations. Modularity is a feature of a network that contains weakly connected subgroups of nodes, which are internally highly interconnected (Dalsgaard et al., 2014; Guimera et al., 2005). Modularity may thus be used to identify subgroups of highly interconnected geographical units, as has been done for the world-wide air transportation network (Guimera et al., 2005) and bird distributions across islands (Dalsgaard et al., 2014). It may also allow one to identify the topological roles of nodes in this modular network; notably to identify which nodes are important for the cohesion within modules (Within module strength, z) and in connecting different modules (Module connectivity, c; Fig. 3), and the entire network (high c and z). In the geographical context, this may be interpreted as geographical units (e.g. countries) being important for interlinking geographical regions (high Module connectivity, c) or being of high importance for interlinking countries within geographical regions (high Within module strength, z) (Dalsgaard et al., 2014; Guimera et al., 2005). We thus applied a network approach to detect modules and the topological roles of each country. To identify geographical modules, the publication data was organized as a quantitative bipartite matrix, with authors' country as columns and case study countries as rows. Each cell entry represents the number of publications in which an author from a given country published a study concerning climate change in the country indicated by the row entry. Based on this author vs case country matrix, we detected modules and topological roles (Guimera et el., 2005; Newman, 2006) with the QuanBiMo algorithm developed for quantitative bipartite networks (Dormann and Strauss, 2014). The modularity analysis was conducted in R (R Core Team, 2013), using the bipartite package (Dormann and Strauss, 2014) (the Supplementary information provides additional details on the network analysis).

We applied tree-based classification approaches to examine how geographic, climatic, economic and political factors are associated with module configuration. First, we built a heavily split tree, with as few as two members for each leaf node. We then pruned back the tree to reach the complexity that produced the minimum cross-validation error. This produced a single tree to describe module structure. However, single trees give only a limited indication of variable importance, since the tree only uses a subset of the predictor variables, and many nearly equally good subsets may exist. To examine this possibility, we used a random forests approach (Breiman, 2001). This approach builds a large number of trees based on random subsets of the predictor variables, and summarizes variable importance across this large set of trees. Here, the importance of a predictor variable was measured as the decrease in node impurity from splitting on that variable (using the Gini coefficient). This tree-based classification analysis was performed in R using the rpart and randomForest packages (Liaw and Wiener, 2002; Therneau et al., 2013).

2.4. Methodological constraints

Several methodological limitations and risk of biases are relevant to publication analyses, including our study (Archambault et al., 2006; Kahn, 2011; van der Zaag et al., 2009) (see also Supplementary information). For instance, language bias is evident, leading climate change publication numbers to be underestimated and skewed towards English speaking regions (Karlsson et al., 2007). This critical bias is part of a bias against publications not meeting the Thomson Reuters quantitative and qualitative standards for inclusions in the Web of Science data base from which we extracted our data set (Thomson Reuters, 2014). As the selection method excludes scientific publications outside the published international peer-reviewed English language journals (Thomson Reuters, 2014), it also excludes other kinds of knowledge in the analyses of the climate change knowledge production. Consequently, the analyses presented in the paper are restricted to scientific knowledge and do not consider local or indigenous knowledge or knowledge from other sources than scientific publications. Still, the main body of evidence-based information

Table 1

Model results for a negative binomial regression for the total number of publications reported for each case country. χ^2-tests of estimates show that country publications are significantly increasing with WTO, democracy score, carbon emissions, but decreasing with mean annual temperature, export, lack of press freedom, and being a small island state.

Parameter	Degrees of freedom	Estimate	Standard error	Wald 95% confidence limits		χ^2	Probability > χ^2
Intercept	1	4.2501	0.3575	3.5495	4.9508	141.34	<.0001
Mean annual temperature (MAT), °C	1	−0.0042	0.0013	−0.0067	−0.0017	10.68	0.0011
Mean annual precipitation (MAP), mm	1	0.0001	0.0001	−0.0002	0.0004	0.26	0.6101
Export (% of GDP)	1	−0.0091	0.0029	−0.0148	−0.0034	9.63	0.0019
WTO	1	0.7076	0.337	0.0471	1.3681	4.41	0.0357
Democracy score	1	0.0439	0.0108	0.0228	0.065	16.66	<.0001
Press freedom index	1	−0.0106	0.005	−0.0203	−0.0009	4.55	0.0328
Carbon emissions from energy consumption (10^6 metric tons)	1	0.0012	0.0003	0.0006	0.0018	17.04	<.0001
Small island state	1	−1.0178	0.4948	−1.9876	−0.0481	4.23	0.0397
Dispersion	1	0.8982	0.104	0.7158	1.1269		

comes from English language journals, justifying the approach taken in this study.

3. Results

3.1. Geographical imbalances in climate change knowledge production

The analysis of >15.000 publications on climate change research illustrates how the publications on climate change generally both concern (i.e. the case country) and are produced (i.e. the author country) by the developed countries and the BRICS countries China, India, and Brazil (Fig. 1, Supplementary information Figs. S1 and S2). When considering publications per capita, some countries with relatively small population sizes (e.g. Iceland, Seychelles and Greenland), are relatively more productive (Supplementary Table S5). Among the more populated countries, the Scandinavian and Northern European countries in general dominate when corrected for population size, while the United States is the 18th most productive and China the 66th most productive (as opposed to being the two most productive, when not correcting for population size).

In the dataset, on average 56.5% of the publications had a first author based in the country the publication concerned; however, large variations among countries are apparent (Fig. 1B). For instance, 922 of the 990 publications by first authors based in China also concern climate change in China. The same is true to a lesser extent for South Africa, India and Brazil, while less than one fourth of publications concerning climate change in Russia have a locally based first author.

We used a negative binomial count regression model to test the correlation between the number of research publications and the associated demographical, geographical, economical, institutional, and environmental factors of case countries (Table 1; Fig. 2).

We found that the number of climate change publications is smaller in the hotter parts of the world where climate change effects are expected to be highest (Table 1, Fig. 2a). Case countries with higher democracy scores (Fig. 2b), countries with high press freedom (Table 1), and countries that are members of the World Trade Organization (WTO) are more studied (Table 1, Fig. 2c). The share of exports of gross domestic product, which is a proxy of the degree of openness towards the rest of the world, surprisingly shows that countries with a large share of exports have a lower number of publications (Table 1). Small countries typically have a higher share of exports than larger countries because the domestic market is too small to support highly specialized production (e.g. Singapore or Malta), and a considerable part of their national income is spent on import. Pearson correlation between share of export and population size is negative ($P < 0.05$) and the number of publications increases with population ($P < 0.001$). Thus, low publication number is probably related to the size and population size of the country rather than its openness as measured by the share of exports. The knowledge production on vulnerable countries such as the island states is significantly lower than for other case countries, indicating that specific local factors are not sufficiently accounted for.

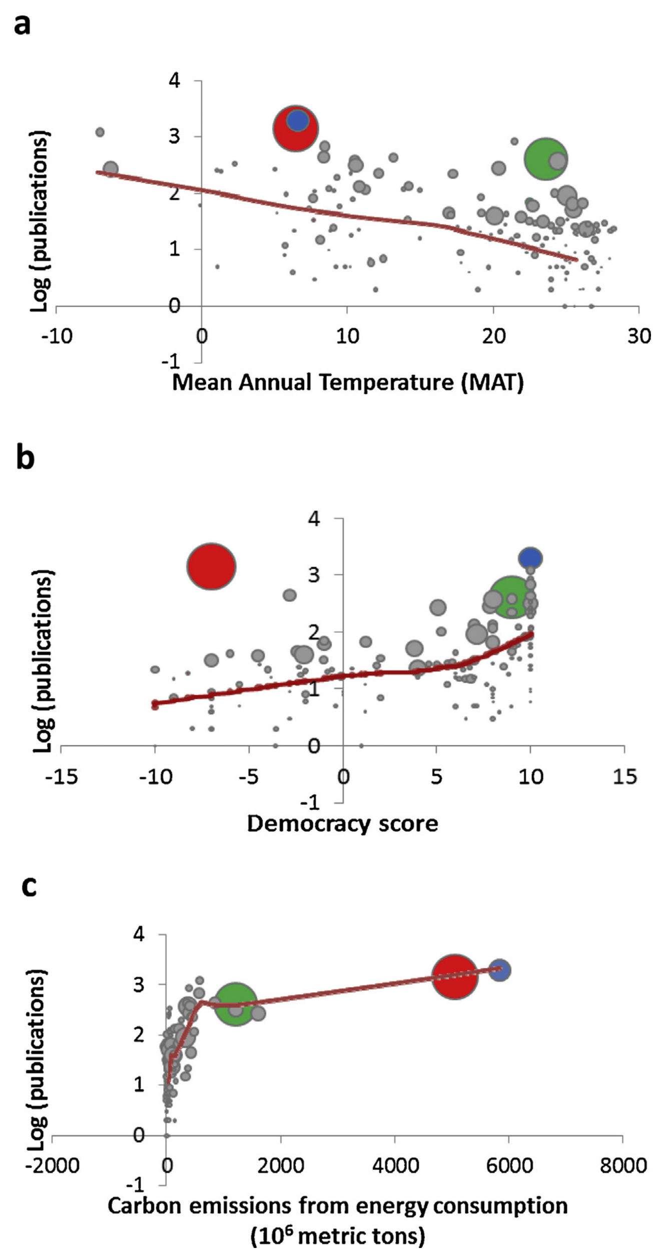

Fig. 2. Number of climate change case country publications of 156 countries compared to the main geographical, economic, political and environmental correlates.
(A) the number of case country publications is negatively associated to mean annual temperature. (B) publications increase with political democracy scores (applying the Polity4 score, www.systemicpeace.org), except for autocratic China which has the second highest number of publication among all countries (United States is highest). (C) publications increase with carbon emissions from energy consumption. Green node is India, red China, and blue USA. The size of the bubbles indicates population size in each country. Lines display lowess regression fits (see also Table 1).

3.2. The global network of climate change publications: modular division and topological roles

The global network of case countries vs authors' country affiliations (first and co-authors) was modular and consisted of 11 distinct modules ($Q = 0.477$; $p_{null} < 0.01$; Fig. 3a). The identified modules illustrate author countries with a common interest in conducting climate change research within the same case countries. It is immediately evident that geographical proximity influences module configuration as nearby countries are often part of the same module (Fig. 3). However, other factors may also shape module configuration. For instance, despite being on different continents, many South American countries have tight links to certain African countries, forming one module, which could be because of similar climates and/or developmental status. We therefore applied a tree-based classification approach to test the importance of geographical, climatic, economical, political, cultural and linguistic factors in forming the 11 modules (Fig. 4). At the highest level the modules split according to latitude and longitude (highest importance scores ~12–17; Table 2, Fig. 4), illustrating

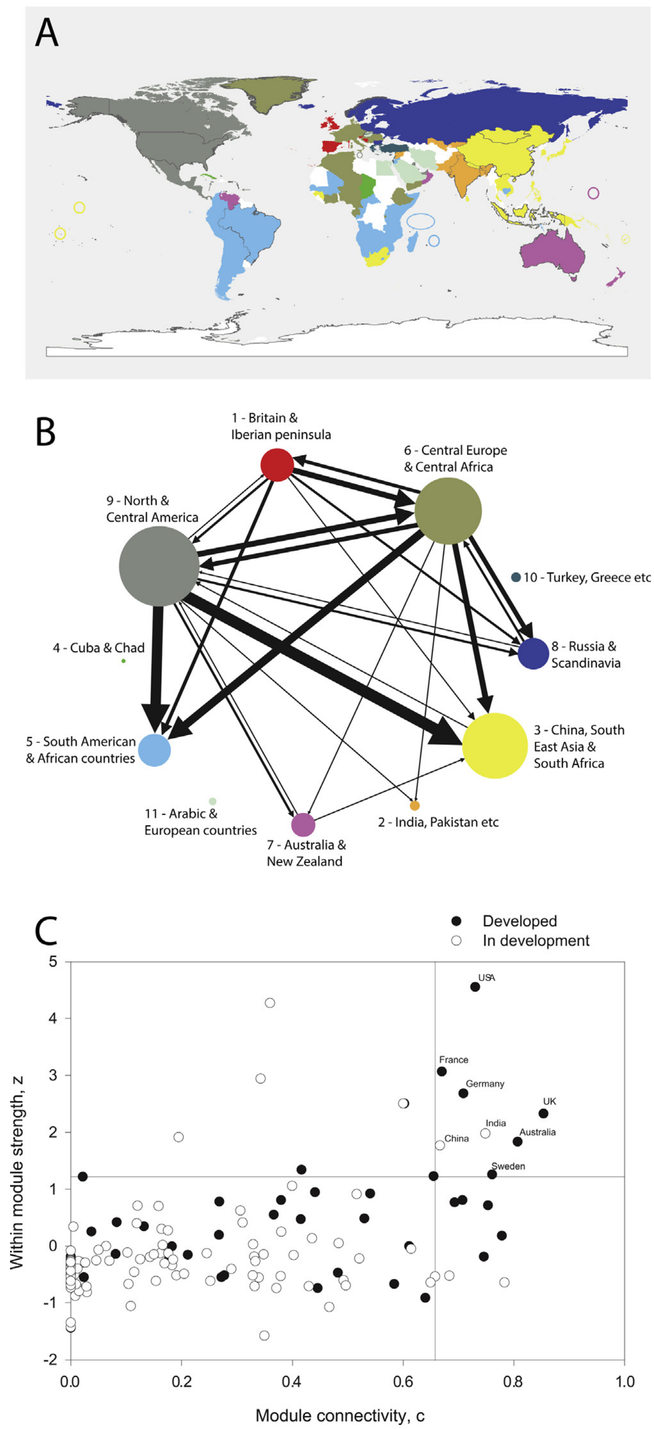

Fig. 3. Network analysis of author affiliations.
(A) Global map illustrating the composition of 11 modules comprised of author countries with a common interest in conducting climate change research within the same case countries. For each country, module identity is indicated by a distinct color. Note that module identity of small island states are highlighted with a colored circle; and countries with ≤1 publication are illustrated in white. (B) Each module is illustrated as a colored node (same colors as in (A); numbered, and named accordingly to their main countries or landmass), with node size illustrating total number of publications on climate change; the direction and strength of connections between modules are illustrated by the arrowhead and thickness of lines connecting modules, showing the tendency of modules of countries studying climate change in case countries outside their module. We used a cut-off value of 100 publications to illustrate a link between modules. (C) the top 10% most important countries in interlinking the world on climate change publications, i.e. network hubs (Dalsgaard et al., 2014; Guimera et al., 2005), are shown above the threshold lines, top right in the plot. These are defined as countries important both within their own modules (Within module strength, z) and in connecting different modules (Module connectivity, c) (Dalsgaard et al., 2014; Guimera et al., 2005).

that geographical proximity indeed largely structures modules of countries with a common interest. Lower-level splits are determined by climate (precipitation and temperature), gross national income per capita, carbon emissions from energy consumption, export, press freedom, and level of democracy (importance scores ~6–10; Table 2, Fig. 4). Linguistic and cultural ties, on the other hand, did not have a detectable influence on module configuration (importance scores <2; Table 2). These results are robust across different thresholds of publication records, i.e. no matter if using only countries with 1, 5 or 10 publications (Supplementary Figs. S3–S5 and Supplementary Table 10).

Next we sought to illustrate which modules are primarily interlinking the global modular network, i.e. which modules (i.e. groups of countries) study climate change in countries outside their module. We explored this by plotting the strongest connections and their direction between modules (Fig. 3B; using ≥100 publications as a threshold). This illustrates that countries in the "North & Central American" and European modules often study climate change outside their own modules, notably in South America, Africa and South East-Asia, whereas countries in other modules rarely study outside their own modules (Fig. 3B). Countries in the "North & Central American" module often study climate change in the "Chinese and surrounding countries" and in the "South American & African" modules, but not vice versa, despite the latter modules being among some of the most productive ones (Fig. 3B). Likewise, the "Central European & African countries" often study climate change in the "Russian, Northern Scandinavian and surrounding countries", "Chinese and surrounding countries" and "South American & African" modules, but rarely the other way around (Fig. 3B). These modular divides in knowledge production are important, as threats and challenges from future climatic changes may be of a comparable character across regions. Thus, countries could benefit from the exchange of knowledge beyond the identified modules, for instance concerning changes in crops, pest management and adaptation to climate hazards. Our study indicates that in much of the world such critical exchange of relevant knowledge and competencies concerning climate change is limited by geographical distances, with the exception of South American and African countries where common climate and/or developmental status may have promoted research between continents (Fig. 3B). Also, political and export ties may have had a positive influence on knowledge transfer between Central European and African countries, likewise connecting continents (Fig. 3B).

Finally, we explored which individual countries are key topological nodes for the spread of knowledge across the modular world-wide climate change production network (Castells, 2000), identifying the top 10% most important countries for the cohesion of the network (indicated by their high c and z-scores, Fig. 3C) (Davies and Pullin, 2007). We also compared this to the top 10 most productive countries on climate change within geographical regions (Supplementary information, Fig. S1). Eight developed countries – United States, United Kingdom, Germany, France, Australia and Sweden – plus China and India, two developing BRICS countries, are the most important countries in generating and spreading climate change knowledge across the globe (Fig. 3C). These countries are also key countries within their modules (indicated by their high z-score, Fig. 3C), e.g. India within the "India, Pakistan" module, United States within the "North and Central America" module, and France/Germany within the "Central Europe and Central Africa" module and so forth.

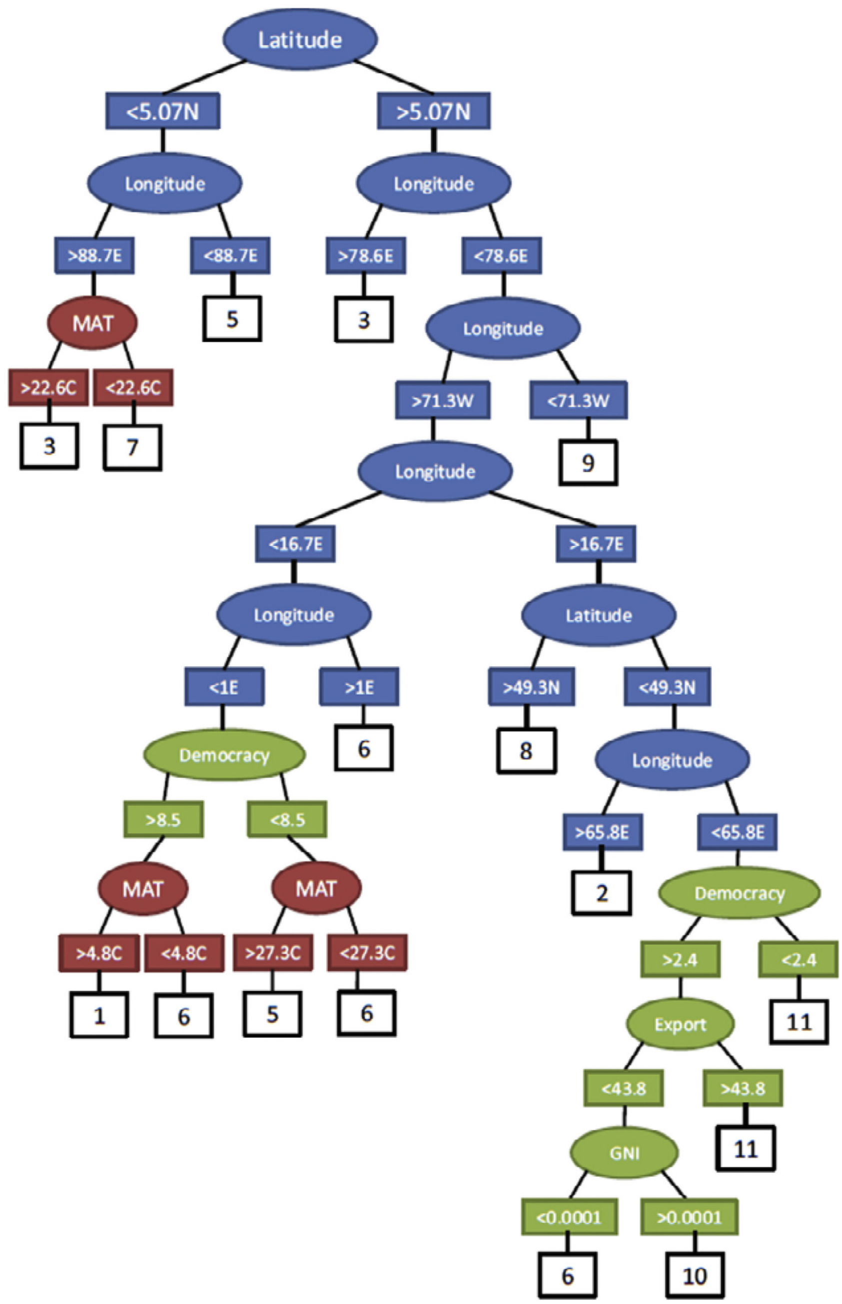

Fig. 4. Classification tree analysis.
Classification tree analysis and the importance of geographical, economical, and political variables in forming the 11 modules of countries (using ≥10 publications as the threshold; see also Fig. 3). A classification tree attempts to assign countries to modules based on recursive splitting of predictor variables. Variables near the top of the tree are most important in determining the overall structure, while those near the bottom are related to finer structure. Each ellipse shows the variable selected for splitting, with the associated colored boxes showing the splitting threshold. The open terminal boxes indicate the predicted modules. At the highest importance level we find longitude and latitude, and at a lower level the modules split according to democracy, temperature, export, and gross national income per capita. Module number codes are as follows: (1) Britain & Iberian Peninsula, (2) India, Pakistan etc., (3) China, South East Asia and South Africa, (4) Cuba & Chad (not predicted at any terminal node), (5) South American & African Countries, (6) Central Europe & Central Asia, (7) Australia & New Zealand, (8) Russia & Scandinavia, (9) North & Central America, (10) Turkey, Greece etc., (11) Arabic & European Countries.

4. Discussion

4.1. Knowledge production gaps and perspectives for climate change adaptation

The strong geographical patterns documented in this study show that the global distribution and production of climate change knowledge is biased away from regions most vulnerable, but less contributing, to climate change (IPCC, 2007; Richardson et al., 2009). We demonstrate that the case country publication bias is towards richer, cooler and less vulnerable countries, with high carbon emissions, with stronger institutions and more press freedom. This underpins the mismatch between the geographical knowledge supply and need for knowledge on climate change. Such a knowledge divide between poor vulnerable regions and richer regions with high mitigation and adaptation capacity may imperil the integration of locally generated knowledge to provide contextually relevant advice (Karlsson et al., 2007). Knowledge

Table 2
Importance scores for predictors of module associations of countries, including all countries with at least 1 publication record. Importance scores are derived from a Random Forest, and describe the total decrease in node impurity (using the Gini index) when splitting on a variable, across all trees. Further explanation of variables can be found in the Supplementary information, Table S3.1.

Variables	Importance score
Longitude	15.73
Latitude	15.14
Mean annual precipitation (MAP)	10.04
Mean annual temperature (MAT)	9.81
GNI–PPP (10^{12} US$/inhabitant)	9.39
Carbon emissions from energy	8.99
Press freedom index	8.51
Export (% of GDP)	6.19
Democracy score	5.78
Spanish	1.87
French	1.41
English	1.17
Culture F	1.05
Culture H	1.00
Culture I	0.62
Arabic	0.86
WTO	0.66
Culture C	0.58
German	0.52
Culture A	0.38
Island state	0.45
Culture E	0.32
Culture B	0.38
Russian	0.34
Culture G	0.16
Portuguese	0.24
Dutch	0.20
Culture D	0.20
Chinese	0.10
Danish	0.05

may disperse across countries and collaborations between co-authors. However, the modular division of the global network of climate change publications shows that there is limited exchange between regions in terms of co-authorships and affiliations, which may affect both mitigation and adaptation potentials (Felton et al., 2009; Kiparsky et al., 2006). Besides the geographical, climatic, socio-economic and political variables examined in this study, the actual process that lies behind the publication of scientific knowledge influences this gap, including the requirements and standards for scientific publishing and the harmonized market-like practices in academia (Paasi, 2005). From a societal perspective, climate change science may therefore not meet the need of a large and vulnerable part of the global population (Kitcher, 2001). Since positivist science and methods are often prioritized by decision-makers (Forsyth, 2010; Jasanoff and Wynne, 1998), we speculate that the lack of scientific knowledge produced in developing regions leaves a critical gap in the political debates.

The relative shortage of locally based authors in the most vulnerable regions of the world constrains the integration of the knowledge produced, especially if we assume that locally based authors have a greater knowledge of the local political and cultural context, as well as greater incentives and opportunities to make local use of research. Without locally generated data and locally based researchers, it is challenging to provide contextually relevant advice; this in turn hampers governmental acknowledgement of the existence and magnitude of environmental degradation with an increased risk of environmental issues becoming low priority or even invisible (Karlsson et al., 2007). The imbalanced distribution of knowledge may thus justify the discussion of political incentives for increasing the production of scientific information in developing and more vulnerable parts of the world, e.g. providing more support to local researchers in scientific publication processes, or schemes promoting scientists in wealthy countries to collaborate with scientists in the developing world. However, the so-called "brain drain" from poor to richer countries complicates this discussion, since many researchers physically based in developed countries are skilled nationals from developing countries. OECD showed that over 20% of nationals from many African countries with a university degree live in an OECD country (OECD, 2015). The extent to which these nationals stay or return to improve the integration of the knowledge they have produced is unclear, as data on return rates is very scarce (OECD, 2006). Such information, and a deeper understanding of the underlying personal and structural mechanisms behind return dynamics, could provide a better indication of the potential ways to improve production and integration of knowledge on climate change in developing countries. Nevertheless, and again assuming that locally based authors are well-equipped to make meaningful use of their research, the results presented here raise a concern about scientific climate change knowledge being implemented to a lesser extent – and with fewer contextual and cultural concerns – in Africa and Latin America than in Europe, North America, and Asia, where relatively more researchers who produce the knowledge are also physically based. Our concern resonates with the call for more local and on-the-ground involvement in the global biodiversity research arena (Smith et al., 2009), and this study contributes with a global climate change perspective to current debates about the role of scientific expertise in policy-making in natural resource management (e.g. Lund, 2015; Thiel and Mukhtarov, 2005) and beyond (Berling and Bueger, 2015).

4.2. Concluding reflections on research and policies

Taken together, our results show that climate change research production mainly takes place in richer, institutionally well-developed countries with cooler climates and high climate footprints. The world is divided into modules of countries with strong common research interests on climate change, but with little knowledge exchange between modules. These modules are determined mainly by geographical proximity, common climates, politics and economy. This indicates that cross-national and regional collaboration, knowledge exchange and strengthening capacities are necessary means to overcome the existing knowledge gaps and divides in environmental science (Karlsson et al., 2007; Kahn, 2011). Such initiatives should not only reduce the well-known latitudinal North-South divides (Karlsson et al., 2007; Rosenzweig et al., 2007), but also the knowledge divides indicated here by modules of common research interest. To have the largest effect, initiatives should focus on strengthening collaborations across geographical distances and across national differences in climate, export, democracy and national economy, as well as strengthening the local production and integration of knowledge. While challenging (Hoekman et al., 2010), this may be an important step for science and society to meet the critical need for a global knowledge (Kitcher, 2001) on climate change and adaptive capacity (Kiparsky et al., 2006). As a final remark, our study stresses the need to further advance our understanding of the specific mechanisms that tie or detach research modules, which may include historical regional and local trends in climate knowledge production, and to better understand the success stories of current local knowledge integration and global research collaboration (e.g. Jappe, 2009; Pham et al., 2015). These are keystones for bridging existing knowledge divides and to facilitate meaningful localized policy intervention.

Competing financial interest

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.09.018.

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