*ICES Journal of Marine Science*, 2022, **0**, 1–15
DOI: 10.1093/icesjms/fsac074
**Quo Vadimus**

# Exponential growth of hadal science: perspectives and future directions identified using topic modelling

**Johanna N. J. Weston** [1,*] **and Alan J. Jamieson** [2]

[1] School of Natural and Environmental Sciences, Newcastle University, Newcastle Upon Tyne NE1 7RU, UK
[2] Minderoo-UWA Deep-Sea Research Centre, School of Biological Sciences and Oceans Institute, The University of Western Australia, IOMRC Building M470, 35 Stirling Highway, Perth, WA 6009, Australia
*Corresponding Author:; e-mail: johanna.weston@ncl.ac.uk

The hadal zone is a cluster of deep-ocean habitats that plunge to depths of 6000–11000 m below sea level. Research of the deepest marine zone has occurred on a disjunct timeline and slower than shallower zones. Over the past 20 years, research efforts have surged with greater sampling capabilities and an expansion of expeditions. We aimed to assess the state of hadal science by quantitively assessing the publishing landscape. We applied a topic modelling approach and fit a Latent Dirichlet Allocation model for 12 topics to 520 abstracts from peer-reviewed papers, reviews, and conference proceedings available on the Web of Science's Core Collection between 1991 and 2021. The model outputs were analysed with ecological modelling approaches to identify the main lines of research, track trends over time, and identify strengths and gaps. We found that hadal science is occurring across all five broad disciplines of oceanography and engineering. Hadal research has exponentially grown in the past 30 years, a trend that shows no signs of slowing. The expansion is most rapidly occurring to understand the biogeochemistry of trenches, the functions of microbial communities, and the unique biodiversity inhabiting these ecosystems, and then the application of 'omics techniques to understand hadal life. The topic trends over time are largely driven by available technology to access and sample the deepest depths and not necessarily the pursuit of specific scientific questions, i.e. the hadal research topics are bounded by the capabilities of available exploratory vehicles. We propose three recommendations for future hadal research: (1) conduct multifeature studies that include all hadal geomorphologies across their depth range, (2) establish a programme for seasonal or long-term sampling, and (3) strengthen cross-disciplinary research. This continued acceleration in hadal research is pertinent for this last marine frontier given its vulnerability to multiple anthropogenic pressures and cascading threats from global change.

**Keywords:** deep sea, Latent Dirichlet Allocation model, literature review, Ocean Decade, text analysis.

## Introduction

Named a homage to *Hades*, the Greek god of the underworld and his home (Bruun, 1956), the hadal zone extends from 6000 to 11000 m deep and consists of at least 47 geographically disjunct ecosystems that punctuate the abyssal plains as subduction trenches, transform faults/fracture zones, and troughs/basins (Stewart and Jamieson, 2018). While characterized by high hydrostatic pressure, near-freezing temperatures, and food scarcity (Jamieson *et al.*, 2010), no two hadal habitats are identical. Each feature varies in geomorphology, total area, maximum depth, proximity to land, hydrography, geologic age, and degree of seismicity (Jamieson *et al.*, 2010). Subduction trenches, 94% of the hadal zone, act as depocenters by funnelling sediment and organic carbon to the trench axis (Glud *et al.*, 2013; Ichino *et al.*, 2015). These feature-specific conditions coupled with the separation of thousands of kilometres shape isolated ecosystems to have high levels of endemic species (Belyaev, 1989; France, 1993). The hadal faunal community hosts representatives from nearly all major taxa, e.g. fishes, cephalopods, crustaceans, echinoderms, polychaetes, molluscs, cnidarians, bryozoans, foraminifera, bacteria, and archaea (Gooday *et al.*, 2008; Paterson *et al.*, 2009; Ritchie *et al.*, 2015; Peoples *et al.*, 2019a; Jamieson and Vecchione, 2020; Jamieson *et al.*, 2021a, 2021b; Swan *et al.*, 2021). The hadal faunal community is distinct from the shallower zones, like the communities of abyssal plains, and most species are known from a single locality (Belyaev, 1989).

Due to extreme depths and the associated technological challenges, hadal exploration and research have lagged that of the shallower deep-sea and coastal ecosystems (Danovaro *et al.*, 2014; Jamieson, 2018). The number of hadal-rated technologies has increased over the past fifteen years, such as sensors and cameras (Glud *et al.*, 2013; Brandt *et al.*, 2016), autonomous landers (Jamieson *et al.*, 2009; Peoples *et al.*, 2019b), epibenthic sledges (Brandt *et al.*, 2013), and submersible vehicles (Kyo *et al.*, 1995; Bowen *et al.*, 2009; Jamieson *et al.*, 2019a). The technological advancements have coincided with a rise in the number of multidepth and/or multitrench sampling programmes, e.g. the HADal Environment and Educational Program (HADEEP) (Jamieson *et al.*, 2010), HADal Ecosystems Study (HADES) (Linley *et al.*, 2017), the Kuril-Kamchatka Biodiversity Studies (KuramBioI & II) (Brandt and Malyutina, 2015; Brandt *et al.*, 2020), the Vema-TRANSIT Bathymetry of the Vema-Fracture Zone and Puerto Rico TRench and Abyssal AtlaNtic BiodiverSITy Study (Vema-TRANSIT) (Riehl *et al.*, 2018), the HADES–ERC Advanced Grant and the recently established Danish Center for Hadal Research—HADAL (Glud *et al.*, 2021), the Five Deeps and Ring of Fire expeditions (FDE and RoF) (Jamieson *et al.*, 2019a, 2021b), and expeditions support by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Kitahashi *et al.*, 2012; Kobayashi *et al.*, 2012) and the Chinese Academy of Sciences (Cui, 2018; Cui and Wu, 2018; Chan *et al.*, 2020). The expansion of sampling capabilities and programmes has

**Received:** September 29, 2021. **Revised:** April 1, 2022. **Accepted:** April 4, 2022
© The Author(s) 2022. Published by Oxford University Press on behalf of International Council for the Exploration of the Sea. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

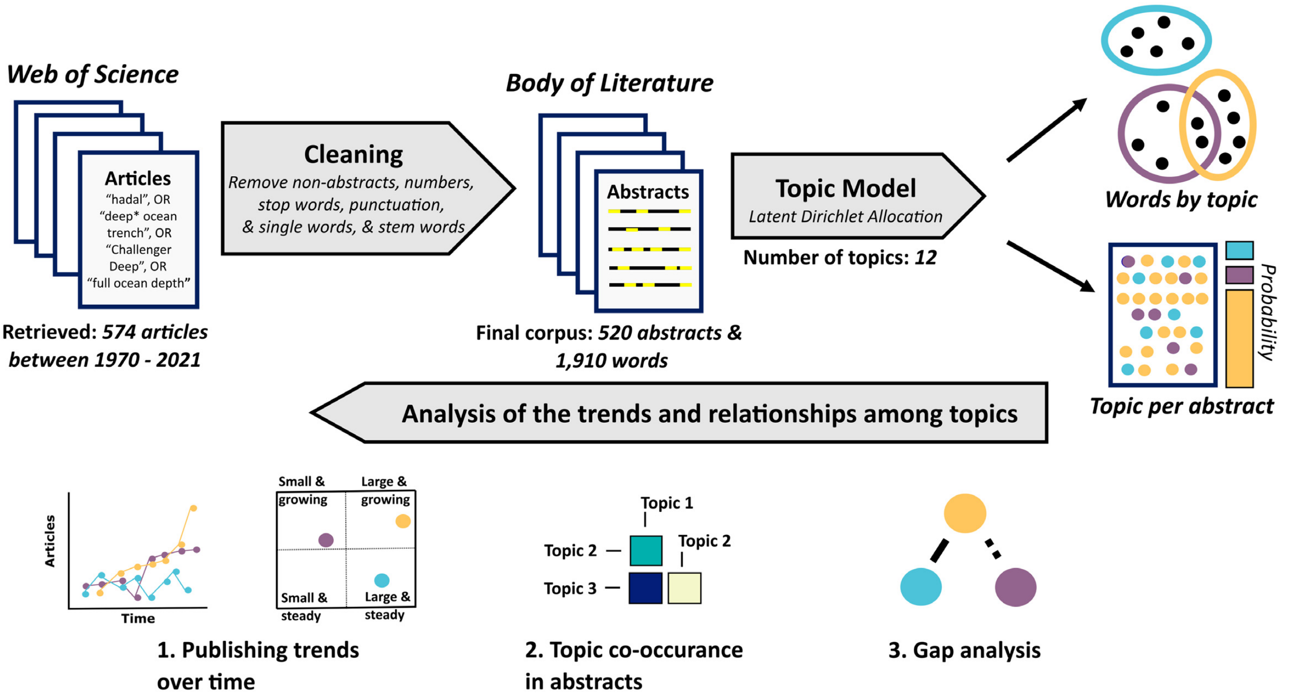

**Figure 1.** Schematic of the topic modelling workflow used to investigate the trends across the hadal science publishing landscape.

translated to an increase in the number of peer-reviewed published papers (Jamieson, 2018). Hadal science has been postulated to be past the exploration era and transitioning from an observational to an experimental era (Jamieson, 2018).

Despite the recent growth of hadal science, these ecosystems are comparatively understudied to shallower zones, leaving deep data and knowledge gaps in our understanding of how these ecosystems function, which limits our ability to develop strategies for monitoring and conserving the hadal zone (Angel, 1982; Jamieson, 2018; Danovaro *et al.*, 2020). The United Nations has declared 2021–2030 an international Decade of Ocean Science for Sustainable Development (Ocean Decade), served to focus research and technological development in oceanography on protecting the World's Ocean through ten priority challenges (Ryabinin *et al.*, 2019). These priority challenges include the hadal zone, specifically the need to "Understand and beat marine pollution" (Challenge 1) and "Protect and restore ecosystems and biodiversity" (Challenge 2). Despite the remoteness of the hadal zone, human impacts are evidenced, from plastic pollution to high levels of persistent organic pollutants and mercury (Jamieson *et al.*, 2017, 2019b; Blum *et al.*, 2020; Weston *et al.*, 2020; Vescovo *et al.*, 2021), and likely multiple other unmeasured ongoing and future stressors. These impacts highlight that the extreme depths and remoteness do not shield the hadal zone from the changes and pressures occurring at the surface and on land. At the beginning of the Ocean Decade, there is a critical opportunity to assess the state of hadal science to identify research strengths and potential data and knowledge gaps.

In this study, we aim to assess the state of hadal science and understand the drivers of growth by developing a broad picture of the publishing landscape. We employed a text analysis method, topic modelling—a statistical approach that assesses the text in a corpus of abstracts and then identifies topics that represent the key ideas based on the co-occurrence patterns of words. Topic modelling uses a Latent Dirichlet Allocation model (LDA) (Silge and Robinson, 2017), and model outputs can be analysed with ecological modelling techniques (Westgate *et al.*, 2015). Topic modelling has been applied across a variety of fields, such as conservation science (Westgate *et al.*, 2015; Mair *et al.*, 2018), arid ecology (Greenville *et al.*, 2017), fisheries science (Syed *et al.*, 2018), and animal pollination (Millard *et al.*, 2020). Herein, we collated a body of hadal literature from Web of Science (520 abstracts from 1991 to 2021) and fit an LDA model for 12 topics (Figure 1). We analysed the outputs to (i) uncover the main lines of research or disciplines in hadal science, (ii) track how hadal research has changed and grown over time, and (iii) identify the strengths and gaps among the disciplinary and interdisciplinary topics within hadal science. This broad view of the state of hadal research aims to support future work within the international research community to strategically use valuable resources for sampling and data collection, develop new research directions, and inform strategies to conserve the deepest parts of the ocean.

## Material and methods

### Literature search and abstract cleaning

A literature search was conducted on 16 December 2021, using the Web of Science's Core Collection database for peer-reviewed research papers, reviews, and conference proceedings, herein collectively termed articles, published between 1970 and 2021. A total of 574 articles were returned using the search terms, "hadal", "full ocean depth", "deep∗ ocean∗ trench", and "Challenger Deep", in the title, abstract, or author keywords. The asterisk captured the root word and any suffixes, such as deep and deepest. These search terms were selected to focus on research exclusive to the hadal zone. While a term as specific as "Challenger Deep" is less desirable, as

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

it is restrictive and may introduce potential bias, this term caught several articles not captured by the other terms. Other place-specific terms, such as “Mariana Trench” and “Japan Trench”, were tested but determined to provide too broad of results with research at shallower, non-hadal depths. “Subduction trench” was also considered as a search term, but it retrieved many non-marine studies.

We downloaded a BibTex file with the full record of the 574 articles from 1970 to 2021 and imported the file into the programme R v. 3.6.3 (R Core Team, 2020) using the package *bibliometrix* v 3.1.3 (Aria and Cuccurullo, 2017) (see Supplementary material S1). Seven articles were manually removed as determined to not be focused on the hadal zone. A total of 47 articles lacked abstracts and were removed from the text analysis. The remaining 520 articles with abstracts were transformed into a corpus or “body of literature” and prepared for the topic modelling analysis using the R package *tm* v. 0.7–8 (Feinerer *et al*., 2008). For the abstract cleaning, the search terms were removed, as they were common to all abstracts (Figure 1). Numbers 1–11 written as words and numerals were removed. The 174 common English words, a pre-defined list of in the *tm* package, were discarded. Further, the words “marine”, “deep-sea”, “sea”, “also”, “can”, “may”, “like”, “well”, “will”, “along”, “the”, and publisher’s copyright terms were removed. Hyphens and slashes were changed to spaces, and punctuation was stripped. The remaining words were stemmed back to their root. A total of 4599 words (∼70%) appeared in three or fewer abstracts and were discarded, as rarely shared words are found to have minimal influence on topics (Lu *et al*., 2017). The final corpus had a vocabulary of 1910 words, and this was converted into a matrix of document-term frequencies or a document-term matrix.

The process of topic modelling requires text to analyse, such as whole text or abstracts, used herein. The Web of Science’s Core Collection database is limited to articles post-1970. While the other Web of Science databases do return publications before 1970, the abstracts are not configured to be exported. Thus, these articles are unable to be part of our topic modelling analysis. To account for the early hadal science publishing landscape, we conducted a search on the Web of Science’s All Databases between 1950 and 1990 using the four search terms, “hadal”, “full ocean depth”, “deep∗ ocean∗ trench”, and “Challenger Deep”. A total of 50 articles were returned. Two articles were manually removed as duplicates, and another 14 articles were duplicate articles returned by the Core Collection search.

For research field comparison, we gathered total article counts for research of other ocean zones or ecosystem types. The Web of Science’s Core Collections was searched between 1970–2000 and 2001–2021 using separate search terms, “hadal”, “abyssal”, “hydrothermal vent”, “seamount”, “continental shelf”, and “coral reef” in the title, abstract, or author keywords.

## Topic modelling

The LDA model requires two inputs, the document-term matrix and the number of topics to be identified by the user. To determine the number of topics, we first calculated the number of topics using the R package *ldatuning* v1.0.2 (Nikita, 2019) for 2 to 20, 25, 40, 50, 80, 100, 150, and 200 topics with the metrics Griffiths and Steyvers 2004; Cao Juan, 2009, and Arun 2010. The *ldatuning* results indicated the number of topics to be between 50 and 80. Second, we ran a series of test models for 8, 10, 12, 14, 15, 18, 20, 22, 24, 25, 30, and 50 topics. We manually inspected each model output for the 20 highest weighted words per topic, the titles per topic, and the number of articles per topic over time. Each model output was evaluated against three criteria: (1) a minimum of 15 articles per topic, (2) topics started before 2010, and (3) the articles in a topic were largely derived from multiple journals and research groups (i.e. not from a single special issue). We determined 12 topics to best fit these criteria, providing a balance between capturing corpus complexity and interpretability. The final LDA model was fit with Gibbs sampling, 5000 iterations, and discarding the first 1000 runs using the R package *topicmodels* v 0.2 (Grün and Hornik, 2011).

The LDA model outputs two matrixes, the probability of words per topic and the probability of topics per abstract (Grün and Hornik, 2011). Each topic is defined by a set of co-occurring words. Then, each article is assigned to a topic based on the highest probability. Following protocols in Westgate *et al.* (2015) and Mair *et al.* (2018), the data were analysed for temporal trends of topics, topic co-occurrence within abstracts, and potential research strengths and weakness via a gap analysis.

## Analysis of the trends and relationships among topics

We used two indicators to investigate the publishing trends in hadal science. The first indicator was the total number of articles per topic and per theme. The second indicator was the change in the number of articles per topic to identify if the topic has been growing, declining, or steady over time. To do this, we fit a generalized linear mixed-effects model with a Poisson model and a log link (Westgate *et al*., 2015; Mair *et al*., 2018) using the R package *lme4* (Bates *et al*., 2015). For each topic, a positive slope indicated an increased number of articles published over time, and a positive intercept indicated a higher–than–average number of articles (Westgate *et al*., 2015; Mair *et al*., 2018).

As each abstract is a mixture of topics, we evaluated the frequency that pairs of topics co-occur within each abstract. The topic weights per abstract were log10-transformed and Euclidean distances were calculated. The resulting distances were scaled from zero to one, where zero indicates the pair never co-occurred and one denotes the pair always co-occurred (Mair *et al*., 2018). The pairwise matrix of topic co-occurrence was visualized with the R package *corrplot* v 0.84 (Wei and Simko, 2017).

To uncover the strengths and potential research gaps, we conducted a gap analysis among the 12 topics. We log 10-transformed the word weight per topic and topic weights per abstract, calculated their Euclidean distances, and normalized the results. In the product of the two matrixes, the highly ranked and dissimilar pairs were topics that shared few to no words and rarely co-occurred in articles (Westgate *et al*., 2015). The strongest (< 10% quantile) and weakest (> 90% quantile) connections between topics were visualized as a network diagram with the R package *circleplot* v 0.4.1 (Westgate, 2016).

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

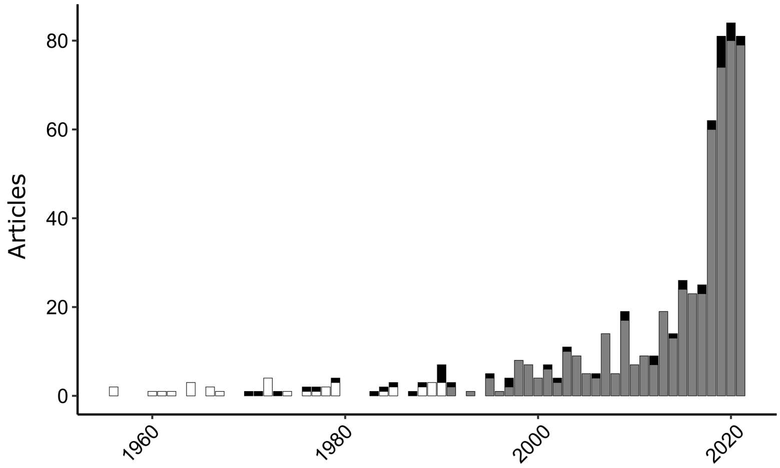

**Figure 2.** An exponential increase in the hadal science literature available on the Web of Science. Grey bars show the 520 hadal science articles with abstracts between 1970 and 2021 and represent the body of literature used for the topic modelling analysis. Black bars represent the 47 articles that lacked abstracts and were not included in the topic modelling analysis. White bars represent the 34 articles retrieved from the All Databases between 1950 and 1970 but lacked abstracts and were not part of the topic modelling analysis.

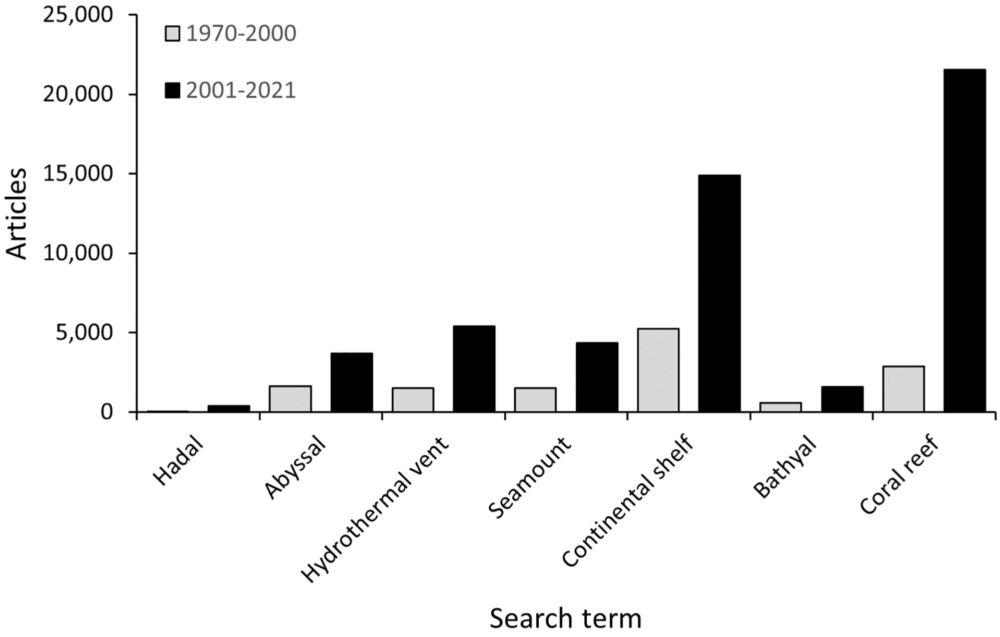

**Figure 3.** Marine ecosystem publication comparisons. The number of articles retrieved from the Web of Science Core Collection database between 1970 and 2000 (grey) and 2001 and 2021 (black) is based on a search of titles, abstracts, and author keywords.

## Results

### An exponential rise in hadal science literature

The number of hadal science publications, including peer-reviewed research papers, reviews, and conference proceedings, has exponentially increased since 1956, the earliest record of the search (Figure 2). The two literature searches resulted in 51 publications before 1991 and 567 after 1990. After 1990, 520 articles had abstracts and were the model inputs. The exponential rise in the publications started between 2007 and 2011, jumping from an average of 3.9 to 34.8 publications each year. Before 1996, some years lacked a single publication. Most of the articles were published in 2020, with 80 articles with abstracts and 4 articles without abstracts, closely followed by 2021, with 79 articles with abstracts and 2 articles without abstracts. A tabular summary of the 81 publications not included in the topic model analysis is found in Supplementary Table S1. A BibTex file of the 567 articles retrieved from Web of Science and the initial input for the topic modelling processing is provided in Supplementary Material S1.

The output of hadal zone research was 5–50-fold lower than other marine zones or ecosystems (Figure 3). To highlight this difference, between 1970 and 2021, the search term "hadal" retrieved 404 articles, while the shallower "abyssal" zone retrieved 5314 articles and "coral reef" 24408 articles.

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

### The hadal science literature is modelled into 12 topics covering 6 broad disciplines

Our topic modelling analysis was conducted on 1910 words found in 520 abstracts collated between 1991 and 2021 and the LDA model was fit for 12 topics. Each topic was named based on the top 20 stemmed words and article titles and further assigned to six broad themes based on the disciplines within ocean sciences: “Contextual”, “Ocean Engineering”, “Physical Oceanography”, “Chemical Oceanography”, “Geological Oceanography”, and “Biological Oceanography” (Table 1, with a full table in Supplementary Table S2). The majority of the articles were placed within the theme of “Biological Oceanography” across five topics, including the largest topic, *Biological diversity*, with 77 articles. The topics of *‘Omics*, *Bait-attending fauna*, and *Microbial communities* were above-average in the number of assigned articles ($> 43$ articles), and the topic of *Geographic & bathymetric patterns* had the lowest number within the theme. The theme of ‘Ocean Engineering’” included two topics, with the topic *Vehicles & sampling systems* being the second-largest topic ($n = 62$). The themes of “Geological, Chemical, and Physical Oceanography” each had a single topic, respectively *Geophysics & plate tectonics*, *Geochemistry*, *Circulation & bathymetry*. The topic of *Geochemistry* was the third most popular topic ($n = 58$). The theme of “Contextual” had the smallest topic, *Pressure adaptions* ($n = 18$). The two “Contextual” topics included words and article titles that were largely either multidisciplinary, field setting, or highlighted the uniqueness of the hadal zone.

### Scientific output is growing exponentially

The analysis of topic frequency allowed us to assess the temporal dimension of the publishing landscape, specifically the rise of topics from the lag to the exponential growth phase of hadal science (Figure 4). Across the study period, all topics have grown or remained steady over time. No topic has decreased in popularity. Two growth patterns were identified, exponential and stair-step. *Vehicles & sampling systems* and *Pressure adaptions* were the only topics present in 1991, whereas most topics first appeared between 1998 and 2004. *Perspectives & human influence* was the latest topic to appear, with the first article published in 2009. *Geochemistry* and *Microbial communities* were the two fastest-growing topics (highly positive slope), and the topics *Designing for full ocean depth* and *‘Omics* also grew. *Bait-attending fauna* and *Biodiversity discovery* have also grown since 2010, however, they displayed a stair-step growth pattern instead of a smooth exponential growth. *Vehicles & sample systems* showed an overall steady but boom-bust trend in the articles over time. *Geophysics & plate tectonics*, *Perspectives & human influence*, and *Geographic & bathymetric patterns* were non-growing topics, each averaging one to three articles per year with a single-year spike in the number of articles. *Pressure adaptions* was the slowest growing topic.

### Co-occurrence of topics and research gaps

The co-occurrence of topics and gap analysis allowed us to investigate the strength of the disciplinary and interdisciplinary connections within hadal science (Figure 5). The correlation matrix highlighted some expected and unexpected levels of co-occurrence (Figure 5a). The two Contextual topics were moderate to frequently co-occurred with other topics across the themes, which was expected given their high generality. Moreover, the highest co-occurrence was between *Pressure adaptions* and *Geographic & bathymetric patterns*, which was closely followed by *Circulation & bathymetry* and *Designing for full ocean depth* and *‘Omics* and *Microbial communities*. The highly specific topic of *Geophysics & plate tectonics* had moderate co-occurrence with most topics, particularly *Circulation & bathymetry* and *Designing for full ocean depth*. While high co-occurrence was initially expected within Biological Oceanography, *Biodiversity discovery* paired with *Microbial communities* and *‘Omics* had surprisingly low co-occurrence. *Biodiversity discovery* was also rarely paired with both Ocean Engineering topics, *Circulation & bathymetry*, and *Geochemistry*. Further, an unexpected disconnection was present between *Vehicles & sampling systems* and *Geochemistry* and the five Biological Oceanography topics, as these disciplines rely on vehicles to collect and recover samples from hadal depths.

We focused the presentation of the gap analysis on the pairs with the highest similarity, suggestive of research strengths, and highest dissimilarity, potentially representing research gaps (Figure 5b). *Microbial communities* and *Pressure adaptions* were hubs for high similarity both between each other and other topics. *Pressure adaption* was highly connected to *Perspective & human influence*, *‘Omics*, and *Designing for full ocean depth*. *Microbial communities* was tightly linked to *Geographic & bathymetric patterns* and *‘Omics*. In contrast, *Vehicles & sampling systems* was highly dissimilar with *Microbial communities*, *Geochemistry, Geophysics & plate tectonics*, *Geographic & bathymetric patterns*, and *‘Omics*. The topics of *Geochemistry* and *Biodiversity discovery* were also highly disconnected.

## Discussion

The most important finding is that research outputs from hadal science are exponentially growing with no indications of slowing, especially within biology and geochemistry. This growth signifies that the historical lack of technical capability that inhibited access to the deepest parts of our oceans no longer exists. However, studying the deepest parts of the ocean remains challenging—success first requires the expensive technical infrastructure to reach and sample the hadal zone, including ship time and resources for expeditions, and not least of all expertise to measure the environment, document biodiversity, and understand how life thrives in this high-hydrostatic pressure environment. With increasing direct and indirect pressures threatening the hadal zone, our gap analysis highlighted that more multifeatures studies and sampling systems and strengthening cross-disciplinary connections are essential to comprehensively understand the deepest marine frontier during the Ocean Decade.

### Hadal publishing timeline—a transition to exponential growth

The hadal science publishing landscape reflects the challenges to studying this remote marine zone, particularly with the low publication rate until the mid-2000s (Figure 2). The 1948 Swedish Albatross expedition proved that, despite the extreme conditions, life existed in the hadal zone with the first successful hadal trawl at the Puerto Rico Trench (Eliason, 1951; Nybelin, 1951; Madsen, 1955). From then, the global *Galathea*

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

**Table 1.** The 12 topics identified by the LDA topic model are listed by the Theme, topic name, number of abstracts, top 10 stemmed words, and a summary of topics based on the article titles.

| Theme | Topic | Topic number | No. of abstracts | Top 10 stemmed words | Summary description based on titles |
|---|---|---|---|---|---|
| Biological oceanography | Biodiversity discovery | 12 | 77 | speci, new, collect, describ, genus, kuril, famili, pacif, genera, mopholog | New species, new records, systematics, and general biodiversity at hadal features. Largely non-microbial fauna. |
| Biological oceanography | 'Omics | 6 | 49 | gene, sequenc, genom, analysi, mariana, relate, isol, strain, adapt, acid | Using genomic, transcriptomic, and proteomic techniques to study cellular to molecular adaptions to the hadal environment. A broad range of fauna from bacteria to fish. |
| Biological oceanography | Bait-attending fauna | 8 | 48 | amphipod, observ, kermadec, fish, speci, zone, mariana, new, found, food | Baited lander studies about amphipods, fishes, decapods, and other bait-attending fauna. Data includes physical specimens and images from stills and/or videos. |
| Biological oceanography | Microbial communities | 10 | 46 | communit, microbi, water, potenti, differ, sediment, studi, howev, associ, domin | Microbial (bacterial, virus, and archaea) communities, ranging from sediment to water column to microbiomes, and the ecosystem function of these communities. |
| Biological oceanography | Geographic & bathymetric patterns | 3 | 32 | abyss, divers, abund, differ, zone, station, region, sampl, area, pattern | Change in meiofauna to megafauna community assemblages across wide geographic ranges (sub-ocean basin transects) and from abyssal to hadal depths. |
| Chemical oceanography | Geochemistry | 11 | 58 | sediment, organ, carbon, water, matter, surfac, part, valu, higher, deposit | Studies on the inorganic and organic geochemistry of hadal sediments and water column, mass wasting events, material transport and deposition, isotopes, trace metals, and mercury. |
| Contextual | Perspectives & human influence | 2 | 26 | present, studi, environ, provid, recent, explor, global, biology, earth, understand | Largely field setting papes (e.g. defining the hadal zone). Summaries and reviews that track progress within the subsets of hadal science. Includes studies on anthropogenic impacts such as plastics, trash, and oil. |
| Contextual | Pressure adaptions | 4 | 18 | high, pressure, activ, low, extrem, increas, chang, condit, result, show | Collection of studies on the cellular, enzymatic, and morphological adaptions to high hydrostatic pressure. Include respiration studies and pressure testing. |
| Geological oceanography | Geophysics & plate tectonics | 1 | 24 | mariana, similar, subduct, observe, result, near, plate, data, region, pacif | Formation of subduction trenches and studies of plate tectonics at convergent boundaries. Includes studies on locations of hadal features. |
| Ocean engineering | Vehicles & sampling systems | 9 | 62 | system, vehicl, develop, oper, cabl, paper, submers, design, dive, underwater | Design, deployment, and loss of the hadal-rated vehicles and sampling systems, which includes human-occupied submarines, cabled systems, HROVs, landers, and sediment traps. |
| Ocean engineering | Designing for full ocean depth | 7 | 32 | sampl, method, pressure, test, use, process, element, base, provid, sampler | Engineering and design species of hadal-rates vehicles and sampling devices. |
| Physical oceanography | Circulation & bathymetry | 5 | 48 | use, data, degree, time, water, bottom, measur, estim, current, profil | Studies on circulation patterns, water column parameters, and the use of acoustics and multibeam systems to measure the depth and bathymetry of hadal features. |

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

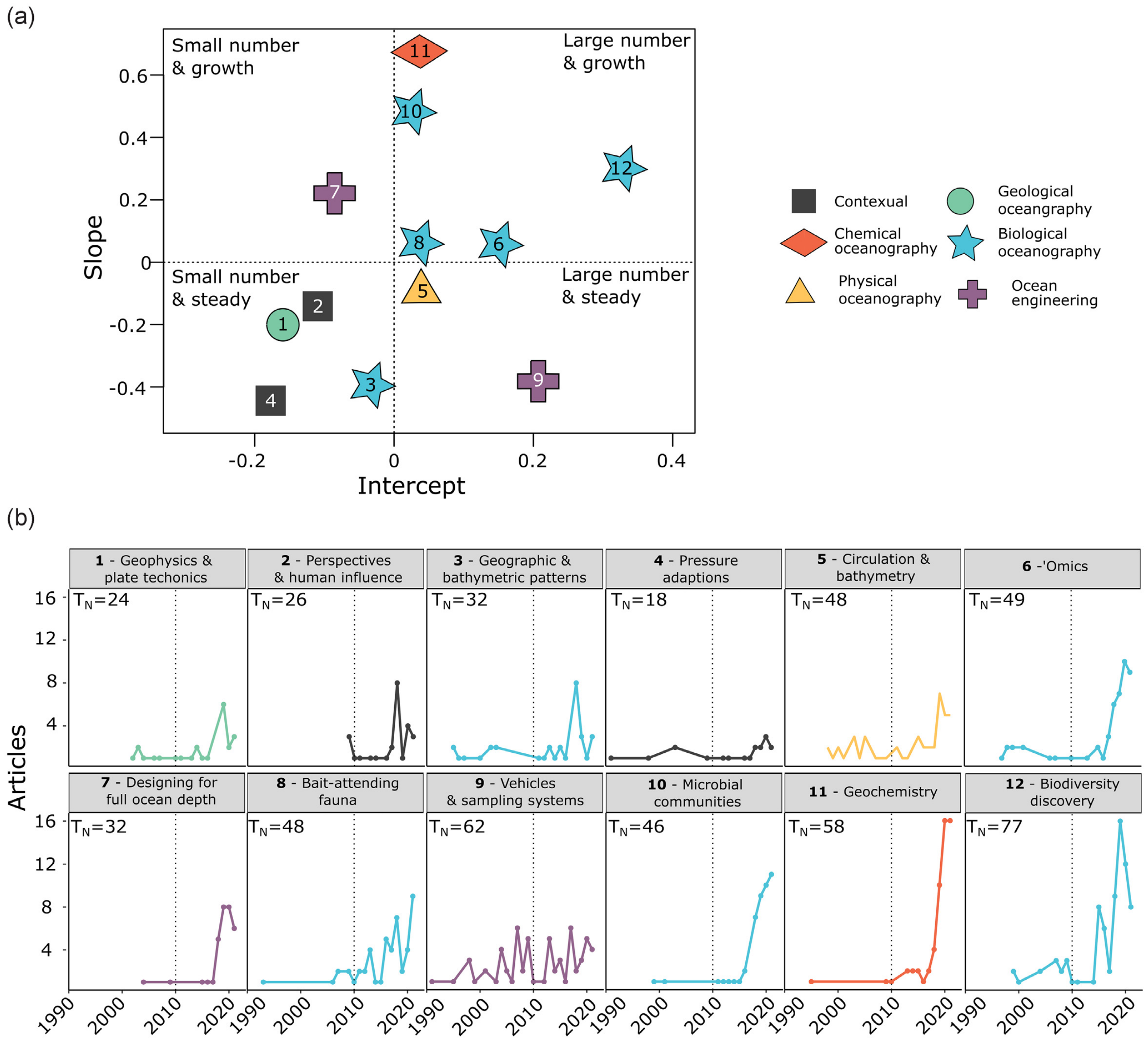

**Figure 4.** Publishing trends in hadal science over time. (a) Topics that have grown in the number of articles have a positive slope, while topics with a constant (or declining) publishing rate have a negative slope. Topics with a higher-than-average number of articles have a positive intercept, and those with a lower-than-average have a negative intercept. (b) Number of articles per topic over time. The dashed vertical line represents 2010 and $T_N$ denotes the total number of articles.

and *Vitjaz* expeditions of the 1950s jump-started the hadal literature with results based on trawl data, first reporting the presence of tanaids, isopods, fishes, and the wider faunal community (Wolff, 1956a, 1956b, 1959), and that life occurs to full ocean depth (Bruun, 1951). These first comprehensive expeditions provided a steady, albeit small, stream of publications, and set the foundation for taxonomy and systematics across all hadal taxa (Belyaev, 1966, 1989). Most importantly, these expeditions provided numerous hypotheses about the dynamics of hadal ecosystems, which are only being tested with modern expeditions. For example, Wolff (1970) proposed that the hadal faunal community was distinct from the abyssal plains, where trench communities exhibited large degrees of endemism, driven by both pressure tolerance and more favourable feeding conditions. The community difference has been further tested and represents an ecotone shift for amphipods, fishes, and microbes at hadal depths (Jamieson *et al.*, 2011; Nunoura *et al.*, 2015; Tarn *et al.*, 2016; Linley *et al.*, 2017) and most recently investigated in fracture zones (Weston *et al.*, 2021). Another example is Wolff (1960) first inferred that hadal trenches supported elevated community biomass relative to the neighbouring abyssal plains. Since then, hadal trenches have been shown to transport organic material at the trench axis and hotspots for early diagenesis (Ichino *et al.*, 2015; Glud *et al.*, 2021). These early papers also led to hypotheses on the antiquity and evolutionary origin of hadal fauna (Andriashev, 1953; Zenkevitch and Birstein, 1953) as highlighted by the *'Omics* topic; this hypothesis is now being coming testable with more extensive specimen collections and the application of genomic techniques.

In the 1990s, hi-tech exploration was being tested with the development and use of the JAMSTEC ROV Kaikō, which became the second vehicle, and the first scientific vehicle, to reach Challenger Deep. ROV Kaikō could collect sediment, which

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

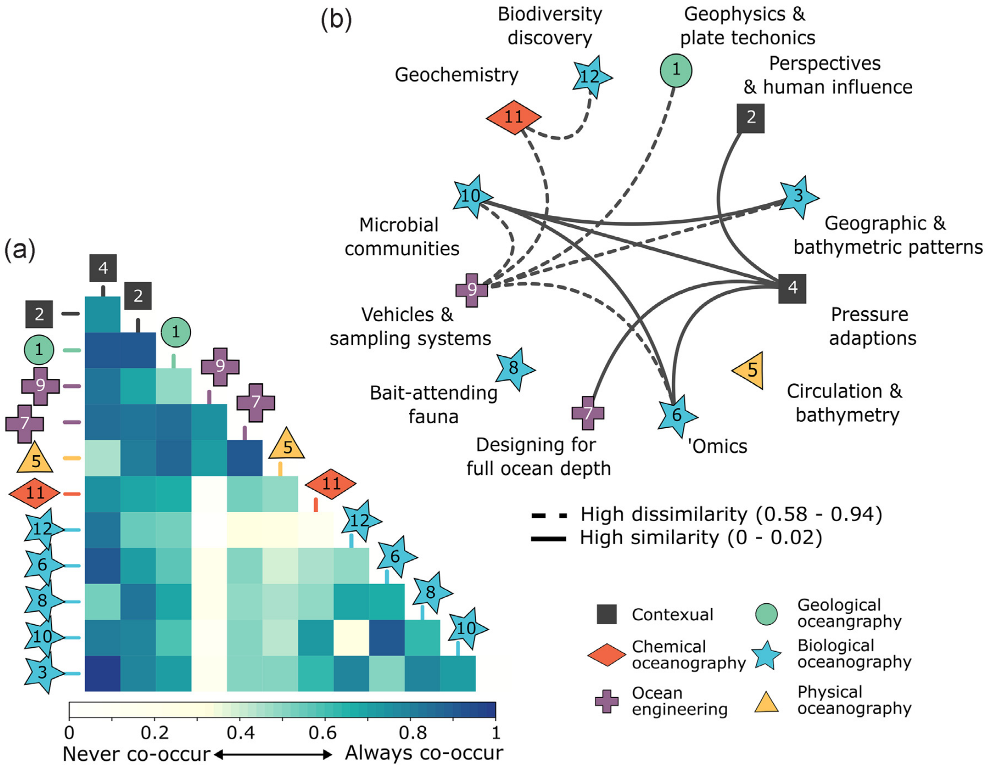

**Figure 5.** Similarity and differences among topics. (a) Correlation matrix of the co-occurrence of topics within abstracts. White/zero indicates that the two topics never co-occurred in an abstract, while dark blue/one denotes that the pair of topics always co-occurred. (b) Gap analysis within the hadal science literature. High similarity (solid line) between topics indicates that words and topics are highly shared within abstracts, indicating research strengths. High dissimilarity (dashed line) between topics represents a lack of shared words and topics within abstracts, suggestive of research gaps.

led to a series of studies on extremophilic microbes and protists (Kyo *et al.*, 1995; Kato *et al.*, 1997, 1998; Akimoto *et al.*, 2001; Barry and Hashimoto, 2009). The loss of ROV Kaikō during a typhoon in 2003 (Momma *et al.*, 2004) highlighted the high cost and risk of loss of large exploratory vehicles and the dramatic effect that the loss of one vehicle could make on an emerging research field. Unfortunately, this type of loss and impact repeated itself with the HROV Nereus in 2014 (Cressey, 2014).

Since 2006, the technological advances in collecting physical samples and making *in situ* measurements have generated larger and comparative datasets, which has directly translated into an exponential growth of the publishing landscape (Figure 2). This resurgence in hadal research has been in part driven by the extensive use of free-fall lander vehicles, due to their lower financial risk to reward ratio compared to ROVs and human-occupied vehicles, the lack of cabling attached to the surface vehicle, which allows them to be deployed and recovered from smaller vessels, and well-suited to complex topography (Jamieson, 2016). Landers have been used across disciplines, including being fitted with still and video cameras that inspect sediment characteristics (Stewart and Jamieson, 2018) and document the diversity and behaviour of bait-attending fauna *in situ* (Jamieson *et al.*, 2013, 2021a; Linley *et al.*, 2017; Jamieson and Vecchione, 2020; Swan *et al.*, 2021), baited traps to collect specimens with minimal physical damage to their body (Lacey *et al.*, 2016; Gerringer *et al.*, 2017b), sediment samplers to recover intact sediment cores (Oguri *et al.*, 2013) and water samples (Nunoura *et al.*, 2016), and $O_2$ profilers to measure rates of benthic respiration rates (Glud *et al.*, 2013; Wenzhöfer *et al.*, 2016). This preferential use of landers is translated within the corpus to the dedicated topic of *Bait-attending fauna* and the fast-paced growth of *Geochemistry* and *Microbial communities* (Figure 4b). In addition to lander-based studies, box corers and epibenthic sledges have been deployed as part of sampling expeditions at the Kuril–Kamchatka Trench and surrounding abyssal plains and transecting across the Mid-Atlantic Ridge from the Vema Fracture Zone to the Puerto Rico Trench (Brandt and Malyutina, 2015; Riehl *et al.*, 2018; Brandt *et al.*, 2020). A high number of these expeditions outputs were sorted into *Biodiversity discovery* and *Geographic & bathymetric patterns* for an extensive range of taxa.

The publishing trends of the theme of "Ocean Engineering" show that continual efforts are being taken to engineer a range of vehicle types to overcome the challenges of studying the hadal zone (Figure 4b). Remarkably before 2019, only two human-occupied vehicles had been to the deepest point on Earth, Challenger Deep (i.e. the bathyscaphe *Trieste* and the submarine *Deepsea Challenger*), albeit there has been hadal depth dives with the *Shinkai* 6500 (Takagawa *et al.*, 1989) and the bathyscape *Archimède* (Jarry, 2003; Jamieson, 2020). This relative lack of submersibles has shifted with the recent development of two full-ocean-depth rated and human-occupied submersibles, the DSV *Limiting Factor* with the adjoining circumglobal Five Deeps and Ring of Fire expeditions 2018–2022 (Jamieson *et al.*, 2019) and the *Fendouzhe* submersible (Du *et al.*, 2021). Further, there are several new remote exploratory vehicles (e.g. *Orpheus*; Shank *et al.*, 2019, *Haidou-1*; Cong *et al.*, 2021), full ocean depth multibeam sonar technologies (Bongiovanni *et al.*, 2021), and the vision to extend the Argo Program to full ocean depth (Roemmich *et al.*, 2019).

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

These recent and significant advances on the horizon in technological abilities to reach, sample the water column, and survey the seafloor are anticipated to bring substantial expansion to the hadal science literature.

## The strengths and drivers of hadal science growth

Our topic modelling analysis has highlighted that hadal science is ongoing across all five broad fields of oceanography and engineering, with the expansion largely driven by research into the geochemistry of trenches (*Geochemistry*), the functions of microbial communities in the sediment, water, and microbiomes (*Microbial communities*), the unique biodiversity inhabiting these ecosystems (*Bait-attending fauna* and *Biodiversity discovery*), and the utilization of genomics, metabarcoding, and transcriptomics to understand hadal life at the genetic and cellular level (*'Omics*) (Figure 4).

Although no topic decreased in popularity, *Pressure adaptions* was the slowest growing and smallest topic (Figure 4b; Table 1). Adaptation to high hydrostatic pressure is such a significant prerequisite to the colonization and survival of hadal fauna that this was unexpected. However, *Pressure adaptions* was represented since 1991, highly co-occurrence with the other topics (Figure 5a), and strikingly, high similarity with "Biological Oceanography" and "Ocean Engineering" topics (Figure 5a). The articles assigned to this topic were also varied across scales, ranging from pressure-tolerant metabolites and enzymes (e.g. Gerringer *et al.*, 2017a; Kaleem *et al.*, 2020) and diverse organisms, including bacteria, stalked crinoids, holothurians, amphipods, and fishes (Oji *et al.*, 2009; Kobayashi *et al.*, 2012; Downing *et al.*, 2018; Li *et al.*, 2018; Gerringer *et al.*, 2020). Yet, the steady growth of this topic may also result from a bias towards visual imaging by hadal-rated landers and vehicles, and the relatively low diversity of taxa obtained by baited traps [e.g. fishes (Gerringer *et al.*, 2017b) and amphipods (Lacey *et al.*, 2016)], which are currently commonplace. It is still generally not feasible to bring live specimens to the surface, thus controlled experimentation is excluded. Overall, *Pressure adaptions* trends with other topics do then reflect its research core within hadal science.

This reliance on so few technologies and limited expeditions to sample the hadal zone is evidenced as the growth of *Bait-attending fauna* and *Biodiversity discovery* displayed a stair-step growth in contrast to smooth exponential growth (Figure 4b). This is mirrored in the topic of *Vehicles & sampling systems* that showed an overall boom-bust trend in the articles over time (Figure 4b). In essence, a new technology comes online, is used to generate new research, which is published and then in some cases that technology is lost or is superseded by the next generation, which prompts another increase in publications. The stair-step is only visible because there are so few technologies in the global pool. As more technologies arise at a more frequent pace, the stair-step trends will likely smooth.

One such example is in the topics of *Geochemistry*, *Microbial communities,* and *'Omics,* which were the three fastest-growing topics (Figure 4b). These sudden increases are in part accounted for by the significant investment by China in hadal infrastructure, with a strong focus on the Mariana Trench (Cyranoski, 2016). To highlight, 40 of the 79 papers published in 2021 were from Chinese scientists, largely on Mariana Trench and 26 were geochemistry or microbial studies (i.e. 56% *Geochemistry*, 88% *'Omics*, and 82% *Microbial communities*). The rise in *'Omics* was strongly connected with *Microbial communities* (Figure 5), which indicates the importance of decreased sequencing cost and increased availability of techniques to answer questions at the molecular and cellular levels. In addition to single cellular species, the topic of *'Omics* also included multicellular organisms such as amphipods and snailfishes (e.g. Ritchie *et al.*, 2018; Li *et al.*, 2019; Mu *et al.*, 2021). We anticipate the topic of *'Omics* to continue to rise and become more tightly linked with other "Biological Oceanography" topics as these techniques are essential to understanding the eco-evolutionary dynamics of life across the hadal zone.

The influence of technology on topic output trends is also evidenced in *Geophysics & plate tectonics* and *Circulation & bathymetry*, as steady but non-growing topics (Figure 4). These subjects are largely based upon ship-mounted technology, and not reliant on expensive, experimental, and rare hadal-rated vehicles. Further, as submersibles and landers are intrinsically linked to the benthos few circulation models extend to full ocean depth and few studies in the hadopelagic beyond microbial studies from water samples. The most comprehensive assessment of the hadopelagic is six decades old (Vinogradov, 1961). Expanding research on these topics in the future is highly pertinent. As several seismically active trenches are located near land (e.g. Peru–Chile, Japan, and Java trenches), understanding subduction dynamics is essential for earthquake and tsunami preparedness, as well as implications for the carbon cycle (Kioka *et al.*, 2019b). Within the topic of *Circulation & bathymetry,* the potential for full ocean depth Argo floats will fill a critical data to understand ecosystem implications for a warming deep ocean (Brito-Morales *et al.*, 2020a; Meinen *et al.*, 2020), leading to the inclusion of the hadal zone in ocean modelling. From an ecological perspective, understanding hadal circulation is important to investigations of dispersal and connectivity within and among hadal features (Ritchie *et al.*, 2017; Weston *et al.*, 2021).

The relative late emergence of *Perspectives & human influence* as a topic in hadal science is perhaps not surprising given it is a very contemporary topic that is emerging across all environmental sciences (Haunschild *et al.*, 2016; Ramírez-Malule *et al.*, 2020; Sorensen and Jovanović, 2021) (Figure 4). While attention had been raised to the need for trench conservation (Angel, 1982), studies of contamination or pollution in sediment or animals and observations of litter on the seafloor are often incidental studies, where the observations are made in the pursuit of other research objectives. The topic of *Perspectives & human influence* also highlighted that the hadal zone is the last marine frontier and thus an overlooked zone within ocean science. As such, many of the articles are focused on introducing and bringing attention to the hadal zone (Blankenship-Williams and Levin, 2009; Jamieson *et al.*, 2010). Interestingly, several articles within our corpus were not hadal-based studies but did contextually reference the hadal zone within the abstract. For example, Frýda *et al.* (2011) describe an Early Devonian tryblidian and highlight that modern-day species inhabit the hadal zone. By providing introductions, *Perspectives & human influence* showed that hadal science, while relatively small is reflective, with multiple reviews, discussions of development, and future strategies (Cui and Wu, 2018; Jamieson, 2018; Xu *et al.*, 2018), which may indicate the desire for the hadal science to be strategic given the high-resource cost.

The fundamental drivers of topic trends over time (increasing, stair-step increasing, or steady but non-growing) are all

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

underpinned by the technology and the frequency of expeditions. *Geochemistry* and *Microbial communities* are increasing as numerous studies can be derived from core samples taken by lander or submersible, whereas understanding pressure adaptations across multiple taxa is hampered by a lack of diversity that can be readily sampled at such depths. Furthermore, the current reliance on submersibles and landers is distinctively lacking in seasonal or inter-annual studies. While there are a few long-term studies in hydrography (Taira *et al.*, 2004; van Haren, 2020), there has yet to be any attempt at monitoring hadal communities for long periods. The gap analysis showed high dissimilarity among *Vehicles & sampling systems* and the topics within all four Oceanography themes (Figure 5b). Therefore, the gaps are likely derived from research topics that require samples or datasets that are not easily obtained from contemporary vehicles, and expanding research requires the capability to recover more samples and conduct *in situ* experiments across the hadal zone.

## Gaps within hadal science

While topic modelling illustrates an expansion of hadal research, these efforts have largely focused on one location. The underlying location bias resulted from the search terms "full ocean depth", "deep∗ ocean trench", and "Challenger Deep." These search terms increased the number of abstracts that were not captured by the term "hadal" at the expense of largely focusing the corpus on the Mariana Trench and more specifically the Earth's deepest point, Challenger Deep. This bias has been coined as the "Challenger Deep effect" (Jamieson, 2018). Further, Jamieson (2018) warned that focusing on one location would hinder progress in understanding the complexity across the entire hadal zone. The place terms, such as "kermadec" within *Bait-attending fauna* and "kuril" within *Biodiversity discovery*, do illustrate that substantial research does exist outside of the Mariana Trench. However, knowledge gaps are present. This gap is readily seen with recently resolved uncertainty with the deepest location in each ocean and poorly resolved bathymetric maps (Stewart and Jamieson, 2019). Further, vast swathes of the hadal zone remain unexplored and unstudied (Jamieson, 2018), especially with non-subduction features and hadal features outside the Pacific Ocean (Stewart and Jamieson, 2019; Weston *et al.*, 2021). Meanwhile, the Mariana Trench has undergone an immense degree of scrutiny regarding simply how deep it is (Fujimoto *et al.*, 1993; Gardner *et al.*, 2014; van Haren *et al.*, 2017; Bongiovanni *et al.*, 2021; Greenaway *et al.*, 2021).

Although rapidly growing, hadal science still lags behind other marine zone and ecosystems, as evidenced in the bulk number of publications (Figure 3). Further, disciplines and topics were absent from topic modelling outputs, which are present in more established fields (Mair *et al.*, 2018; Costa *et al.*, 2020). These absences are critical to highlight at the start of the Ocean Decade, especially with the recognition of the threats to the deep sea from multiple direct and indirect pressures (Ramirez-Llodra *et al.*, 2011; Howell *et al.*, 2020). While the topic of *Perspectives & human influence* included anthropogenic impacts, from microplastic contamination to halogenated organic pollutants (Jamieson *et al.*, 2017; Peng *et al.*, 2018; Blum *et al.*, 2020; Cui *et al.*, 2020), topics or words related to conservation, management, and climate change were noticeably absent. Further, the high disconnect between *Geochemistry* and *Biodiversity discovery* indicates knowledge gaps between organisms, species, and communities with their hadal environment (Figure 5b). Climate change, a warming deep ocean, and the predicted cascading effects do pose a serious threat to the hadal zone communities (Levin and Bris, 2015; Brito-Morales *et al.*, 2020b). These communities are intrinsically linked to surface-derived food supply and the organisms are highly evolved to the low-temperature conditions (Smith *et al.*, 2008; Gerringer, 2019; Meinen *et al.*, 2020).

Danovaro *et al.* (2020) conducted an expert elicitation to identify the most important ecological variables needed to manage and conserve the deep sea. We can compare the state of hadal science to those top identified ecologies variables for five scientific areas. For "Biodiversity", the essential ecological variables were identified classifying and quantifying macro- and meso-zooplankton in the water column, macro- and mega-fauna in the sediment, and measuring community composition and species distributions. As evidenced from topic modelling, these biodiversity variables are within the strengths of hadal science (e.g. the topics of *Biodiversity discovery*, *Baited-lander fauna*, *Microbial communities*, and *Geographic & bathymetric patterns*). However, the studies within these topics have been largely one-off sampling events at a fixed lander point and often lack multidepth and multitrench sampling, and never seasonally or inter-annually. The essential variables for "Ecosystem functions" are trophic structure and benthic faunal biomass. Several studies have investigated the trophic structure and food webs (Blankenship and Levin, 2007; Liu *et al.*, 2020; Tokuda *et al.*, 2020), putting hadal science on track to monitor these values. However, these studies only provided a limited snapshot for that one hadal feature. Hadal science is severely lacking in the remaining three scientific areas, namely "Impact/risk assessment", "Global change, adaption, and evolution", and "Conservation". The essential ecological variables for these scientific areas are dependent on having a baseline to track changes over time, such as habitat loss, population size, and species distribution, which are only able to be measured through repeated sampling strategies. Another key variable is the identification of vulnerable habitats. Arguably, discovery is still ongoing for all the types of hadal habitats present (Stewart and Jamieson, 2018). Furthermore, given that trenches are depocenters of material, pollution will only increase in these enclosed ecosystems that host endemic species (Peng *et al.*, 2020). It could be reasonable to classify large portions of the hadal zone as a vulnerable habitat.

The topic modelling approach allowed us to distil and gain an overarching view of the past 30 years of hadal research. Yet, there are considerations given that topic modelling has typically been predominantly applied to a larger corpus, with > 1000 articles and > 20 topics (Westgate *et al.*, 2015; Greenville *et al.*, 2017; Mair *et al.*, 2018), yet not exclusively, as Tulloch *et al.* (2016) analysed 641 articles within the species distribution model literature. With a smaller corpus, one consideration was capturing the highest number of articles. With the small size of hadal literature, we included reviews and conference proceedings, as these articles do reflect a time point within hadal science. Some articles are not captured by the Web of Science search, particularly papers published in Russian and those lacking the search terms in the title, abstract, or keywords (e.g. Shimanaga and Yanagi (2016) on litter in the Ryukyu Trench). To not introduce bias, we adhered to the results from search terms. Given both the size and

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

temporal dynamics of the hadal corpus, the number of topics was given much consideration. This step is critical as the number of topics influences the interpretation of patterns in the corpus (Westgate *et al.*, 2015). We found that > 15 topics lead to splitting or over-subdividing of topics, reducing the overall explanatory power. For example, with 18 topics, there were topics for both new species and new records of known species, yet new records only spanned between 2016 and 2020. Opposingly, fewer than eight topics resulted in an over-lumping of topics. Based on our developed criteria, we chose 12 topics to best capture the complexity of the corpus, although the optimal number of topics is likely between 10 and 14 topics. Our results do demonstrate that topic modelling can be applied to a small corpus to qualitatively track research changes over time, with strong attention paid to the search terms that maximize the recovered articles and selection of comparatively few topics.

### Recommendations for the future of hadal science

By conducting a broad assessment of hadal science through the literature, we targeted the research strengths within the field, and importantly identified gaps and the drivers thereof. This reflection, at the start of the UN's Ocean Decade, allows for the projection of research avenues and directions for the next 30 years of hadal science. Thus, we propose three recommendations for future hadal research.

The first recommendation is to conduct multifeature sampling that spans seismic and aseismic features of various geomorphologies (trench, trough, fracture zone, basin, etc.). As each hadal habitat has unique feature-specific conditions and hosts high levels of endemic biodiversity, it is critical to discover the species that live there and then contextualize the role of depth, feature type, and local environmental conditions on those ecosystems. Studies should resist focusing on the deepest point and capture the changes across the entire hadal depth range and connections to the surrounding abyssal plains. Non-subduction (aseismic) features and features outside of the Pacific Ocean have been under-represented in the literature, largely because most hadal trenches are in the western Pacific (Stewart and Jamieson, 2018). Future research expeditions should endeavour to include non-subduction hadal features, particularly those nearby or adjoining larger subduction features. Expeditions such as the Five Deeps and the Ring of Fire expeditions have begun to provide a strong example of the benefits of global multifeature and depth studies. For example, a multitrench assessment of fish, gelatinous organisms, and decapods are revealing contrasting diversity of families within different trenches and shifts in vertical distribution that appear driven by local bottom temperature and oxygen (Jamieson *et al.*, 2021a, 2021b; Swan *et al.*, 2021). Further, there is a growing body of papers demonstrating even large and conspicuous animal groups, such as the octopods and squids (Jamieson and Vecchione, 2020, 2022), are present at hadal depths, but so far discovered in a limited number of trenches. Therefore, these trends of presence/absences and the documenting of the geographic and bathymetric distribution of fauna only become apparent in multifeature studies.

The second recommendation is to conduct seasonal or long-term sampling of select hadal features. With the technological and logistical challenges associated with conducting hadal science, most sampling effort is focused on one-time campaigns to a feature. While there are many campaigns to Challenger Deep, they often occur by different research groups and are not designed for comparability. Both situations have resulted in a gap in tracking and understanding temporal dynamics at hadal depths. With engineering and technological innovation strongly embedded within hadal science, future directions should aim to develop a long-term sampling strategy and install hydrographic observations/moorings (e.g. Itou *et al.*, 2000). Within this strategy, a focus should be given to capturing large events, such as mass wasting following earthquakes, rather than simply examining the after-effects (Oguri *et al.*, 2013; Bao *et al.*, 2018; Kioka *et al.*, 2019a), that might be rare but have extensive implications for biological succession, trophic coupling and element cycling (Bigham *et al.*, 1893; Heezen *et al.*, 1955). A long-term sampling strategy will simultaneously be essential for developing a baseline for identifying and tracking the impacts of global change.

Finally, the third recommendation is to strengthen the disciplinary and cross-disciplinary connections existing within hadal research. While this recommendation may seem obvious, it is essential to accelerate the elucidation of important ecological aspects in which to contextualize with the wider ocean environment. The hadal zone is an inherently dynamic suite of ecosystems, where the physical, chemical, and biological are closely intertwined across geographic space and time, and each discipline faces similar logistical challenges. Given the multiple impacts and grand challenges facing the deepest marine zone, the future of hadal science should continue to expand with cross-disciplinary research projects, teams, and missions that leverage the global expertise of engineers, geologists, oceanographers, geochemists, and biologists.

## Supplementary Data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

## Conflict of interest statement

The authors declare no conflict of interest within this manuscript.

## Author contribution

Both authors contributed to the conceptualization, interpretation, and writing and editing of this work. Johanna Weston conducted the topic modelling and data analysis.

## Data availability

The data underlying this article are available in the article and in its online supplementary material.

## Acknowledgements

We are grateful to Louise Mair (Newcastle University, UK) for sharing her topic modelling code and knowledge and Danielle Robinson (Newcastle University) for coding support. More generally, we are appreciative of all the scientists and engineers who have asked, are asking, and will ask questions focused on the deepest depths of the ocean and the captains and crew of the vessels sailing us there. We are appreciative of the thorough, insightful, and constructive comments from the three reviewers and the editor, which greatly improved this work.

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

## References

Akimoto, K., Hattori, M., Uematsu, K., and Kato, C. 2001. The deepest living *Foraminifera*, challenger deep, Mariana trench. Marine Micropaleontology, 42: 95–97.

Andriashev, A. P. 1953. Archaic deep-sea and secondary deep sea-fishes and their role in zoogeographical analysis. Essays on the General Problems of Ichthyology, 58: 64.

Angel, MV. 1982. Ocean trench conservation. The Environmentalist, 2: 1–17.

Aria, M., and Cuccurullo, C. 2017. Bibliometrix: an R-tool for comprehensive science mapping analysis. Journal of Informetrics, 11: 959–975.

Arun, R., Suresh, V., Madhavan, C. E. V., and Murty, M. N. 2010. On finding the natural number of topics with Latent Dirichlet Allocation: Some Observations. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 6118 LNAI. 391–402. Springer, Berlin, Heidelberg. https://link.springer.com/chapter/10.1007/978-3-642-13657-3_43, (Accessed 21 April 2022).

Bao, R., Strasser, M., McNichol, A. P., Haghipour, N., McIntyre, C., Wefer, G., and Eglinton, T. I. 2018. Tectonically-triggered sediment and carbon export to the hadal zone. Nature Communications, 9: 1–8.

Barry, J. P., and Hashimoto, J. 2009. Revisiting the challenger deep using the ROV Kaiko. Marine Technology Society Journal, 43: 77–78.

Bates, D., Mächler, M., Bolker, B. M., and Walker, S. C. 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67: 1–48.

Belyaev, G. 1966. Bottom Fauna of the Ultraabyssal Depths of the World Ocean. (In Russian). Trudy Instituta Okeanologii Akademija Nauk S.S.S.R. 1–247. Moscow

Belyaev, G. M. 1989. Deep-sea Ocean Trenches and their Fauna. Nauka Publishing House, Nauka, Moscow.

Bigham, K. T., Rowden, A. A., Leduc, D., and Bowden, D. A. 1893. Review and syntheses: impacts of turbidity flows on deep-sea Benthic communities. Biogeosciences, 18: 1893–1908.

Blankenship, L. E., and Levin, L. A. 2007. Extreme food webs: foraging strategies and diets of scavenging Amphipods from the ocean's deepest 5 kilometers. Limnology and Oceanography, 52: 1685–1697.

Blankenship-Williams, L. E., and Levin, L. A. 2009. Living deep: a synopsis of hadal trench ecology. Marine Technology Society Journal, 43: 137–143.

Blum, J. D., Drazen, J. C., Johnson, M. W., Popp, B. N., Motta, L. C., and Jamieson, A. J. 2020. Mercury isotopes identify near-surface marine mercury in deep-sea trench biota. Proceedings of the National Academy of Sciences, 117: 29292–29298.

Bongiovanni, C., Stewart, H. A., and Jamieson, A. J. 2021. High-resolution multibeam sonar bathymetry of the deepest place in each ocean. Geoscience Data Journal. 00: 1–16.

Bowen, A. D., Yoerger, D. R., Taylor, C., McCabe, R., Howland, J., Gomez-Ibanez, D., Kinsey, J. C. *et al.* 2009. The nereus hybrid underwater robotic vehicle. Underwater Technology, 28: 79–89.

Brandt, A., Brix, S., Riehl, T., and Malyutina, M. 2020. Biodiversity and biogeography of the abyssal and hadal Kuril-Kamchatka trench and adjacent NW Pacific deep-sea regions. Progress in Oceanography, 181: 102232.

Brandt, A., Elsner, N., Brenke, N., Golovan, O., Malyutina, M. v., Riehl, T., Schwabe, E. *et al.* 2013. Epifauna of the Sea of Japan collected via a new epibenthic sledge equipped with camera and environmental sensor systems. Deep Sea Research Part II: Topical Studies in Oceanography, 86–87: 43–55.

Brandt, A., Gutt, J., Hildebrandt, M., Pawlowski, J., Schwendner, J., Soltwedel, T., and Thomsen, L. 2016. Cutting the umbilical: new technological perspectives in Benthic deep-sea research. Journal of Marine Science and Engineering, 4: 36.

Brandt, A., and Malyutina, M. v. 2015. The German–Russian deep-sea expedition Kurambio (Kurile kamchatka biodiversity studies) on board of the RV sonne in 2012 following the footsteps of the legendary expeditions with RV vityaz. Deep Sea Research Part II: Topical Studies in Oceanography, 111: 1–9.

Brito-Morales, I., Schoeman, D. S., Molinos, J. G., Burrows, M. T., Klein, C. J., Arafeh-Dalmau, N., Kaschner, K. *et al.* 2020. Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. Nature Climate Change 10: 576–581.

Brito-Morales, I., Schoeman, D. S., Molinos, J. G., Burrows, M. T., Klein, C. J., Arafeh-Dalmau, N., Kaschner, K. *et al.* 2020. Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. Nature Climate Change 10: 576–581.

Bruun, A. 1951. The Philippine trench and its bottom fauna. Nature, 168: 692–693.

Bruun, A. 1956. Animal life of the deep sea bottom. The Galathea Deep Sea Expedition, 1950-1952, pp. 157–170. Ed. by A. Bruun, S. Greve, H. Mielche, and R. Sparck. George Allen and Unwin LTD, London.

Cao, J., Xia, T., Li, J., Zhang, Y., and Tang, S. 2009. A density-based method for adaptive LDA model selection. Neurocomputing, 72: 1775–1781. Elsevier.

Chan, J., Pan, B., Geng, D., Zhang, Q., Zhang, S., Guo, J., and Xu, Q. 2020. Genetic diversity and population structure analysis of three deep-sea Amphipod species from geographically isolated hadal trenches in the Pacific ocean. Biochemical Genetics, 58: 157–170.

Cong, Y., Gu, C., Zhang, T., and Gao, Y. 2021. Underwater robot sensing technology: A survey. Fundamental Research, 1: 337–345. Elsevier.

Core Team, R. 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Costa, C., Fanelli, E., Marini, S., Danovaro, R., and Aguzzi, J. 2020. Global deep-sea biodiversity research trends highlighted by science mapping approach. Frontiers in Marine Science, 7: 384.

Cressey, D. 2014. Submersible loss hits research. Nature, 509: 408–409.

Cui, J., Yu, Z., Mi, M., He, L., Sha, Z., Yao, P., Fang, J. *et al.* 2020. Occurrence of halogenated organic pollutants in hadal trenches of the western Pacific ocean. Environmental Science & Technology, 54: 15821–15828.

Cui, W. 2018. An overview of submersible research and development in China. Journal of Marine Science and Application, 17: 459–470.

Cui, W., and Wu, X. 2018. A Chinese strategy to construct a comprehensive investigation system for hadal trenches. Deep Sea Research Part II: Topical Studies in Oceanography, 155: 27–33.

Cyranoski, D. 2016. What China's latest five-year plan means for science. Nature, 531: 424–425.

Danovaro, R., Fanelli, E., Aguzzi, J., Billett, D., Carugati, L., Corinaldesi, C., Dell'Anno, A. *et al.* 2020. Ecological variables for developing a global deep-ocean monitoring and conservation strategy. Nature Ecology & Evolution 4: 181–192.

Danovaro, R., Snelgrove, P. V. R., and Tyler, P. 2014. Challenging the paradigms of deep-sea ecology. Trends in Ecology & Evolution, 29: 465–475.

Downing, A. B., Wallace, G. T., and Yancey, P. H. 2018. Organic osmolytes of Amphipods from littoral to hadal zones: increases with depth in *Trimethylamine N-oxide*, scyllo-inositol and other potential pressure counteractants. Deep Sea Research Part I: Oceanographic Research Papers, 138: 1–10.

Du, M., Peng, X., Zhang, H., Ye, C., Dasgupta, S., Li, J., *et al.* 2021. Geology, environment, and life in the deepest part of the world's oceans, The Innovation, 2: 100109. Cell Press.

Eliason, A. 1951. Polychaeta. Reports of the Swedish Deep-Sea Expedition, 2, Zoology. 11: 130–148.

Feinerer, I., Hornik, K., and ,Meyer d, D. 2008. Text mining infrastructure in R. Journal of Statistical Software, 25: 1–54.

France, S. C. 1993. Geographic variation among three isolated population of the hadal amphipod hirondellea gigas (*Crustacea: Amphipoda: Lysianassoidea*). Marine Ecology Progress Series, 92: 277–287.

Frýda, J., Blodgett, R. B., Lenz, A. C., and Frýdová, B. 2011. Jardamarekia enigma, a new early devonian *Tryblidioidean* from royal creek area (Yukon Territory, Canada), and paleobiogeography of the early devonian of northwestern Canada. Zootaxa, 2905: 57–62.

Fujimoto, H., Fujiwara, T., Kong, L., and Igarashi, C. 1993. Sea Beam Survey Over The Challenger Deep Revisited. Preliminary Report of

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

The Hakuho-Maru Cruise KH92-1. Ocean Research Institute, the University of Tokyo, Tokyo. pp. 26–27 .

Gardner, J. V., Armstrong, A. A., Calder, B. R., and Beaudoin, J. 2014. So, How Deep is The Mariana Trench?. Marine Geodesy, 37: 1–13.

Gerringer, M. E. 2019. On the success of the hadal snailfishes. Integrative Organismal Biology, 1: 1–18

Gerringer, M. E., Drazen, J. C., and Yancey, P. H. 2017. Metabolic enzyme activities of abyssal and hadal fishes: pressure effects and a re-evaluation of depth-related changes. Deep Sea Research Part I: Oceanographic Research Papers, 125: 135–146.

Gerringer, M. E., Linley, T. D., Jamieson, A. J., Goetze, E., and Drazen, J. C. 2017b. *Pseudoliparis swirei* sp. Nov.: a newly-discovered hadal snailfish (*Scorpaeniformes: Liparidae)* from the Mariana trench. Zootaxa, 4358: 161–177.

Gerringer, M. E., Yancey, P. H., Tikhonova, O. V., Vavilov, N. E., Zgoda, V. G., and Davydov, D. R. 2020. Pressure tolerance of deep-sea enzymes can be evolved through increasing volume changes in protein transitions: a study with *Lactate Dehydrogenases* from abyssal and hadal fishes. The FEBS Journal, 287: 5394–5410.

Glud, R. N., Berg, P., Thamdrup, B., Larsen, M., Stewart, H. A., Jamieson, A. J., Glud, A. *et al.* 2021. Hadal trenches are dynamic hotspots for early diagenesis in the deep sea. Communications Earth & Environment, 2: 1–8.

Glud, R. N., Wenzhöfer, F., Middelboe, M., Oguri, K., Turnewitsch, R., Canfield, D. E., and Kitazato, H. 2013. High rates of microbial carbon turnover in sediments in the deepest oceanic trench on earth. Nature Geoscience 6: 284–288.

Gooday, A. J., Todo, Y., Uematsu, K., and Kitzato, H. 2008. New organic-walled *Foraminifera* (Protista) from the ocean's deepest point, the challenger deep (western Pacific ocean). Zoological Journal of the Linnean Society, 153: 399–423.

Greenaway, S. F., Sullivan, K. D., Umfress, S. H., Beittel, A. B., and Wagner, K. D. 2021. Revised depth of the challenger deep from submersible transects; including a general method for precise, pressure-derived depths in the ocean. Deep Sea Research Part I: Oceanographic Research Papers, 178: 103644.

Greenville, A. C., DIckman, C. R., and Wardle, G. M. 2017. 75 years of dryland science: trends and gaps in arid ecology literature. PLoS One, 12: e0175014.

Griffiths, T. L., and Steyvers, M. 2004. Finding scientific topics. Proceedings of the National Academy of Sciences, 101: 5228–5235. National Academy of Sciences.

Grün, B., and Hornik, K. 2011. Topicmodels: an R package for fitting topic models. Journal of Statistical Software, 40: 1–30.

Haunschild, R., Bornmann, L., and Marx, W. 2016. Climate change research in view of bibliometrics. PLoS One, 11: e0160393.

Heezen, B. C., Ewing, M., and Menzies, R. J. 1955. The influence of submarine turbidity currents on abyssal productivity. Oikos, 6: 170.

Howell, K. L., Hilário, A., Allcock, A. L., Bailey, D., Baker, M., Clark, M. R., Colaço, A. *et al.* 2020. A decade to study deep-sea life. Nature Ecology & Evolution 5: 265–267.

Ichino, M. C., Clark, M. R., Drazen, J. C., Jamieson, A., Jones, D. O. B., Martin, A. P., Rowden, A. A. *et al.* 2015. The distribution of benthic biomass in hadal trenches: a modelling approach to investigate the effect of vertical and lateral organic matter transport to the seafloor. Deep Sea Research Part I: Oceanographic Research Papers, 100: 21–33.

Itou, M., Matsumura, I., and Noriki, S. 2000. A large flux of particulate matter in the deep Japan trench observed just after the 1994 Sanriku-oki earthquake. Deep Sea Research Part I: Oceanographic Research Papers, 47: 1987–1998.

Jamieson, A. J. 2016. Landers: baited cameras and traps. Biological Sampling in the Deep Sea, pp. 228–259. Ed. by M. Clark, M. Consalvey, and A. Rowden. John Wiley & Sons, Ltd.

Jamieson, A. J. 2018. A contemporary perspective on hadal science. Deep Sea Research Part II: Topical Studies in Oceanography, 155: 4–10.

Jamieson, A. J. 2020. The five deeps expedition and an update of full ocean depth exploration and explorers. Marine Technology Society Journal, 54: 6–12.

Jamieson, A. J., Brooks, L. S. R., Reid, W. D. K., Piertney, S. B., Narayanaswamy, B. E., and Linley, T. D. 2019. Microplastics and synthetic particles ingested by deep-sea amphipods in six of the deepest marine ecosystems on Earth. Royal Society Open Science,6: 180667.

Jamieson, A. J., Fujii, T., Mayor, D. J., Solan, M., and Priede, I. G. 2010. Hadal trenches: the ecology of the deepest places on Earth. Trends in Ecology and Evolution, 25: 190–197.

Jamieson, A. J., Fujii, T., Solan, M., and Priede, I. G. 2009. Hadeep: free-falling landers to the deepest places on Earth. Marine Technology Society Journal, 43: 151–160.

Jamieson, A. J., Kilgallen, N. M., Rowden, A. A., Fujii, T., Horton, T., Lörz, A. N., Kitazawa, K. *et al.* 2011. Bait-attending fauna of the Kermadec trench, SW Pacific ocean: evidence for an ecotone across the abyssal-hadal transition zone. Deep Sea Research Part I: Oceanographic Research Papers, 58: 49–62.

Jamieson, A. J., Lacey, N. C., Lörz, A. N., Rowden, A. A., and Piertney, S. B. 2013. The supergiant amphipod alicella gigantea (*Crustacea: Alicellidae*) from hadal depths in the Kermadec trench, SW Pacific ocean, Deep Sea Research Part II: Topical Studies in Oceanography, 92: 107–113.

Jamieson, A. J., Linley, T. D., Eigler, S., and Macdonald, T. 2021b. A global assessment of fishes at lower abyssal and upper hadal depths (5000 to 8000 m). Deep Sea Research Part I: Oceanographic Research Papers, 178: 103642.

Jamieson, A. J., Linley, T. D., Jamieson, A. J., and Linley, T. D. 2021. Hydrozoans, scyphozoans, larvaceans and ctenophores observed in situ at hadal depths. Journal of Plankton Research, 43: 20–32.

Jamieson, A. J., Malkocs, T., Piertney, S. B., Fujii, T., and Zhang, Z. 2017. Bioaccumulation of persistent organic pollutants in the deepest ocean fauna. Nature Ecology & Evolution, 1: 1–4.

Jamieson, A. J., and Vecchione, M. 2020. First in situ observation of cephalopoda at hadal depths (*Octopoda: Opisthoteuthidae: Grimpoteuthis* sp.). Marine Biology, 167: 1–5.

Jamieson, A. J., and Vecchione, M. 2022. Hadal cephalopods: first squid observation (*Oegopsida, Magnapinnidae, Magnapinna* sp.) and new records of finned octopods (*Cirrata*) at depths > 6000 m in the Philippine trench. Marine Biology, 169: 1–5.

Jamieson, A., Ramsey, J., and Lahey, P. 2019. Hadal manned submersible. Sea Technology, 60: 22–24.

Jamieson, A., Ramsey, J., and Lahey, P. 2019a. Hadal manned submersible. Sea Technology, 60: 22–24.

Jarry, J. 2003. L'aventure des Bathyscaphes : Marins, Inge´nieurs et Savants au Plus Profond des Mers. E´d. du Gerfaut, Paris.

Kaleem, S., Qin, L., Yi, W., Lian, X. Y., and Zhang, Z. 2020. Bioactive metabolites from the Mariana trench sediment-derived fungus *Penicillium* sp. SY2107. Marine Drugs, 18: 258.

Kato, C., Li, L., Nogi, Y., Nakamura, Y., Tamaoka, J., and Horikoshi, K. 1998. Extremely barophilic bacteria isolated from the mariana trench, challenger deep, at a depth of 11,000 meters. Applied and Environmental Microbiology, 64: 1510–1513.

Kato, C., Li, L., Tamaoka, · J, Horikoshi, · K, Kato, C., Li, L., Tamaoka, J. *et al.* 1997. Molecular analyses of the sediment of the 11000-m deep Mariana trench. Extremophiles 1: 117–123.

Kioka, A., Schwestermann, T., Moernaut, J., Ikehara, K., Kanamatsu, T., Eglinton, T. I., and Strasser, M. 2019b. Event stratigraphy in a hadal oceanic trench: the Japan trench as sedimentary archive recording recurrent giant subduction zone earthquakes and their role in organic carbon export to the deep sea. Frontiers in Earth Science, 7: 319.

Kioka, A., Schwestermann, T., Moernaut, J., Ikehara, K., Kanamatsu, T., McHugh, C. M., dos Santos Ferreira, C. *et al.* 2019. Megathrust earthquake drives drastic organic carbon supply to the hadal trench. Scientific Reports 9: 1–10.

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

Kitahashi, T., Kawamura, K., Veit-Köhler, G., Danovaro, R., Tietjen, J., Kojima, S., and Shimanaga, M. 2012. Assemblages of harpacticoida (*Crustacea: Copepoda*) from the Ryukyu and Kuril trenches, northwest Pacific ocean. Journal of the Marine Biological Association of the United Kingdom, 92: 275–286.

Kobayashi, H., Hatada, Y., Tsubouchi, T., Nagahama, T., and Takami, H. 2012. The hadal amphipod hirondellea gigas possessing a unique cellulase for digesting wooden debris buried in the deepest seafloor. PLoS One, 7: e42727.

Kyo, M., Miyazaki, E., Tsukioka, S., Ochi, H., Amitani, Y., Tsuchiya, T., Aoki, T. *et al.* 1995. Sea trial of "KAIKO," the full ocean depth research ROV. "Challenges of Our Changing Global Environment." Conference Proceedings. pp. 1991–1996. OCEANS'95 MTS/IEEE, Washington, DC

Lacey, N. C., Rowden, A. A., Clark, M. R., Kilgallen, N. M., Linley, T., Mayor, D. J., and Jamieson, A. J. 2016. Community structure and diversity of scavenging amphipods from bathyal to hadal depths in three South Pacific trenches. Deep Sea Research Part I: Oceanographic Research Papers, 111: 121–137.

Levin, L. A., and Bris, N. L. 2015. The deep ocean under climate change. Science, 350: 766–768.

Li, J. Y., Song, Z. L., Yan, G. Y., and He, L. S. 2019. The complete mitochondrial genome of the largest amphipod, *Alicella Gigantea*: insight into its phylogenetic relationships and deep sea adaptive characters. International Journal of Biological Macromolecules, 141: 570–577.

Li, Y., Kong, X., Chen, J., Liu, H., and Zhang, H. 2018. Characteristics of the copper,zinc superoxide dismutase of a hadal sea cucumber (*Paelopatides* sp.) from the Mariana trench. Marine Drugs, 16: 169.

Linley, T. D., Stewart, A. L., McMillan, P. J., Clark, M. R., Gerringer, M. E., Drazen, J. C., Fujii, T. *et al.* 2017. Bait attending fishes of the abyssal zone and hadal boundary: community structure, functional groups and species distribution in the Kermadec, new hebrides and Mariana trenches. Deep Sea Research Part I: Oceanographic Research Papers, 121: 38–53.

Liu, M., Xiao, W., Zhang, Q., Shi, L., Wang, X., and Xu, Y. 2020. Methylmercury bioaccumulation in deepest ocean fauna: implications for ocean mercury biotransport through food webs. Environmental Science & Technology Letters, 7: 469–476.

Lu, K., Cai, X., Ajiferuke, I., and Wolfram, D. 2017. Vocabulary size and its effect on topic representation. Information Processing & Management, 53: 653–665.

Madsen, F. 1955. Holothurioidea, Reports on the Swedish Deep-Sea Expedition, 2, Zoology. 12: 151–173.

Mair, L., Mill, A. C., Robertson, P. A., Rushton, S. P., Shirley, M. D. F., Rodriguez, J. P., and McGowan, P. J. K. 2018. The contribution of scientific research to conservation planning. Biological Conservation, 223: 82–96.

Meinen, C. S., Perez, R. C., Dong, S., Piola, A. R., and Campos, E. 2020. Observed ocean bottom temperature variability at four sites in the northwestern argentine basin: evidence of decadal deep/abyssal warming amidst hourly to interannual variability during 2009–2019. Geophysical Research Letters, 47: e2020GL089093.

Millard, J. W., Freeman, R., and Newbold, T. 2020. Text-analysis reveals taxonomic and geographic disparities in animal pollination literature. Ecography, 43: 44–59.

Momma, H., Watanabe, M., Hashimoto, K., and Tashiro, S. 2004. Loss of the full ocean depth ROV kaiko-Part 1: ROV kaiko-A review. In The Fourteenth International Offshore and Polar Engineering Conference. OnePetro.

Mu, Y., Bian, C., Liu, R., Wang, Y., Shao, G., Li, J., Qiu, Y. *et al.* 2021. Whole genome sequencing of a snailfish from the yap trench (~7,000 m) clarifies the molecular mechanisms underlying adaptation to the deep sea. PLoS Genetics,17: e1009530.

Nikita, M. 2019. ldatuning: Tuning of the Latent Dirichlet Allocation Models Parameters version 1.0.2 from CRAN. CRAN,

Nunoura, T., Hirai, M., Yoshida–Takashima, Y., Nishizawa, M., Kawagucci, S., Yokokawa, T., Miyazaki, J. *et al.* 2016. Distribution and niche separation of planktonic microbial communities in the water columns from the surface to the hadal waters of the Japan trench under the Eutrophic ocean. Frontiers in Microbiology, 7: 1261.

Nunoura, T., Takaki, Y., Hirai, M., Shimamura, S., Makabe, A., Koide, O., Kikuchi, T. *et al.* 2015. Hadal biosphere: insight into the microbial ecosystem in the deepest ocean on earth. Proceedings of the National Academy of Sciences of the United States of America, 112: E1230–E1236.

Nybelin, O. 1951. Introduction and station list. Reports of the Swedish Deep-Sea Expedition, 2, Zoology. 1: 1–28.

Oguri, K., Kawamura, K., Sakaguchi, A., Toyofuku, T., Kasaya, T., Murayama, M., Fujikura, K. *et al.* 2013. Hadal disturbance in the Japan trench induced by the 2011 Tohoku–oki earthquake. Scientific Reports 3: 1–6.

Oji, T., Ogawa, Y., Hunter, A. W., and Kitazawa, K. 2009. Discovery of dense aggregations of stalked crinoids in Izu-Ogasawara trench, Japan. Zoological Society of Japan, 26: 406–408.

Paterson, G. L. J., Glover, A. G., Barrio Froján, C. R. S., Whitaker, A., Budaeva, N., Chimonides, J., and Doner, S. 2009. A census of abyssal polychaetes. Deep Sea Research Part II: Topical Studies in Oceanography, 56: 1739–1746.

Peng, G., Bellerby, R., Zhang, F., Sun, X., and Li, D., 2020. The ocean's ultimate trashcan: hadal trenches as major depositories for plastic pollution. Water Research, 168: 115121.

Peng, X., Chen, M., Chen, S., Dasgupta, S., Xu, H., Ta, K., Du, M. *et al.* 2018. Microplastics contaminate the deepest part of the world's ocean. Geochemical Perspectives Letters, 9: 1–5.

Peoples, L. M., Grammatopoulou, E., Pombrol, M., Xu, X., Osuntokun, O., Blanton, J., Allen, E. E. *et al.* 2019a. Microbial community diversity within sediments from two geographically separated hadal trenches. Frontiers in Microbiology, 10: 347.

Peoples, L. M., Norenberg, M., Price, D., McGoldrick, M., Novotny, M., Bochdansky, A., and Bartlett, D. H. 2019. A full-ocean-depth rated modular lander and pressure-retaining sampler capable of collecting hadal-endemic microbes under in situ conditions. Deep Sea Research Part I: Oceanographic Research Papers, 143: 50–57.

Ramirez-Llodra, E., Tyler, P. A., Baker, M. C., Bergstad, O. A., Clark, M. R., Escobar, E., Levin, L. A. *et al.* 2011. Man and the last great wilderness: human impact on the deep sea. PLoS One, 6: e22588.

Ramírez-Malule, H., Quiñones-Murillo, D. H., and Manotas-Duque, D., 2020. Emerging contaminants as global environmental hazards. A bibliometric analysis. Emerging Contaminants, 6: 179–193.

Riehl, T., Kaiser, S., and Brandt, A. 2018. Vema-TRANSIT – an interdisciplinary study on the bathymetry of the vema-fracture zone and Puerto Rico trench as well as Abyssal Atlantic biodiversity. Deep Sea Research Part II: Topical Studies in Oceanography, 148: 1–6.

Ritchie, H., Jamieson, A. J., and Piertney, S. B. 2015. Phylogenetic relationships among hadal amphipods of the superfamily *Lysianassoidea*: implications for taxonomy and biogeography. Deep Sea Research Part I: Oceanographic Research Papers, 105: 119–131.

Ritchie, H., Jamieson, A. J., and Piertney, S. B. 2017. Population genetic structure of two congeneric deep-sea amphipod species from geographically isolated hadal trenches in the Pacific ocean. Deep Sea Research Part I: Oceanographic Research Papers, 119: 50–57.

Ritchie, H., Jamieson, A. J., and Piertney, S. B. 2018. Heat-shock protein adaptation in abyssal and hadal amphipods. Deep Sea Research Part II: Topical Studies in Oceanography, 155: 61–69.

Roemmich, D., Alford, M. H., Claustre, H., Johnson, K. S., King, B., Moum, J., Oke, P. R. *et al.* 2019. On the future of Argo: a global, full-depth, multi-disciplinary array. Frontiers in Marine Science, 6: 439.

Ryabinin, V., Barbière, J., Haugan, P., Kullenberg, G., Smith, N., McLean, C., Troisi, A. *et al.* 2019. The UN decade of ocean science for sustainable development. Frontiers in Marine Science, 6: 470.

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022

Shank, T. M., Machado, C., German, C. R., Bowen, A., Leichty, J. M., Klesh, A. T., Smith, R. G. *et al.* 2019. Development of a new class of autonomous underwater vehicle (AUV), Orpheus, for the exploration of ocean world analogues. Ocean Worlds 4, 2168: 6021. https://ui.adsabs.harvard.edu/abs/2019LPICo2168.6021S/abstract.

Shimanaga, M., and Yanagi, K. 2016. The Ryukyu trench may function as a “depocenter” for anthropogenic marine litter. Journal of Oceanography, 72: 895–903.

Silge, J., and Robinson, D. 2017. Text mining with R. O’Reilly Media, Inc. Sebastopol, CA

Smith, C. R., de Leo, F. C., Bernardino, A. F., Sweetman, A. K., and Arbizu, P. M. 2008. Abyssal food limitation, ecosystem structure and climate change. Trends in Ecology & Evolution, 23: 518–528.

Sorensen, R. M., and Jovanović, B. 2021. From nanoplastic to microplastic: a bibliometric analysis on the presence of plastic particles in the environment. Marine Pollution Bulletin, 163: 111926.

Stewart, H. A., and Jamieson, A. J. 2018. Habitat heterogeneity of hadal trenches: considerations and implications for future studies. Progress in Oceanography, 161: 47–65.

Stewart, H. A., and Jamieson, A. J. 2019, The Five Deeps: The Location and Depth of the Deepest Place in each of the World’s Oceans. Elsevier B.V., Amsterdam.

Swan, J. A., Jamieson, A. J., Linley, T. D., and Yancey, P. H. 2021. Worldwide distribution and depth limits of decapod crustaceans (Penaeoidea, Oplophoroidea) across the abyssal-hadal transition zone of eleven subduction trenches and five additional deep-sea features. Journal of Crustacean Biology, 41: ruaa102.

Syed, S., Borit, M., and Spruit, M. 2018. Narrow lenses for capturing the complexity of fisheries: a topic analysis of fisheries science from 1990 to 2016. Fish and Fisheries, 19: 643–661.

Taira, K., Kitagawa, S., Yamashiro, T., and Yanagimoto, D 2004. Deep and Bottom Currents in the Challenger Deep, Mariana Trench, Measured with Super-Deep Current Meters. Journal of Oceanography, 60: 919–926. Springer.

Takagawa, S., Takahashi, K., Sane, T., Kyo, M., Mori, Y., and Nakanishi, T. 1989. 6,500 m deep manned research submersible “SHINKAI 6500” system. Proceedings OCEANS, pp. 741–746. IEEE.

Tarn, J., Peoples, L. M., Hardy, K., Cameron, J., and Bartlett, D. H. 2016. Identification of free-living and particle-associated microbial communities present in hadal regions of the Mariana trench. Frontiers in Microbiology, 7: 665.

Tokuda, A. K., Drazen, J. C., Gerringer, M. E., Popp, B. N., Grammatopoulou, E., and Mayor, D. J. 2020. Trophic interactions of megafauna in the Mariana and Kermadec trenches inferred from stable isotope analysis. Deep Sea Research Part I: Oceanographic Research Papers, 164: 103360.

Tulloch, A. I. T., Sutcliffe, P., Naujokaitis-Lewis, I., Tingley, R., Brotons, L., Ferraz, K. M. P. M. B., Possingham, H. *et al.* 2016. Conservation planners tend to ignore improved accuracy of modelled species distributions to focus on multiple threats and ecological processes. Biological Conservation, 199: 157–171.

van Haren, H. 2020. Challenger Deep internal wave turbulence events. Deep Sea Research Part I: Oceanographic Research Papers. 165: 103400. Pergamon.

van Haren, H., Berndt, C., and Klaucke, I. 2017. Ocean mixing in deep-sea trenches: new insights from the challenger deep, Mariana trench. Deep Sea Research Part I: Oceanographic Research Papers, 129: 1–9.

Vescovo, V. L., Jamieson, A. J., Lahey, P., McCallum, R., Stewart, H. A., and Machado, C. 2021. Safety and conservation at the deepest place on Earth: a call for prohibiting the deliberate discarding of nondegradable umbilicals from deep-sea exploration vehicles. Marine Policy, 128: 104463.

Vinogradov, M. E. 1961. Quantitative distribution of deep-sea plankton in the western Pacific and its relation to deep-water circulation. Deep Sea Research (1953), 8: 251–258. Elsevier.

Wei, T., and Simko, V. 2017. Corrplot: Visualization of a Correlation Matrix version 0.92 from CRAN. CRAN.

Wenzhöfer, F., Oguri, K., Middelboe, M., Turnewitsch, R., Toyofuku, T., Kitazato, H., and Glud, R. N. 2016. Benthic carbon mineralization in hadal trenches: assessment by in situ $O_2$ microprofile measurements. Deep Sea Research Part I: Oceanographic Research Papers, 116: 276–286.

Westgate, M. 2016. Circleplot: Circular plots of distance and association matrices. CRAN.

Westgate, M. J., Barton, P. S., Pierson, J. C., and Lindenmayer, D. B. 2015. Text analysis tools for identification of emerging topics and research gaps in conservation science. Conservation Biology, 29: 1606–1614.

Weston, J. N. J., Carrillo-Barragan, P., Linley, T. D., Reid, W. D. K., and Jamieson, A. J. 2020. New species of eurythenes from hadal depths of the Mariana trench, Pacific ocean (*Crustacea: Amphipoda*). Zootaxa, 4748: 163–181.

Weston, J. N. J., Peart, R. A., Stewart, H. A., Ritchie, H., Piertney, S. B., Linley, T. D., and Jamieson, A. J. 2021. Scavenging amphipods from the wallaby-zenith fracture zone: extending the hadal paradigm beyond subduction trenches. Marine Biology, 168: 1–14.

Wolff, T. 1956a. Crustacea Tanaidacea from depths exceeding 6000 meters. Danish Science Press. Denmark

Wolff, T. 1956b. Isopoda from depths exceeding 6000 meters. Danish Science Press. Denmark

Wolff, T. 1959. The hadal community, an introduction. Deep Sea Research (1953), 6: 95–124.

Wolff, T. 1960. The hadal community, an introduction. Deep Sea Research, 6: 95–124. Elsevier.

Wolff, T. 1970. The concept of the hadal or ultra-abyssal fauna. Deep Sea Research and Oceanographic Abstracts. 17: 983–1003. Elsevier.

Xu, Y., Ge, H., and Fang, J. 2018. Biogeochemistry of hadal trenches: recent developments and future perspectives. Deep Sea Research Part II: Topical Studies in Oceanography, 155: 19–26.

Zenkevitch, L., and Birstein, J. 1953. On the problem of the antiquity of the deep-sea fauna. Deep-Sea Research, 7: 10–23.

*Handling Editor: Howard Browman*

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsac074/6576454 by guest on 02 May 2022