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Assessing the global ocean science community: understanding international collaboration, concerns and the current state of ocean basin research

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Web of Science data covering 2000–2020 was used to analyse trends in ocean research, specific to the five ocean basins (Arctic, Atlantic, Indian, Pacific, Southern), to investigate its state and any underlying concerns for addressing UN Decade of Ocean Science goals and UN Sustainable Development Goal 14 "Life Below Water". Though Atlantic research has dominated, Pacific research is nearing parity with its neighbour due to significant output growth by China and is soon likely to become the most researched basin. International collaboration, built around G7 countries and China, has increased by 10 percentage points since 2000 but research remains mainly domestic. Outside these countries, there has been growth in collaborations involving Small Island Developing States and a doubling of South America's global share of ocean basin papers. However, sub-Saharan African research output has not mirrored this expansion. Further growth could be catalysed by increased support for educational efforts and infrastructure development, particularly given the highly specialised and institutionally driven nature of ocean basin research.

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INTRODUCTION

The fate of our Earth is tied inextricably to our oceans. Given the toll that humans have exacted on the marine environment within a relative handful of decades[1–4], the need for detailed, globally networked, scientific scrutiny of our ocean basins has never been more acute. Oceans are now under even greater pressure due to the human-accelerated changes in climate and ocean systems as well as the rapidly growing blue economy[5,6], which supports tens of millions of jobs in sectors including fishing, tourism and transport and has a GDP of trillions of dollars[7].

The intersection between these areas motivates the UN Decade of Ocean Science[8] (UNDOS) projected to run through 2030, with the mission of ensuring sustainable ocean development using transformative ocean science. The accomplishment of these outcomes will require a global community of ocean scientists to work together to both quantify the global oceans and develop region-specific knowledge. There is, however, a severe imbalance between countries with developed ocean science programmes (e.g., G7 countries) and those most affected by ocean changes, which tend to be Small Island Developing States[9] (SIDS) as well as larger continental countries that have limited resources for adaptation, for example, countries in Africa and Southeast Asia. Many of these countries are heavily reliant on the blue economy for their livelihood and growth, and additional factors such as small land mass, remoteness, fragile ecosystems and dependence on foreign imports increase their vulnerability to ocean changes. Island countries with a low GDP per capita, high population density and/or a long coastline, such as Micronesia and the Marshall Islands, have been identified as the least resilient to ocean changes[10].

UNDOS is one of several programmes that fall within the UNs 2030 Agenda for Sustainable Development[11], the core of which are the Sustainable Development Goals (SDGs): a set of seventeen call-to-action goals to produce a more sustainable future for all Earth by 2030[12]. Sustainable Development Goal 14 "Life Below Water" deals specifically with oceans to protect and manage this heavily abused resource more effectively. SDG 14 has several defined targets including "(14.7) [increasing] the economic benefits to Small Island Developing States and least developed countries from the sustainable use of marine resources".

The global state of ocean science has previously been summarised by United Nations Educational, Scientific and Cultural Organization (UNESCO)[13], as part of the UNs 2030 Agenda for Sustainable Development. Another report, by IOC-UNESCO[14], was published in anticipation of the UNDOS launch, as well as a major integrated assessment of world oceans[15] at environmental, economic, and social levels. Additionally, two UN ocean conferences in New York City (2017) and Lisbon (2022) to mobilise action on SDG 14 and UNDOS, respectively, and to present innovative solutions have taken place thus far; an assessment of the impact of voluntary commitments from the 2017 conference has also been published[16].

These UN reports used various degrees of bibliometrics ("the application of mathematics and statistical methods to books and other forms of written communication"[17]) and scientometrics ("quantitative aspects of science and scientific research"[18]) to understand the global publication patterns of ocean science. More academic work has continued this approach, including a study of publications funded by the National Oceanic and Atmospheric Administration (NOAA) Office of Ocean Exploration and Research[19]; a comparison of different countries' contributions to the International Ocean Discovery Programme[20]; a survey of research activity in oceanography and marine geoscience since the end of the Second World War[21]; and an analysis of ocean remote-sensing research over the last three decades[22]. Papers serve as a proxy for activity in terms of research output and the sweep and depth of research themes illustrate one of the benefits of scientometric analysis: a top-down view derived from analysis

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of the global research literature offers insights that are beyond even the knowledge and experience of researchers themselves.

This work provides scientometric analysis of global ocean basin science literature across the 21st century, to quantify the structure of the ocean science community and identify how to increase the sustainability and global connectedness of this community. Ocean science represents a broad collection of research topics, which range from the biological, chemical, geological, and physical aspects of oceanography to the various human-ocean interacting systems (politics, economics, health, archaeology, engineering etc.) and various multi-disciplinary research amongst these realms. We identify the number and geographical (basin-level) focus of published ocean science papers (over 100,000) at an institutional and international level, and how this has changed between 2000 and 2020. We map international collaborative networks and identify which basin-/country-specific research is reliant on a small number of research institutes, or countries, with significant infrastructure. Together, these results could inform scientists and funding agencies in targeting effort and resources to create a more sustainable and diverse global ocean science network.

RESULTS

Ocean basin output

The totality of ocean basin research has increased since 2000 at a greater rate than total research indexed within the entire Web of Science (three times compared to 2.5). The Atlantic Ocean is the most studied basin over the entire period (Fig. 1; 47,368 articles overall), though its relative share has decreased from almost 50 to 40%. This lost share is primarily due to a rapid increase in Pacific Ocean studies (40,275 articles), which have seen a fourfold increase in output over the period (all other basins increased threefold) and is now nearing parity with the Atlantic study numbers. Indian Ocean research has accounted for around 9–14% of output over the period (11,079 articles) and in the most recent year published ~1000 papers, up from ~500 papers in 2010 and ~270 in 2000. Research output in each of the polar (Arctic and Southern) oceans has remained around 5% of total output throughout the period and now number around 300 to 400 papers per year (totalling 5185 and 4008 articles, respectively, across the entire analysis period).

Country output

At the country level, USA is the greatest producer of ocean basin research (Fig. 2), having more than doubled its output since 2000. However, as with the Atlantic, its relative share over the period has decreased from almost 40% in the early 2000s to 25% by 2020. Output is dominated by G7 countries (Canada, France, Germany, Italy, Japan, United Kingdom, USA; Italy ranked 15th in publication output), however, their relative share of papers have either stagnated or decreased. Conversely, China (including Macau and Hong Kong) has rapidly increased its output, particularly since 2010, surpassing United Kingdom as the second-largest producer

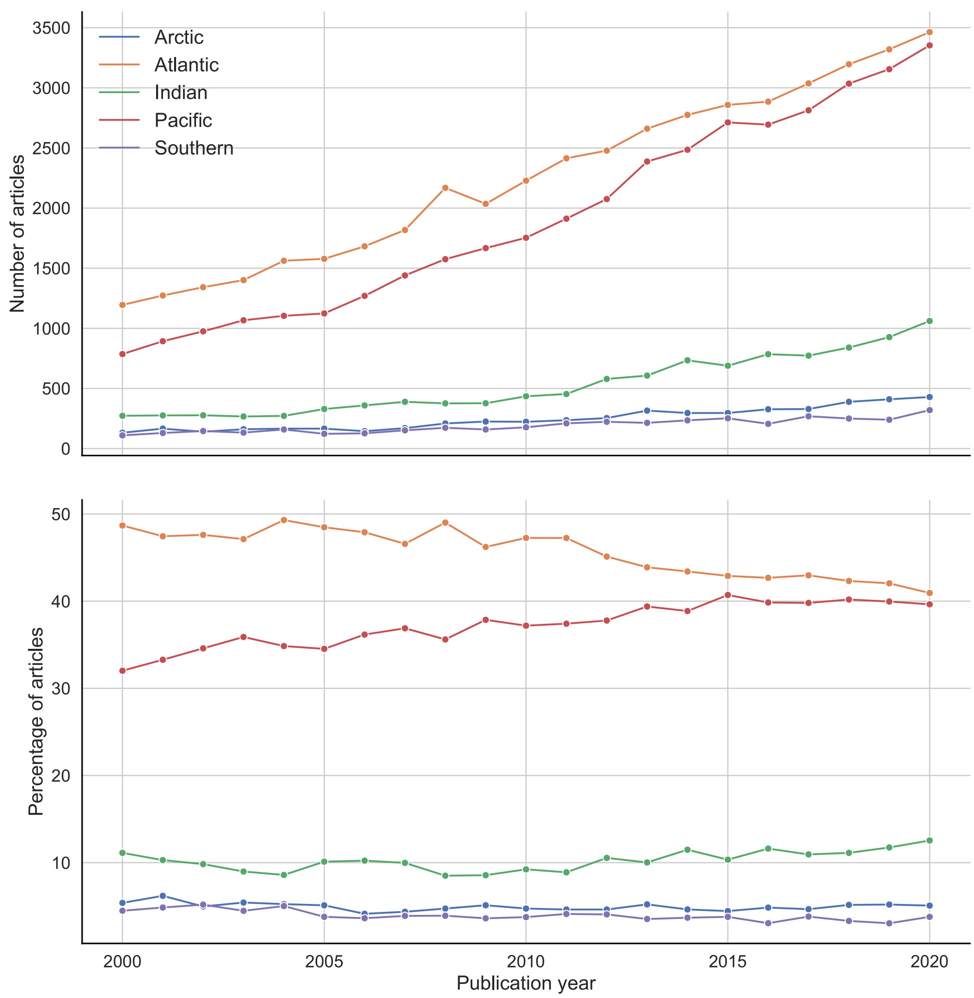

Fig. 1 Research output by ocean basin. Top panel presents absolute output (i.e., articles) and the bottom panel presents relative output (i.e., percentage).

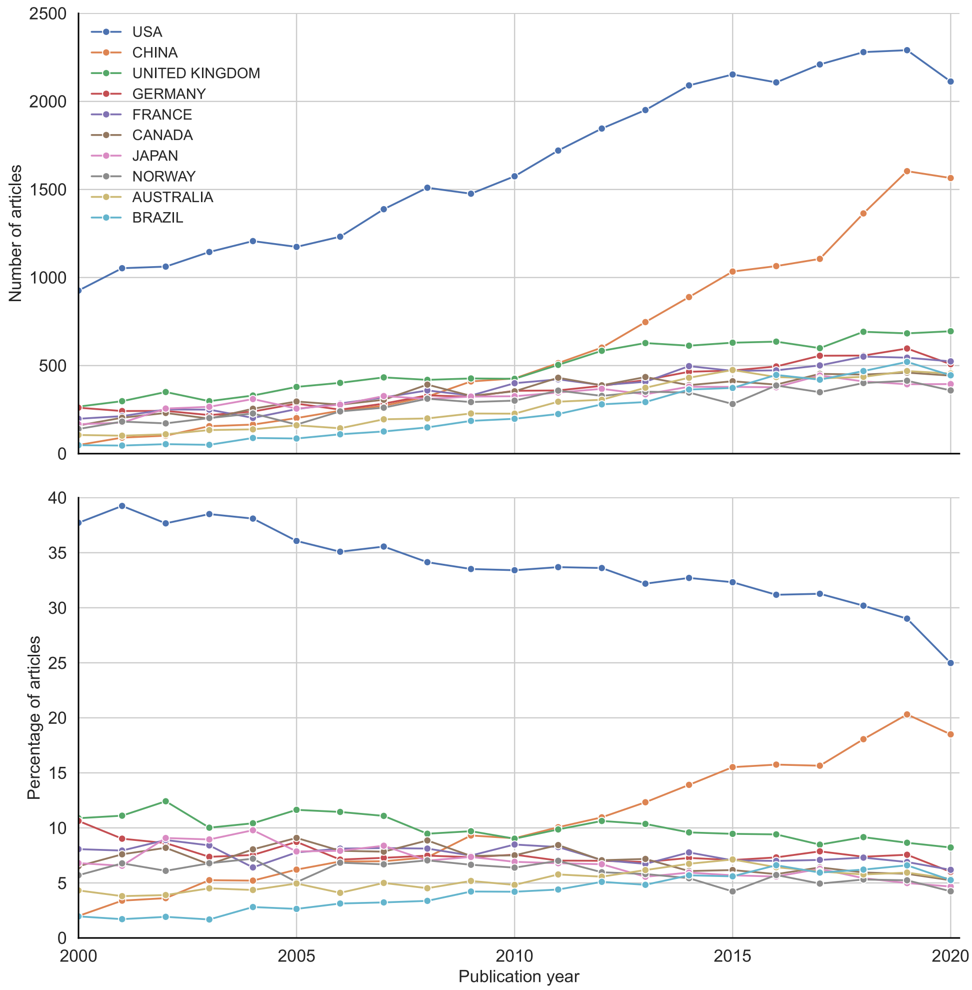

Fig. 2 Research output by ocean basin for selected countries. Top panel presents absolute output (i.e., articles) and the bottom panel presents relative output (i.e., percentage) for the top 10 most productive countries by publication count over the period 2000–2020.

in 2011, and has consequently seen its relative share of papers increase from only a few percent in 2000 to almost 20% in 2020, ranking only behind USA. This growth is largely due to its increasing focus on the Pacific, where its share has increased from about 5% in 2000 to over 40% in 2020 (Supplementary Fig. 1), making it the largest contributor for the most recent year of analysis. USA, on the other hand, has seen its Pacific share decrease from 45% in 2000 to 30% by 2020. Though less significant than China, Brazil's relative share of overall output also increased over the period from less than 2% to above 6%. This growth is largely attributable to its increasing focus on Atlantic Ocean research, where its output share increased from ~4% in 2000 to 13% in 2020, ranking it second behind USA in contribution (Supplementary Fig. 1). Year-on-year data is aggregated in Table 1 to illustrate the overall distribution of research by ocean using the G20 countries and five comparators, in terms of research output and GERD (gross domestic expenditure on research and development; Supplementary Table 1), with prominent coastal locations. Ocean basin research output of USA stands at about a third of world output (slightly more than its world share of Web of Science articles over the same period), for all but the Indian Ocean. China's output is generally below its world share (about 12%), except in the Pacific, where its share is greater and second to USA. The G7 countries of Germany, France, and UK have a sizeable share of output across all oceans.

Russia holds the largest share of Arctic research (30%), just ahead of USA (29%). Given the length of Russian coastline on the Arctic this is not surprising. However, Russia does not contribute much to research on any other ocean. Canada and Norway have a similar share of Arctic research (about 19%) which may be explained by extensive research networks and ocean proximity. In the Atlantic, behind USA, United Kingdom has the highest share (14%). Norway, Germany, France, Canada, and Brazil have a similar output (around 10%) demonstrating an Americas-European research dominance in this basin. Pacific research is dominated by its proximal, large research economies: USA, China, Japan, Australia, Mexico and Canada. Each command has at least a 5% share. United Kingdom and France's shares are similar to that of Russia (about 4%).

There is little remarkable about India claiming the largest share for its namesake ocean basin (26%). France holds a 9% share, which is greater than established research economies that are far closer geographically, such as China (8%) and Australia (6%). USA, geographically remote from the Indian Ocean, nonetheless has a share of 20%. Iran (9%), Saudi Arabia (7%) and Egypt (6%) exhibit a focus on the Indian Ocean. Year-on-year, Iran and Saudi Arabia have increased their Indian Ocean research programmes at a similar rate, with both having a near zero share in 2000 and a roughly 13% share by 2020, ranking them behind only India, USA and China, having substantially surpassed countries including Germany, Japan and Australia (Supplementary Fig. 1).

The Southern Ocean is the only basin where research is not dominated by proximal countries. USA (37%) and United Kingdom (22%) have the largest shares of Southern Ocean research, despite

Table 1. Percentage share of research output by ocean basin for G20 countries and five comparators.

Country	Arctic	Atlantic	Indian	Pacific	Southern
Argentina	0.08	1.94	0.05	0.22	1.07
Australia	1.37	2.48	6.47	8.37	**16.72**
Brazil	0.15	9.8	0.48	0.69	1.17
Canada	**18.92**	9.13	1.74	4.92	3.97
China	6.33	2.4	8.19	**26.57**	4.32
France	4.01	9.43	9.15	4.64	**10.38**
Germany	**13.85**	8.89	8.02	3.88	**17.84**
India	0.17	0.32	**26.12**	1.09	2.82
Indonesia	0.02	0.04	1.01	0.79	0
Italy	1.49	4.43	1.85	0.89	7.91
Japan	4.24	1.23	7.97	**12.72**	4.44
Mexico	0.08	2.99	0.23	5.77	0.2
Russia	**29.84**	1.89	1.85	4.35	3.49
Saudi Arabia	0.17	0.23	7.38	0.17	0.15
South Africa	0.17	0.81	3.25	0.31	3.39
South Korea	1.95	0.4	1.31	4.26	2.87
Turkey	0.12	0.67	0.21	0.13	0.02
United Kingdom	6.83	**13.98**	7.15	4.54	**22.33**
USA	**28.79**	**32.95**	**20.01**	**35.98**	**36.7**
Egypt	0.08	0.18	5.29	0.05	0
Iran	0.02	0.08	9.01	0.15	0
Malaysia	0.02	0.07	0.63	1.01	0.12
New Zealand	0.14	0.38	0.7	3.13	7.31
Norway	**18.51**	9.89	1.04	0.69	3.52

Comparators were chosen based on research output, GERD (gross domestic expenditure on research and development), and location (i.e., coastal). Shares may total more than 100% for any basin as collaborative efforts count towards multiple countries. Countries with at least a 20% share have values underlined and in bold, countries with shares between 10 and 20% are in bold.

their Northern hemisphere locations. Other countries with notable research shares are Germany (18%), Australia (17%), France (10%), Italy (8%), and New Zealand (7%); Norway (4%), Chile (2%) and Argentina (less than 1%) have more modest shares. These high rates of research output appear to be linked to the Southern Ocean research infrastructure of these countries and specific institutions (all the listed countries have at least one research base in Antarctica). Many of these countries also have territorial claims in Antarctica, with the notable exception of Germany which has the Southern Ocean as its largest relative contribution of any ocean basin. This is mainly due to the work of the Alfred Wegener Institute of Polar and Marine Sciences (see 'Institutional output' section, Table 3).

Despite the African continent's extensive coastline on the Indian and Atlantic basins, only two African countries have a significant share of research output in any ocean basin: Egypt's 5% in the Indian Ocean and South Africa's 3% in both the Indian and Southern Oceans.

International collaboration network

The two largest countries by research output, USA and China, collaborate with international partners on just under 50 and 40%, respectively, of their total ocean output (see Supplementary Table 1 for all countries' collaboration percentages). Both figures are far higher than their respective average academic collaboration rates[23]. G7 European countries average around 70% collaboration, as do Australia and Egypt. However, the large, populous G20 countries of Russia, Brazil and India have collaboration rates of 35 to 40%. Conversely, the G20 countries of South Africa, Saudi Arabia, and Indonesia have collaboration rates of around 80%. Iran has the lowest collaboration rate of all countries at 31%. Of the internationally collaborative papers, two-thirds are international bilateral; 19% are international trilateral; and 10% involve four or more countries. Of all ocean basin science papers, the percentage of internationally collaborative papers increased from 27% in 2000 to 34% in 2010 and to 36% in 2020.

The global ocean research collaboration network is illustrated in Fig. 3 for country pairs with at least 100 collaborative papers (roughly five collaborative papers per year). These collaborations represent all types of international collaboration, ranging from bilateral to highly (>10 countries) and even hyper (>30 countries) multilateral collaborations. The network corroborates the previously described results, with USA the largest collaborator amongst a central Americas-European nexus containing countries such as United Kingdom, Germany and Canada. Around this network is a secondary group of European countries (e.g., Norway, Spain), including the landlocked countries of Austria and Switzerland, as well as Brazil and an Asian network, where China is the central partner.

A third, peripheral, layer of this network encompasses countries from all continents, including SIDS. For example, collaborations of New Caledonia with USA (136), Australia (135), and France (242, which is 61% of all New Caledonia's collaborations); Fiji with Australia (137, or 60% of Fiji's collaborations); Bermuda with USA (159, or 87% of Bermuda's collaborations), demonstrate the global nature of ocean basin research. Singapore, also a SIDS, has a strong collaboration network with its East Asian neighbours albeit with a lower collaboration rate (40%) than many other SIDS (generally >50%). Countries from North Africa (Egypt, Morocco and Tunisia) are also represented in the network but there is a notable absence of countries from sub-Saharan Africa, save for South Africa.

Figure 3 will tend to highlight countries that have a substantial output (i.e., greater chances for collaboration); over 100 countries produced less than 100 articles (Supplementary Table 1). Lowering the collaboration threshold to at least 15 collaborations between country pairs, therefore, reveals the presence of a far larger network (Supplementary Fig. 2) illustrating sub-Saharan African contributions to the Atlantic (e.g., Benin, Cote d'Ivoire, Namibia, Senegal) and the Indian (Kenya) oceans; contributions from SIDS in the Caribbean (e.g., St. Kitts and Nevis) and Pacific (Vanuatu, Palau) also appear at this level (see Supplementary Fig. 3 for individual ocean networks). Though these collaborations may represent a significant percentage of a country's ocean basin output they are, ultimately, small in absolute terms.

Small Island Developing States (SIDS) and coastal countries

As noted previously, island and coastal countries are particularly vulnerable to changing ocean systems. Figure 4 illustrates the evolving global share of ocean basin papers for South and Central American, as well as African, coastal countries and SIDS (countries are listed in Supplementary Table 1). South America has more than doubled its global share over the period from 2000 to 2020; no other region is comparable. This growth is largely due to an increase in the research activity of Brazil, as shown in Fig. 2. Without Brazil's contributions, South America, Africa and SIDS have similar initial evolution over the period, all starting with a ~ 2% global share and increasing steadily. However, in the last five to ten years, South America's global share (reaching 5% in 2019) has distanced itself from SIDS and Africa, whose global shares appear to have plateaued at around 3%. Central America's share has remained constant over the entire period around (1%).

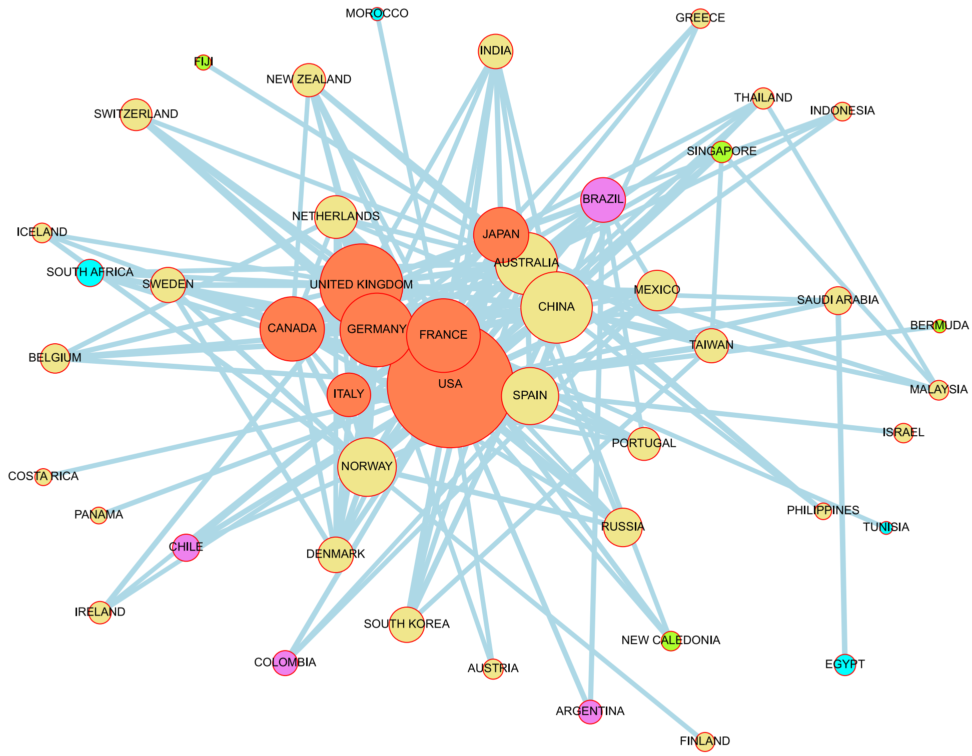

Fig. 3 Global network of country pairs that collaborate on at least 100 articles together. Node size is scaled by the absolute number of collaborative articles (USA largest node with 16,483 collaborative articles in total); line thickness is scaled by the number of collaborative articles between country pairs. G7 country nodes are coloured red; South American countries purple; African countries cyan; SIDS (Small Island Developing States) green; other countries yellow.

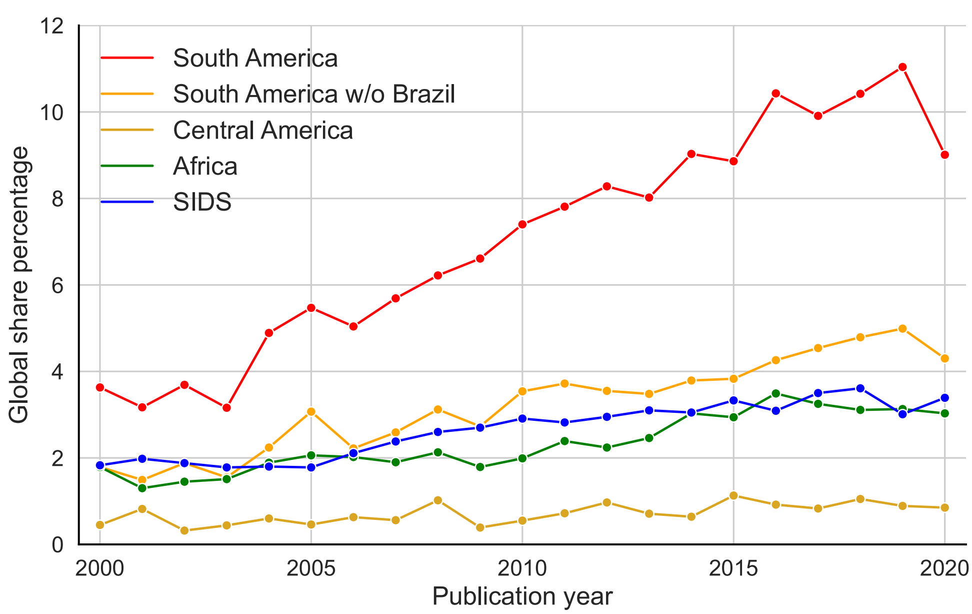

Fig. 4 Global share of ocean basin research output for several world regions. South America data are presented with and without Brazil. See Supplementary Table 1 for a list of countries for each region.

To gain further insight into the geographic sub-group trends, Fig. 5 shows cumulative density plots conveying the fraction of countries (y-axis) within each geographic sub-group that were below a given publication count (x-axis) within two six-year periods (2000–2005 and 2015–2020). For example, in the period 2000–2005, the 50% of South American countries with the lowest publication counts produced ~10 total articles. By 2015–2020, the 50% of South American countries with the lowest publication counts (not necessarily the same countries) produced ~100 total articles.

The global publication count (i.e., across all countries) has increased over the past 20 years (2000–2005 vs. 2015–2020). The publication counts for the geographical sub-groups have increased at a faster relative (percentage) rate than the global counts over this period, as seen by the rightward shift of all lines, relative to the black line, in the more recent time period. For most

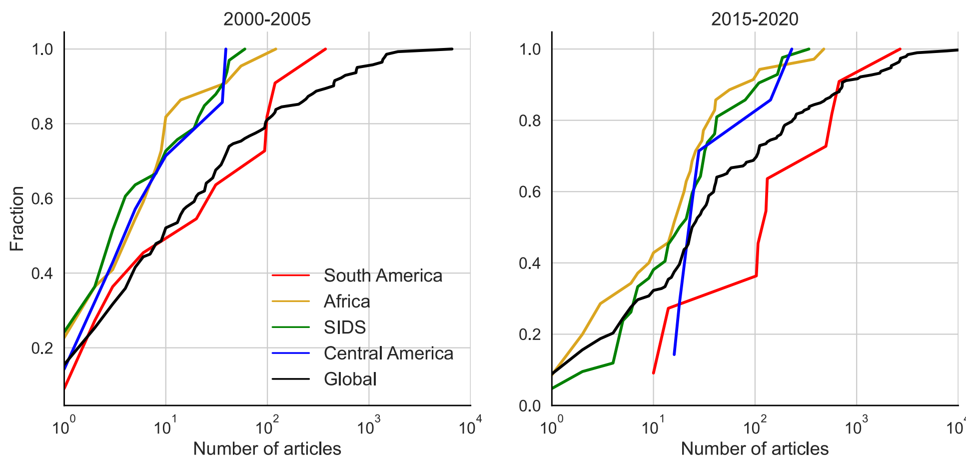

Fig. 5 Cumulative distribution frequency plots of research output (article counts) for selected regions between the periods 2000–2005 and 2015–2020. Black lines show the global distribution of national publication counts for these periods, and coloured lines show specific sub-groups of countries. Lines to the left of the global distribution indicate that low-publication count countries in that sub-group are more prevalent than in the global dataset. Steeper lines indicate a larger number of that sub-group's countries were responsible for producing a particular publication count (x-axis), and the x-axis value at which the lines reach the top of the figure indicates the publication count of the most research-productive country(ies) in the sub-region for that period.

regions, this increased publication count has moved absolute publication counts of both high- and low- publication-count countries closer to the global distribution. In South America, the growth in publication count distribution has grown to exceed the global average for almost the entire range of the plot (its largest producer, Brazil, published less than the largest global producers). The publication counts of the smallest producers in Central and South America are now high relative to the global smallest producers (10 vs. one research paper output).

Institutional output

Analysis at the institutional level by ocean basin (Table 2) permits a more granular analysis of research, providing a sub-national perspective as well as context for national trends. From an ocean basin viewpoint, research on the polar (Southern and Arctic) oceans is dominated by a few institutions with >10% contributions to the global literature. This is indicative of the infrastructure required to conduct in situ ocean science in these remote and challenging environments. The most diversified basin is the Atlantic, where only three institutes contribute more than 3% of global research.

From an institutional/national perspective, Table 2 elucidates the leading role of specific institutes and countries for every ocean basin. Arctic Ocean research is dominated by four institutions across Russia and Germany, with the Russian Academy of Sciences contributing over 20% of Arctic research. At the other pole, Southern Ocean research is dominated by three institutes in the United Kingdom and two in Germany. Interestingly, the same German institutes lead research at both poles (the Helmholtz Association and the Alfred Wegener Institute of Polar and Marine Research; the former also contributes significantly to Atlantic Ocean research) while the Russian and United Kingdom's institutes have dominance at one pole or the other.

Institutionally, the largest producer of Indian Ocean research is CSIR (Council of Scientific and Industrial Research) in India, which covers a wide spectrum of scientific fields, accounting for 8% of output. Indian institutions (mostly government) are four of the top five largest producers, having shares of ~4.5–7%; Centre National de la Recherche Scientifique (CNRS) of France has a share of almost 6%. In the Pacific, the institutions with the highest output are from the two main research-producing countries: USA and China. While the USA produced the largest country share of Pacific Ocean research over most of the analysis period (Supplementary Fig. 1), the Chinese Academy of Sciences is the largest institutional contributor in the Pacific, with an 11% share; NOAA has a share of ~6%. Research in the Atlantic appears more diversified. CNRS is the largest producer but accounts for less than 5.5% of output. One university, Université Bretagne Loire, accounts for nearly 3% of Atlantic output.

Most of the top-producing institutions across all oceans are government or research institutes, with a relatively small number of universities. Government or research institutes also play a significant role in national-level research output (Table 3) where 12 institutions account for over 60% of their country's ocean basin research (when considering countries with at least 100 publications). This list does however highlight that less developed research economies, which have a limited research capacity, are more likely to have their research concentrated in these institutes. For example, the Greenland Institute of Natural Resources accounts for 96% of Greenland's ocean research output (though the country has only a handful of research institutions) and the various branches of the University of the West Indies account for 80% of Jamaica's ocean basin research output. The most notable exception to this trend is Russia, where the Russian Academy of Sciences, which leads in Arctic Ocean research output (Table 2), is responsible for ~74% of Russia's nearly 4500 papers. There is one comparator to this, CNRS produced almost 4800 papers, accounting for 61% of France's total output. Other national academies in more populous countries have a notable proportion of their ocean basin research output: the Czech (53%), Polish (49%) and Ukraine (48%) Academies. The list also includes several SIDS institutions, including those from Jamaica, Singapore and New Caledonia.

DISCUSSION

The Atlantic and Pacific basins take the largest shares of ocean basin article output, consistent with them being the most voluminous basins and their proximity to well-established large research economies. China is leading a rapid growth in Pacific Ocean publications, which could see Pacific research surpass Atlantic in the coming years. China's interest in the Pacific is likely manifold (science, political, technological), but its growth (in absolute and relative terms) mirrors that in other disciplines[24–26]. Though not on China's scale, notable increases from near-zero global shares for Middle Eastern countries (Iran, Saudi Arabia) in the Indian Ocean could also signal multiple interests and motivations. Specific motivations would probably be elucidated

Table 2. Top five institutions, per ocean basin, by percentage of global output for that basin.

Ocean	Rank	Institution	Country	Institution's papers	Percentage of ocean output[a]
Arctic	**1**	**Russian Acad. Sciences**	**Russia**	**1083**	**20.9**
Arctic	**2**	**Helmholtz Association**	**Germany**	**526**	**10.1**
Arctic	**3**	**Shirshov Inst. Oceanology**	**Russia**	**461**	**8.9**
Arctic	**4**	**Alfred Wegener Inst. Polar Marine Research**	**Germany**	**414**	**8.0**
Arctic	**5**	**Fisheries and Oceans Canada**	**Canada**	**296**	**5.7**
Atlantic	1	Centre National de la Recherche Scientifique (CNRS)	France	2588	5.5
Atlantic	2	NOAA	USA	1910	4.0
Atlantic	3	Helmholtz Association	Germany	1627	3.4
Atlantic	4	State Univ. system Florida	USA	1372	2.9
Atlantic	5	Université Bretagne Loire	France	1313	2.8
Indian	**1**	**Council of Scientific and Industrial Research (CSIR)**	**India**	**921**	**8.3**
Indian	**2**	**Ministry of Earth Sciences**	**India**	**814**	**7.4**
Indian	**3**	**National Inst. Oceanography**	**India**	**809**	**7.3**
Indian	**4**	**CNRS**	**France**	**641**	**5.8**
Indian	**5**	**Department of Space**	**India**	**503**	**4.5**
Pacific	1	Chinese Acad. Sciences	China	4446	11.0
Pacific	2	NOAA	USA	2498	6.20
Pacific	3	Univ. California system	USA	2283	5.70
Pacific	4	Ocean Univ. China	China	1566	3.90
Pacific	5	Univ. Chinese Acad. Sciences	China	1527	3.80
Southern	**1**	**Helmholtz Association**	**Germany**	**475**	**11.9**
Southern	**2**	**Natural Environment Research Council (NERC)**	**UK**	**444**	**11.1**
Southern	**3**	**UK Research and Innovation (UKRI)**	**UK**	**444**	**11.1**
Southern	**4**	**NERC British Antarctic Survey**	**UK**	**433**	**10.8**
Southern	**5**	**Alfred Wegener Inst. Polar Marine Research**	**Germany**	**403**	**10.1**

[a]Total ocean paper counts: Arctic, 5185; Atlantic, 47,368; Indian, 11,079; Pacific, 40,275; Southern 4008. Ocean groups are alternately bolded for clarity.

Table 3. Top 20 institutions by percentage of the output of their respective country (countries with ≥ 100 papers).

Institution	Country	Institution's papers	Country's papers	Percentage of country output
Greenland Inst, Natural Res.	Greenland	101	105	96.2
Univ. West Indies	Jamaica	213	269	79.2
Smithsonian Institute	Panama	231	308	75.0
Smithsonian Tropical Res. Inst.	Panama	230	308	74.7
Univ. West Indies	Barbados	169	227	74.5
Russian Acad. Sciences	Russia	3268	4433	73.7
Univ. West Indies	Trinidad & Tobago	259	370	70.0
Bermuda Inst. Ocean Sciences	Bermuda	124	189	65.6
Univ. Costa Rica	Costa Rica	269	432	62.3
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)	Argentina	647	1043	62.0
CNRS	France	4784	7841	61.0
Univ. Republic Uruguay	Uruguay	117	193	60.6
National Univ. Singapore	Singapore	357	606	58.9
Univ. South Pacific	Fiji	178	318	56.0
Czech Acad. Sciences	Czech Rep,	121	227	53.3
Institut de Recherche pour le Développement	New Caledonia	219	428	51.2
Polish Acad. Sciences	Poland	221	450	49.1
National Acad. Sciences Ukraine	Ukraine	50	103	48.5
Hellenic Centre for Marine Res.	Greece	254	534	47.6
University of Vienna	Austria	221	482	45.9

by a topical analysis of research, which is outside the scope of this work.

The increase in international collaboration (27% in 2000 to 36% in 2020) for ocean basin research mirrors that of all research fields[27]. Ocean basin research is globally connected with the G7 countries in North America and Europe, as well as China, acting as regional hubs for other G20 countries as well as countries in North Africa, Central America and, importantly, SIDS such as Fiji, New Caledonia and Singapore, which are literally at the forefront of the ocean's impact.

Collaboration can bring numerous benefits and these, as well as policy implications, have been discussed copiously[28–30]. Collaboration is a particularly important element of ocean science research, where the infrastructural needs to conduct research require significant resources. International collaborations are often the only way for researchers to access this required infrastructure. Based on these results, collaborations are likely driven by the proximity of well-established large research economies, with Australia being a collaborator hub for Pacific countries and USA for Atlantic countries. However, collaboration is not always effective and equitable, and can preclude positive outcomes[31]. Physical distance can negatively affect collaboration activities[30] as it requires additional costs to bridge the distance (and potentially time zones) as well as overcome institutional differences[32–34] and can increase conflict[32]. Furthermore, these costs tend to reduce the quality of communication, coordination and monitoring[34]. Consequently, some collaborations can create a closed-shop elite innovation network, where only specific institutions (and therefore countries) benefit, widening the gap between institutions[35].

Collaborations are also likely built through common language from historical ties such as Spain with Latin America[36] and France and UK with African countries[37,38]. Other factors include regional partnerships such as Malaysia and Singapore, both part of ASEAN (Association of Southeast Asian Nations), and the Nordic countries as part of NordForsk (a body providing funding and facilitating for Nordic cooperation on research and research infrastructure).

Despite the global connectedness of ocean sciences, Sub-Saharan Africa (bar South Africa) is a notable exception in this global network despite its extensive coastline and historical relationships with numerous well-developed research economies. Many African countries are reliant on the ocean and its resources, so would be expected to have a greater presence in the global network. The lack of sub-Saharan African collaboration is likely due to three related factors: low research output, low GERD, and limited ocean science infrastructure. Other factors impacting research, and likely contributing to low collaboration, include unwillingness to collaborate[38], a low number of researchers compounded by brain drain[39], the vocational nature of universities[40], an incomplete and under-resourced national institutional framework[40,41], and poor internet and mobile data access[42].

Research in sub-Saharan Africa is dominated by South Africa, which accounted for two-thirds of the region's output. Outside of this, Kenya was the largest producing nation but with only 81 ocean basin science articles—a little over four articles a year on average over the period in question; 40 countries produced <50 papers each. This small article count limits opportunities for collaboration in terms of both research and absolute output. Even intra-African collaboration is sparse or haphazard, something that has been noted to affect other research areas of concern such as greenhouse gases[43]. This is further evidenced by Kapuka et al.[44] who found geographical imbalance and inadequate use of advanced methodologies restricted climate change research opportunities in southern Africa (countries below a latitude of approximately −6°). Outside of Africa, the USA is the largest collaborator for South Africa and Kenya (of countries producing >40 papers). France is generally the main collaborator for African countries, and this is likely due to historical relationships as noted above.

In 2014, the African Union Commission[45] agreed to invest 1% of GDP in research and development (GERD). However, the latest available data (Supplementary Table 1) suggest no country has met this. North African countries generally have the highest GERD—Egypt has almost reached this target (0.96%)—while values in Sub-Saharan Africa are generally <0.6% with Kenya's 0.69% being the largest (Supplementary Table 1). Consequently, many countries do not have the funds available to invest in research and development. This may explain the large imbalance in ocean basin science research output between North and sub-Saharan Africa.

Lo Bue et al.[46] describe the importance of research infrastructures for extreme ocean events (cyclones, tsunamis, etc.) but many of their arguments can also be applied to continuous processes. Namely, events or processes generally exceed the study capabilities of a single country, requiring strong collaborations which likely include complex equipment and facilities, broad expertise, and high-quality data over a globally distributed network. Lo Bue et al.[46] note that large observational gaps, especially in Africa (as well as South America and South-East Asia), remain. Underinvestment in infrastructure across Africa is common[29]. South Africa, the largest African contributor, offers examples of infrastructure that will strengthen and improve its research: the shallow Marine and Coastal Research Infrastructure[47] and a concerted effort to develop capacity for deep sea research[48].

The African continent is, however, aware of its research challenges and limitations in general[49] and in relation to ocean science[50], such as limited marine and coastal ecosystems mapping, insufficient fundamental knowledge of species diversity and taxonomy, and ineffective marine ecosystem governance. This is evidenced by generally sparse African involvement in, and therefore progress toward achieving, UNDOS programmes, with none led by African institutions[50]. However, these are being addressed as part of Africa's roadmap built around UNDOS[50] which consists of nine priority future Decade Actions including Sustainable Ocean Management, Unlocking the Blue Carbon Potential, and Ocean Observations and Forecasting Systems. Other African Union frameworks such as Agenda 2063: The Africa We Want[51], Africa's Integrated Maritime Strategy (2050 AIM Strategy)[52], and Africa Blue Economy Strategy[53] and 2015–2025 Decade of African Seas and Oceans will also support the development of the ocean economy and the achievement of SDG targets.

Despite its current limitations, Africa's long-term vision is to become a more independent research hub in terms of finances and resources through improved governance and intra-Africa collaboration[50]. Educational and early career development programmes such as Global Ocean Corps and Conveyer[54], which aims to sustain "long-term education research collaborations between scientists from under-resourced nations and higher resourced nations" and the related COESSING[55] (Coastal Ocean Environment Summer School in Nigeria and Ghana), a summer school to educate ocean scientists in Africa and build collaborations with USA and other international scientists, will help this goal. For now, however, proactivity from larger research economies may be needed to better entrain low research output countries into the ocean-science fold; financial and social support for such activity could be stimulated by SDGs that target international progress or collaboration (e.g., SDG 14 targets[56] 14.2, 14.3, 14.5, 14.7, 14.a, 14.c).

Despite the challenges described above for ocean science research, Africa's global share of papers did show a modest increase (Fig. 4). This appears to be driven by a rapid increase in publication rate from countries in the middle of the ocean science production rankings for the continent (Fig. 5) while the increases in low- and high-producing countries have generally followed global output patterns.

South America has seen a significant increase (~150%) in its share of global output. This is largely due to the growth of output by Brazil. Given that Brazil has a population (~215 M) and GERD (1.21%, Supplementary Table 1) over four and two-and-a-half times bigger than the next largest countries (Colombia and Uruguay, respectively) this is not unexpected. However, South America's global share increased 100% even when excluding Brazil. This growth has been particularly rapid in the last five years and stands in contrast to the lower growth rate of African ocean basin research. South American countries (excluding Brazil) do have a slightly higher average GERD (0.36%) than sub-Saharan Africa (0.30; Supplementary Table 1) but they generally have lower levels of international collaboration (35–40%) and fewer researchers per million inhabitants (Colombia had only 88 in 2017; South Africa, which produced a similar number of papers, had 484 in 2019; Supplementary Table 1). Colombia, Chile, and Argentina each produced over 1000 papers over the period (Brazil produced >5000) while only South Africa produced >1000 in sub-Saharan Africa. Seven of the eight South American countries producing >40 papers (in fact all eight produced >100 papers) have the USA as their main international collaborator, in contrast to African countries. Cumulatively, South America's output grew faster than the global distribution between 2015–2020, particularly its lower paper-producing countries, which far exceeded the output rates of the lowest-producing countries globally (Fig. 5).

The relatively rapid growth of ocean basin research output in South America compared to Africa may be due in part to its slightly higher average GERD and its collaborations with American institutions that may, but not always, provide access to infrastructure. Consequently, South America has improved its global share despite economic benchmarks being similar to or below those of Sub-Saharan Africa. Closer links between science and diplomacy[57] as well as policy[58] and greater support for early career scientists[59] may further strengthen ocean science in South America. Other initiatives, such as MetaDocencia[60] which aims to support scientific and technical capacity in Spanish-speaking communities across the globe, particularly in South America, are also beneficial. These educational and early career development efforts should be paired with infrastructural development to advance and sustain international collaborative research communities. South America does both and has shown strong growth, while Africa has not had the infrastructural development.

SIDS' global world share was greater than that of Africa from 2005–2012 but its stagnation, especially since 2015 suggests these countries, which are most vulnerable to ocean and climate change, have not substantially increased their output, relative to other regions since the introduction of SDGs. However, collaborations with SIDS are abundant with most having collaboration rates of >50% (i.e., most articles with authors from these states also involve international collaborators; Supplementary Table 1). GERD values are mainly absent but, from those available, SIDS (except for Singapore: 1.89%), are comparable to both South American and sub-Saharan African (<0.5%) countries. This suggests that collaboration is needed to help these countries address SDG 14 goals.

Tables 2 and 3 illustrate that ocean basin research is mainly conducted by research institutes, national academies, or other governmental organisations. This is likely due to the highly specialised resource-intensive nature of ocean research. For example, the physical challenges when observing remote ocean regions, deep below the surface, or in challenging conditions (e.g., polar oceans) require cutting-edge technology alongside expensive research vessels and associated costs (crew, land-side facilities, maintenance, etc.). Even in fields such as computational oceanography, where high-performance computing (HPC) systems are often used to simulate the ocean and analyse large datasets, the required HPC resources are usually organised at a national or institutional level. This creates an access barrier for ocean scientists from institutions and countries that do not have this expensive infrastructure. However, there are ongoing efforts to create open-source computational resources and data access for ocean and climate science, e.g., Pangeo[61].

A good example of this resource-dependent output boost, as well as the economic cost of these resources, is the Alfred Wegener Institute of Polar and Marine Research which is one of the leading contributors in the polar oceans. Though only founded in 1980, the institute has substantial infrastructure including shipping vessels, aircraft, laboratories, research stations and observatories to operate and conduct research in these regions. It is a member of the Helmholtz Association, the largest scientific organisation in Germany. The Association's 2021 budget was €5.8B with 70% of funding sourced from Germany's federal and state governments; the budget for earth and environment research, which covers the Alfred Wegener Institute's studies, was over €700M[62].

For comparison, the Smithsonian Tropical Research Institute, accounted for 75% of Panama's ocean basin research. The institute has existed in various forms since 1910 and has research facilities and field stations throughout the country with many located along the Panama Canal, providing easy access to the highly contrasting ecosystems in the Caribbean and Pacific. The institute's operating budget was around $30 M (~€27.5 M) in 2018[63] The Tropical Research Institute is one of the Smithsonian's research facilities; the Smithsonian's federal funding for the 2021 fiscal year was $1B (about €900 M), which was 62% of its total funding[64]. In the Atlantic, the Bermuda Institute of Ocean Sciences, founded in 1903, has an ocean class vessel for research purposes. In 2021 it had a net position of $40 M, as well as investments of $20 M and endowments of $20M[65].

Generally, the infrastructure or federal or private funding for in-depth ocean basin research is not available at an institutional level, as noted in relation to Africa earlier. Leveraging the relevant SDGs and the United Nations Convention on the Law of the Sea[66] (UNCLOS), particularly Part XIII Section 2 (which governs "Marine Scientific Research: International Cooperation") should help unite priorities with development assistance. However, even where ocean policies are well developed, such as the South Pacific, knowledge and awareness of initiatives and investment related to SDG 14 are negligible; better coherency in policy and investment is needed to effectively address SDG goals[67] as well as responsible financial use[68].

This paper's focus has been the volume of publications indexed within the Web of Science. This journal citation database has traditionally favoured international and influential English-language journals over those of national importance published in local language journals (e.g., Spanish or Portuguese in Latin America[69–71]). Consequently, Web of Science, and other major Global North journal citation databases, provide an incomplete representation of research systems in the Global South. Regional journal citation databases such as the Scientific Electronic Library Online (SciELO)[72] for Latin America and the African Journal OnLine (AJOL) in Africa give greater visibility to research from these regions. These regional journals also contain significant Open Access content further increasing visibility. Simard et al.[73] showed that sub-Saharan Africa publishes and cites Open Access papers at a higher rate than the rest of the world concluding this may be because article processing charges are normally waived for low-income countries.

A direct assessment on the impact of the ocean basin research analysed here is outside its remit. However, highly multilateral collaborative papers receive more citations[74–77] and, consequently, gain a higher Category Normalised Citation Impact (CNCI: citation counts normalised by year of publication, subject category, and document type[74,78,79]). It is generally held that there is a correlation between citation counts and peer judgements of quality (i.e., higher citation counts are associated with better peer judgement) in science and technology fields[80,81] and that highly cited publications contribute significantly to academic knowledge[82]. The citation of an article is therefore an indication of that article's influence. This implies that the multilateral collaborations highlighted in Fig. 3, will be more influential than purely domestic output. However, when citations are additionally normalised by collaboration type (e.g., international bilateral papers are compared only to other international bilateral papers) domestic research can be shown to be more influential than some types of internationally collaborative research[78,79].

Research leaders, funders and other decision-makers must account for the inequitable structure of the ocean science research community, particularly in the context of the UN Decade of Ocean Science and UN Sustainable Development Goal 14 "Life Below Water". By quantifying the structure and evolution of this community since 2000, the results presented here can aid in decision-making, such as targeting effort and resources, to support the growth and success of the global ocean science community.

METHODS

Data source and retrieval

This work expanded upon material originally presented in a Clarivate Global Research Report[83]. The Web of Science, including its Expanded API[84], was used to retrieve research articles and their associated metadata (e.g., journal, authors, affiliations, abstract) published between 2000 and 2020, inclusive, using specific title and abstract term searches relevant to the five ocean basins—Arctic, Atlantic, Indian, Pacific, Southern (e.g., Barents Sea, Bering Strait, Gulf of Mexico; see Supplementary Methods for full search criteria and the GitHub repository[85] for code). Terms had to appear in both the title and abstract of a document for its inclusion. This yielded a total dataset of ~106,000 articles with very high precision in terms of ocean basin-relevant documents. This was more valued than a larger (i.e., higher recall) less-specific dataset, such as using the Web of Science subject category "Oceanography" which returned ~124,000 articles for the same period. Consequently, this analysis excluded studies with global or coastal foci, as well as studies investigating general ocean processes rather than regions. Both small and large research economies contribute to these topics so, while these remain important ocean science topics, their exclusion from this study did not bias the ocean basin science dataset in terms of countries involved. The method of using specific term searches is somewhat similar to that used in the IOC-UNESCO report[14] though that study used Elsevier's citation database Scopus and had a more general scope.

Data classification

Each document was assigned to one (or more) ocean basins based on the search term criteria, i.e., an article that included 'Gulf of Mexico' in its title and abstract was assigned as an Atlantic Ocean paper. Most papers (98%) were assigned to one basin, though 2% were assigned to two; 19 papers were assigned to three basins. Institutional and national affiliations were taken from article author metadata. Affiliations for all authors on any given publication were extracted and then deduplicated. An internationally collaborative article was defined as any article that had at least two different countries present in the deduplicated list, regardless of the number of authors (e.g., a single-author paper could be internationally collaborative). International collaboration counts for each country pair were calculated using the number of articles on which both countries were present, regardless of the presence of any additional countries. Consequently, when considering output on the individual country level, some articles were counted multiple times—once for each collaborating country. This was also true when considering output at the ocean basin level, as articles could be relevant (via the search terms) to multiple basins. Conversely, when considering output on the global scale, each article was only counted once. Subsequently, collaboration percentages when viewed on the global scale were lower than many individual country collaboration percentages because each collaborative paper is counted multiple times in the latter, once for each collaborating country. Due to missing or unavailable data, some affiliation metadata were incomplete. However, previous studies[78,86] have shown that these cases will not affect outcomes given a large enough sample.

Article output was compared in terms of absolute output and world share. The population was not used as a normalising factor as some less (in relative terms) populous countries have notable research output (e.g., New Zealand: population ~5 M, output ~1800 articles) and more populous countries have little output (e.g., Algeria, population ~45 M, 58 articles). Where appropriate, gross domestic expenditure on research and development (GERD) and researchers per million inhabitants values (taken from UNESCOs Institute for Statistics website[87]) were quoted as a proxy for research capability and to provide context on national output. Values for these indicators are provided, where available, in Supplementary Table 1.

In the Web of Science, institutional affiliations can be unified under a parent institution. However, in some cases, affiliations can be unified to more than one parent institution (for example, MIT and Harvard University are both parents of the Broad Institute). This can lead to similarly named institutions, or divisions of institutions, being listed as parent affiliations. This is demonstrated in Table 3 where both the Smithsonian Institute and Smithsonian Institute of Tropical Research (a subdivision of the Smithsonian Institute) are both listed as Panamanian institutions. This is because both can be defined in the Web of Science as being a parent of the Smithsonian Institute of Tropical Research. Some affiliations, representing consortiums of institutions, were removed from the analysis as they did not truly represent a unified institution.

DATA AVAILABILITY

Summary data supporting these findings are found in the Supplementary Information file. All background data are available to academic researchers in institutions that subscribe to the Web of Science.

CODE AVAILABILITY

The underlying code for this study is available at https://doi.org/10.5281/zenodo.8270555.

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AUTHOR CONTRIBUTIONS

Conceptualisation: R.W.K.P.; methodology: R.W.K.P., B.C.P.; data curation: R.W.K.P.; data analysis: R.W.K.P.; data consultation: B.C.P.; manuscript writing: R.W.K.P.; manuscript review and editing: R.W.K.P., B.C.P.

COMPETING INTERESTS

R.W.K.P. declares no competing non-financial interests but the following competing financial interests: R.W.K.P. is employed by Clarivate, which owns the Web of Science. All other authors declare no competing interests.

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