How reproducible is geophysical research? A review of the availability of code, software and data in journals

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Abstract

Geophysical research frequently makes use of agreed methodologies, formally published software, and bespoke code to process and analyse data. The reliability and repeatability of these methods is vital in maintaining the integrity of research findings and thereby avoiding the dissemination of unreliable results. In recent years there has been an increased attention on aspects of reproducibility, which includes data availability, across scientific disciplines. This review considers aspects of reproducibility of geophysical studies relating to their publication in peer reviewed journals. Specifically, it considers: 1) the extent to which reproducibility in geophysics is the focus of published literature; 2) journal policies on the requirements for providing code, software, and data for submission and, 3) the availability of code, software and data associated for existing journal articles. The findings show that: 1) between 1991 and 2021 there were 27 articles with reproducibility in the title and 222 with reliability, with a year on year increases in both over the same period; 2) while 60% of journals have a definition of research data, only 20% of journals have a requirement for a data availability statement, and 3) despite ~86% of randomly sampled journal articles including a data availability statement, only 54% of articles have the original data accessible via data repositories or web servers. It is suggested that despite journals and authors working towards improving the availability of data, frequently these data are not easily accessible, therefore limiting possibility of reproducing studies.

Non-technical summary

In studies of the Earth, other planets, oceans and atmospheres, scientists often carry out quantitative analysis of measurements from specialist instruments or create numerical models to represent complex natural systems. These approaches are useful for understanding important processes such as plate tectonics and patterns of ocean circulation, and often have wider societal importance, such as understanding natural hazards or the distribution of economically significant natural resources. When scientists present the findings of their work in scientific publications, the focus is primarily on the written narrative. However, a cornerstone of scientific studies should be the ability to replicate an experiment or study. To enable this the input data and details of the methodology, for example the computer code used, are essential. This work reviewed how reproducible the published work in the field of geophysics has been to date. The findings show that despite most publications now requiring the underlying data to be made available, most of the time these data are not easily accessible, and therefore limit the opportunity for scientists to verify existing findings.

1 Introduction

Geophysics is perhaps best described as the application of physics to study the Earth, oceans, atmosphere and near-Earth space, including other planets ('What Is Geophysics?', 2014). Geophysical methods, which, typically, either take raw records from instrumentation and process the recorded signals, or carryout numerical modelling, rely on quantitative analysis to make robust interpretations of these systems. Frequently geophysical methods use processing flows with numerous steps which are often iterative to, for example, distinguish signal from noise (Robinson & Treitel, 2000), or to model the behavior of complex systems such as a mantle convection (Hager & Clayton, 1989). Across all geophysical methods, the use of software or code to process and analyse data is ubiquitous, driven by the quantitative nature of geophysical methods (e.g. Lowrie & Fichtner, 2020). The reproducibility and reliability of these methods is vital to ensure that the scientific community can verify previous findings and avoid the dissemination, or misinterpretation, of results which are unreliable or ambiguous (Steventon et al., 2022). Computer analysis has long been vital to geophysical methods (cf. Reese, 1965), and this continues to be true today, where most methods involve the use of code or software to process and analyse data sets of ever increasing volume.

To date the existing published literature on the topic of reproducibility in geophysics can broadly be grouped into four areas: 1) the benefits of specific open-source software for improved repeatability (e.g. Oren & Nowack, 2018); 2) the repeatability of surveying techniques (e.g. Waage et al., 2018); 3) the reproducibility of individual studies (e.g. Walker et al., 2021) and 4) improving the repeatability of specific workflows (e.g. Jun & Cho, 2022). There has been, to date, no empirical consideration of the extent to which the existing publications and published work are reproducible. This work attempts to address this by quantify the way in which existing peer reviewed geophysical research has acted to enabling reproducibility, and repeatability through code and data sharing.

2 Reproducibility, repeatability, and data availability

In recent years there has been an increased attention on aspects of reproducibility, including data availability, across all scientific disciplines (e.g. Tedersoo et al., 2021) with limited focus on areas of Earth sciences (Wildman & Lewis, 2022). At the 2016 G20 Summit, the G20 leaders formally endorsed the application of FAIR principles to research data (*G20 Leaders' Communique Hangzhou Summit*, 2016). The FAIR principles set out the importance of research data being *Findable, Accessible, Interoperable and Reusable* to improve and accelerate scientific research (Hodson et al., 2018) and were set out by a diverse set of stakeholders across academia, industry, funding agencies, and scholarly publishers. Contemporaneous to this, computational approaches have become increasingly important as more and more scientists are now able to adopt computational methods due to the improved ease and availability of both hardware and software (c.f Mesirov, 2010). Evolving methods, the availability and support for large scale data sharing have led to increased attention and resources to enable scientists to share data (Tenopir et al., 2011). Despite computational and storage infrastructure being in place, there are still perceived barriers to effective data sharing (Tenopir et al., 2011) and code sharing (Gomes et al., 2022). In a survey of >1300 scientists on data sharing practices, Tenopir et al., (2011) found that one third of the respondents chose not to answer whether they make their data available to others, and of those that did respond 46% reported they do not make their data electronically available to others. In exploring why researchers chose not to make their data available Tenopir et al., (2011) found the leading reason is insufficient time (54%), followed by lack of funding (40%), having no place to put the data (24%), lack of standards (20%), and "sponsor does not require" (17%), with only 14% of respondents stating their data "Should not be available". For code sharing, Gomes et al., (2022) identified reasons why code sharing is not more common in biological sciences, including perceived barriers such as: unclear process, complex workflows, data too large, lack of incentives, and concerns on re-use of data.

3 Review Methodology

This study considers the reproducibility of geophysical studies which have been published in peer reviewed journals. It does not include any consideration of the reproducibility of geophysical studies outside of this, for example unpublished work from the private sector, or non-peer reviewed published reports. The analysis consists of three parts, 1) a systematic review of the extent to which reproducibility in geophysics is explored in the literature; 2) a review of journal's policies on the requirements for providing code, software, and data for submission and then 3) for a random selection of articles examines the availability of code, software, and data.

Each of the analysis is based on geophysical journals as identified by SCImago Journal Rank (see "DataTable1_JournalListSciMargo" in linked repository). SCImago Journal Rank (SJR) is a numeric value representing the average number of weighted citations received during a selected year per document published in that journal during the previous three years, as indexed by

Scopus (SCImago, n.d.). While journal metrics are frequently misused to assess the influence of individual papers (Pendlebury, 2009), here the list is simply used as a mechanism to firstly identify journals by subject area and then to sub sample the journal population. Each journal in the list is assigned a subject area and subject category. We include journals where either the first or second subject category is "geophysics". The journals identified using SCImago are a broad representation of journals which may be widely read and used by the geophysics community, or they frequently publish articles where geophysics is the dominant discipline. Journals whose exclusive focus are review articles are excluded from the analysis. The review does use the SJR as a measure of the 'prestige' of any individual journal, nor to make any comparison or interpretations between individual journals.

3.1 Subject Review Protocol

This study used an approach akin to a systematic review, designed to identify as many primary studies relating reproducibility in geophysics as possible without manually selecting which articles to include. The aim was to enable a quantified assessment of the extent to which studies focus on the topic of reproducibility (or reliability) in geophysics and determine how frequently the primary focus of studies is to investigate reproducibility or reliability. To do this, search strings were constructed using either "reproducibility" and "reliability" as the search terms and were restricted to search the titles of articles only. We restricted the search to the journals ranked in the top 100 by SCImago (see "DataTable1_JournalListSciMargo" in linked repository). The searches are conducted using Publish or Perish software (Harzing, 2010).

3.2 Review of Journal Policies

To evaluate journal's existing policies relating to the inclusion of code, software, and data we use the list of 20 geophysical journals identified using SCImago Journal Rank. For each of these journals the requirements for code, software, and data, as per the 'instructions for authors' and the publishers' policies were compiled. Table 1 shows the criteria for which we reviewed if journals policy referred to. As rarely are the criteria outlined in Table 1 a clear binary yes/no, a scoring criterion was used. The scoring criteria used is shown in Table 2. It is acknowledged that using a scoring criterion like this could be considered subjective, however, by using a descriptor of the criteria it is anticipated that aspects of bias are minimized.

3.3 Review of Journal Submissions

To evaluate the extent to which published peer review articles make available data and code, again the list of 20 geophysical journals identified using SCImago Journal Rank was used (see Supplementary Data table 1). As journals do not currently include search filters to discern between articles which make data and/or code available (this is discussed later), a random sample of individual publications were selected to evaluate the extent to which they meet the criteria set out by a journals policy. 200 articles were randomly selected between the same 3-year period (2019-2021). Each article is noted as either *open access* or *paywalled*. This is on a per article basis, rather than by journal, since authors may opt to make an article in a subscription

access journal available open access by paying a journal an Article Publication Charge (APC). Again, as rarely can the availability and accessibility be described using binary yes/no criteria a scoring criteria is used, shown in Table 3.

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Included in policy/guidance	Category
Has definition of 'research data'	Policy
Includes separate 'data policy' section	Policy
Requirement to include data availability statement	Data
Requirement to include citations for data	Data
Requirement to make data available	Data
Guidance to include data in dedicated data repository	Data
Requirement to include software/code availability statement	Code/Software
Requirement to include citations for software/code	Code/Software
Requirement to make software/code available	Code/Software
Guidance to include data in supplementary materials	Data Sources

Table 1. Criteria for which journal policies and guidelines were reviewed against.

Score	Summary	Descriptions
1	Required	Required, (e.g., must) with very limited exceptions (for example to preserve confidentiality of human participants)
2	Partial requirement	Partial requirement with flexibility around inclusion method.
3	Encouraged	Encouraged, with wording proactively encouraging (e.g., *should*) authors to include
4	Mentioned	Mentioned or implied but not proactively encouraged
5	Not mentioned	No mention in guidance to authors
6	Not allowed	Inclusion of data or content not permitted.

Table 2. Scoring-criterion used to evaluate the extent to which journals proactively support improving the availability of data and code.

Score	Summary	Descriptions
1	Data available and accessible via dedicated data repository	Data available and is hosted on a repository which provides a DOI for the data. Includes where data is provided in tables within article.
2	Data available via website / webserver	Data available but no DOI.
3	Data source linked	Includes cases where article provides link to a web-hosted database, but the specifics of the dataset (for example time periods, filters) are not clear.
4	Data provided in supplementary information or data	Includes where data are included under 'supplementary information'. The lack of consistency in use of supplementary information makes data frequently harder to access.
5	Data listed as available but not accessible	Includes when authors state 'data available on request'
6	Data not available or no mention of data availability	Includes when authors explicitly state that data is confidential and not available or accessible.
X	Data linked but link no longer valid	

Table 3. Scoring-criterion used to evaluate the availability and accessibility of data in published articles.

4 Results

4.1 Existing Literature

In the 100 journals which publish geophysical research searched there were, between 1991 and 2022, 27 articles with "reproducibility" in the title and 222 with "reliability" in the title (see Figure 1). From 1990 to 1999 there were 33 publications with "reliability" in the title. Compare this with 2000 to 2009, when there were 57, and 2010 to 2019 when there were 102. This represents an increase of 72% and 78% respectively. From 1990 to 1999 there were 4 publications with "reproducibility" in the title, between 2000 to 2009 there were 7 and between

2010 to 2019 there were 11. While these represent an increase of 75% and 57% respectively, there is little difference despite the larger sample size differences.

Of the 100 journals, 20 (20%) have published articles with "reproducibility" in the title, and 50 (50%) have published articles with "reliability" in the title. The Bulletin of Earthquake Engineering has published the most articles with "reliability" in the title, 21. Geochemistry, Geophysics, Geosystems has published the most articles with reproducibility in the title, 3. A full breakdown of the number of publications with either "reproducibility" or "reliability" in the title is provided in Supplementary Data Tables 2 and 3.

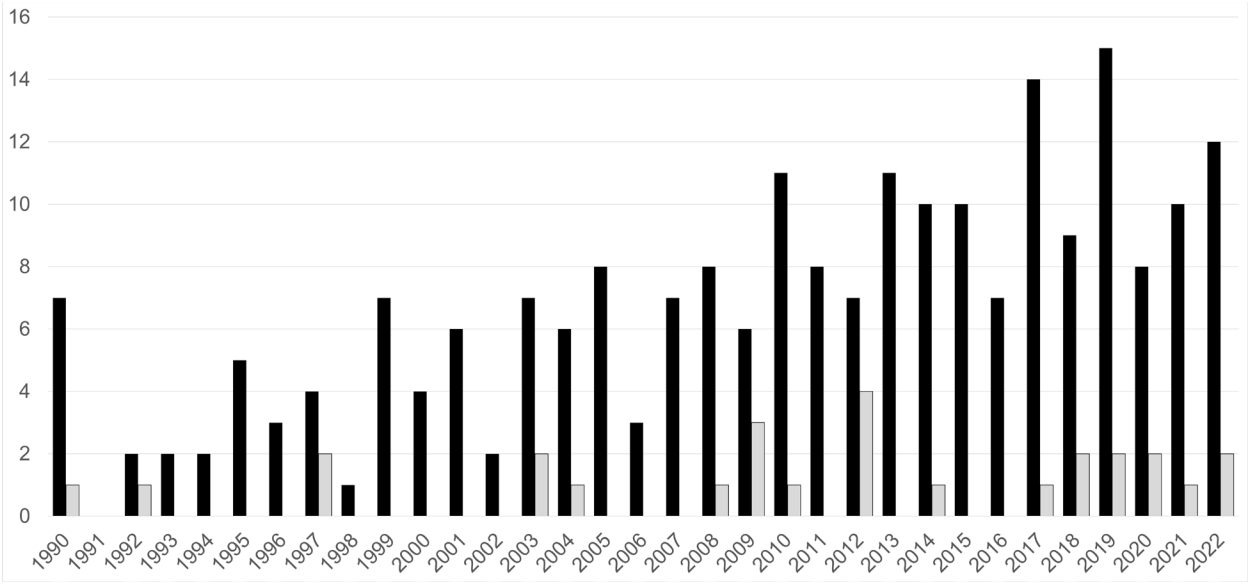


Figure 1. Number of publications, by year with the keyword *reproducibility* (grey bars) and *repeatability* (black bars).

4.2 Journal Policies

From reviewing journal policies, it was found that 12 out of 20 (60%) journals have a definition of research data, while 8 out of 20 (40%) do not have a definition (see Figure 2); 17 out of 20 (85%) of journals have a discrete 'data' section within the journal policies and guidance. Despite 18 of the 20 journals either requiring or mentioning making data available, 8 of these are from a single publisher, the American Geophysical Union (AGU), which applies the same requirements across all its Earth science publications. Only 4 out of 20 (20%) have a requirement for a data availability statement and only one journal, The Journal of Petrology, has an explicit requirement to both inclusion of data and a data availability statement. Information for authors is found within dedicated *data policy* sections for 17 out of 20 (85%), with 3 (15%) embedding the information within other sections.

It is found that only 1 of the 20 journals (5%) reviewed required any code used to be made available and only 1 out of 20 journals (5%) require a code availability statement. There are 12 out of 20 (60%) journals that encourage making code available, while 7 out of 20 make no mention of making code available. No journals have a requirement to make data or code available through repositories, or to include DOIs. However, 15 of the 20 journals (75%) encourage the use of data repositories and 14 of the 20 journals (70%) encourage the use of DOIs. 2 of the 20 journals (10%) mention the use of repositories, and 4 of the 20 (20%) mention the use of DOIs. 2 of the journals (10%) make no mention of the use of repositories and 1 journal makes no mention of the use of DOIs.

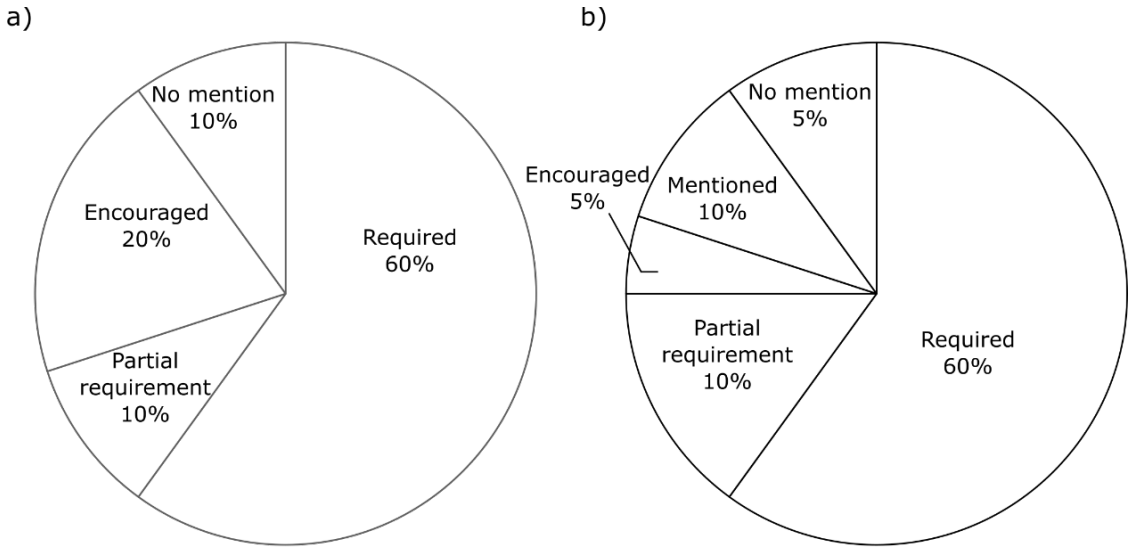
Qualitative analysis of journals policies and guidance suggests that different publishers are adopting different approaches to encouraging making data and code available. Some are clear that they now require the inclusion of available data. For example, the AGU author resources explicitly refer to the FAIR principles and include the following regarding data availability statements:

> *"It is not sufficient to write that your data will be available upon request and to archive and make your data available in the supplementary information of your manuscript."* (*Data and Software for Authors*, n.d.)

In contrast, SEG's Geophysics makes no direct reference in the author instructions to the FAIR principles, although the SEG is a signatory to the Coalition on Publishing Data in the Earth and Space Sciences (COPDESS) Statement of Commitment. In their instructions to authors, they state:

> *"… papers from industry authors and academic researchers whose work is built on unsharable industry-owned data are invited, encouraged, and welcome."*(*GEOPHYSICS Instructions to Authors*, n.d.)

The guidance for authors across journals frequently allows for authors to self-select from a range of options relating to data availability, however only in the case of two publishers, AGU, and Springer, was there any text indicating that the deposition of data was checked as part of the publishing process.



225 DATA AVAILABILITY

Figure 2. Charts demonstrating the requirements for journals to a) making data available and b) including a data availability statement, both based on examining journals and their publisher's author guidelines and policies.

4.3 Journal Submissions

Of the articles with accessible information, it is identified that 165 of the 191 (~86%) articles have data availability statements and 26 (~14%) do not have data availability statements. A 230 breakdown of data availability statements by journal is shown in Table 4. All the randomly sampled articles (n=100) published across the 10 AGU included data availability statements. In contrast, of the 8 randomly sampled articles accessible to us published in Economic Geology, only 1 had a data availability statements, and 7 had no data availability statement.

Of the 191 articles sampled, 90 (~47%) make available original data from their research and a 235 further 9 (~4%) provide information to available secondary data sources. 4 articles state that the original data is available on request and 4 articles state that secondary data is available on request. 4 articles provide no information of the availability of original data, and 38 articles provide no information on the availability of secondary data. 41 of the 191 (~21%) articles have the data available via repositories and 63 of the 191 articles provide weblinks to data sources. 240 Zenodo, FigShare and Mendeley are the most used repositories for data sharing (~75%). Examples of data sources for which articles provide weblinks to include NASA's Planetary Data System (PDS), Incorporated Research Institutions for Seismology (IRIS) and the National Oceanic and Atmospheric Administration (NOAA) data portal. In most instances the exact details of the dataset or search criteria used to return a dataset are not included. For articles 245 sampled from Geophysics, Marine and Petroleum Geology and Economic Geology none of the articles reviewed had made the original data accessible or available.

Of the 200 articles, 132 were open-access (e.g., accessible through the publishers' site without subscription access) and 68 were paywalled access (e.g., required a subscription to access the full article). Of the 132 open access articles it was found that 42% did not make the data available via a data repository or web server (e.g., categories 4-6). Of the 68 paywalled articles, we found that 70% of these did not make the data available via a data repository or web server (Figure 3).

There is, at least qualitatively, a difference in the availability and code between geophysical research which has a basis in resource or economic applications, and those with either a fundamental, or global seismological focus. For example in SEG's Geophysics, which publishes research focused on geophysical method applied to extractive or resource industries (*GEOPHYSICS Instructions to Authors*, n.d.), it was found that none of the ten articles reviewed made the underlying data available. In contrast in the Seismological Society of America (SSA) Seismological Research Letters, whose scope covers a topic of broad interest across seismology, as well as for those interested in seismology and related disciplines, it was found that seven of the ten provided links to underlying data, and the three which did not, their study did not use original data. It is also found that for paywalled articles, publishers take different approaches as to what information to provide in the public domain. For example, in both Tectonophysics and Earth and Planetary Science Letters published by Elsevier, in some instances the data availability statement is not behind the paywall even if the full article is. Whereas Geophysics, published by the SEG, does not make this information available without paid access to the article.

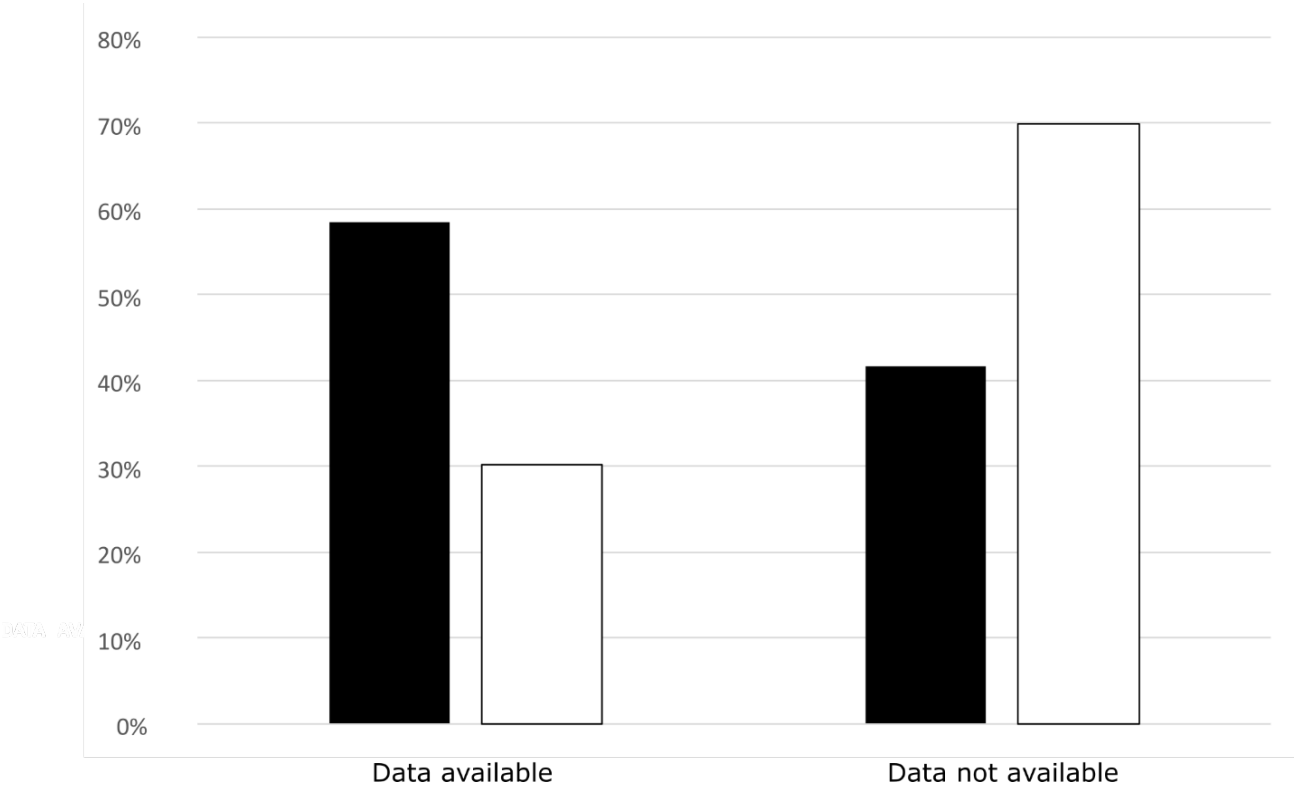


Figure 3. Chart showing the difference in data availability between open access articles (black bars) and paywalled articles (white bars).

Journal	Data Availability Statement		Original Data Accessible	
	Yes	No	Yes	No
Tectonics (10)	10	0	8	2
Geochemistry, Geophysics, Geosystems (10)	10	0	10	0
Geophysical Research Letters (10)	10	0	2	0
Journal of Geophysical Research D: Atmosphere (10)	10	0	10	0
Journal of Geophysical Research B: Solid Earth (10)	10	0	9	0
Journal of Geophysical Research E: Planets (10)	10	0	6	0
Journal of Geophysical Research C: Oceans (10)	10	0	1	1
Journal of Geophysical Research F: Earth Surface (10)	10	0	4	2
Earth and Planetary Science Letters (10)	10	0	10	0
Tectonophysics (10)	5	5	5	4
Geophysics (8)	7	3	0	9
Journal of Petrology (10)	10	0	9	0
Seismological Research Letters (5)	7	3	7	0
Contributions to Mineralogy and Petrology (10)	10	0	10	0
Journal of Geodesy (10)	8	2	2	3
Mineralium Deposita (10)	9	1	8	1
Economic Geology (8)	1	7	3	5
Earthquake Spectra (10)	5	5	5	2
Marine and Petroleum Geology (10)	8	2	1	5
Geophysics Journal International (10)	7	3	3	5

Table 4. Summary data for articles examined, showing the number of articles that 1) provided a data availability statement and 2) whether they made the original data available. As not all articles used original data, or some were solely modelling studies, the total of yes/no for *original data* does not always match the total count.

5 Discussions

5.1 Perceived Barriers

Data and code share are often perceived as being limited by digital infrastructure (Gomes et al., 2022). However, while making data and code available may have been previously limited by such restrictions, there now exits the underlying digital architecture to, for example, host individual files typically up to 20Gb in size on data repositories such as Figshare and Zenodo. Repositories have added the functionality to archive code, for example from GitHub to Zenodo, and assign a DOI. And indeed, many of the perceived barriers, for example challenges in handling large data files, are not unique to geophysics and these concerns have mostly been shown to be relatively straightforward to manage in terms of absolute volume. For example a study in neurosciences by Poldrack and Gorgolewski (2014) described how the sharing of raw MRI data from 1,000 authors would consist of ~2.7 terabytes, a relative modest volume by however there are major challenges in ensuring that data sets are curated to make them accessible and useful to researchers. Indeed the common occurrence of *big data* within nearly all subjects has served to identify that discussing absolute data volume as a barrier in any context is limiting, as computing hardware and software advances at such a rate that any absolute numbers are soon superseded (Oguntimilehin & Ademola, 2014).

5.2 Subjective interpretation of journal policies

The findings indicate that journals have a mixed approach to the wording used in polices relating to the provision of data and code (see Figure 2). We found that journals repeatedly used ambiguous language in their policies when referring to data and code availability. While 60% of journals had a policy which stated that the submission of data was a requirement, the statements used in the other 40% of journals were frequently ambiguous, using terms such as *encourages*, *where possible, where applicable.* Clearly those journals without a clear definition of *data* will likely result in the interpretation of the guidelines, by authors, reviewers, and editors, being more subjective. From the publisher's side, it would seem to make sense from a marketing and commercial perspective sense to have submission guidelines and policies that clearly define data and code access. If data and code are easily identifiable and accessible by a publication, there is empirical evidence to suggest that sharing research data may can be associated with an increased in citations (Christensen et al., 2019; Piwowar et al., 2007). When it comes to the use of *supplementary information,* it is worth highlighting, as in the AGU's data availability statement, that this section of a manuscript is still indicated as a suitable place to accommodate data. There are however issues with this as highlighted by previous studies (Pop & Salzberg, 2015). Most notably there is often a lack of guidance on how supplementary information should be used to include data (e.g. Pop & Salzberg, 2015), means that often data, or information on data, provided in supplementary information results in data being inaccessible.

5.3 Availability vs accessibility

We found that, where journal articles used original data, in general the availability of data was improved over journal articles which used existing, or data derived from third party sources. Frequently where articles used non-original data, while articles provided information on the data in the data availability statements, they provided insufficient information to identify specific datasets, or in several cases the weblinks no longer worked. This suggests that it is not only data availability that is important, but also data accessibility. Starr et al., (2015) list eight core principles of data citation which have been endorsed by 87 scholarly societies, publishers and other institutions. Of relevance to the findings here are the *unique identification and specificity and verifiability*. For the majority of the articles selected at random, there was insufficient information for the dataset to be identified without human search input, in contrast to the recommendation that data identification should be machine actionable (Starr et al., 2015). Commonly it was difficult to identify the specific dataset used in the research, do for example, it was possible to follow a weblink to website which hosts data, but not to identify the data on which the analysis was based. While many articles (>30%) provide weblinks or the names of the organizations which host the data, they frequently provided insufficient information for readers to identify and verify that the data is the same as used by the authors. Frequent issues include, for example, the data linked consists of multiple files and do not explicitly state what files from that dataset they used. Another persistent issue is the use of non-static weblinks for data sets.

5.4 Role of Journals, Editors and Reviewers

The contributions of editors and reviewers for journals, whether they are for-profit or not-for-profit, are invaluable in ensuring the continued and timely publication of scientific findings. In most cases, those scientists that undertake the role do so without renumeration. The role of a journal editor could be summarized as to sustain integrity in published research and enforce the policies and the standards for the journal, both for authors and reviewers (Caelleigh, 1993). The role of reviewers could be summarized as evaluating whether there is a meaningful contribution, whether the constructs are clearly defined, and whether the underlying mechanisms/process are clearly explained (Lepak, 2009). Based on journal (and publisher) policies it is unclear as to whether reviewers are expected to evaluate the suitability of such statements. It could be suggested that there should be a clear distinction then between the role which editors and reviewers have in determining whether an article's approach to data and code availability is suitable or not. In practice, clarification by journals over the role of reviewers and editors could improve the situation. For example, one possibility could for reviewers to have the responsibility for ensuring that the data and code is suitable to demonstrate the scientific findings, and that the editorial board and office has the responsibility to ensure that authors have included a data availability statement and adhered to the requirements for making data accessible and available. Indeed this is how AGU handle the availability of data, as indicated on their information to authors where it clearly states, *"AGU now checks to see if data/software has been properly cited vs simply linking to a DOI, website, platform"*(*Data and Software for Authors*, n.d.).

It is worth noting that while it was found that fewer journals had dedicated requirements for code (or software), sometimes, they are mentioned within the policies, guidelines, and definitions of data. This can lead to some ambiguity when the guidance is interpreted by authors. And while not all studies use bespoke code or software, there are very few aspects of geophysical research which do not have some reliance on computer-based analysis. Therefore, journals could perhaps consider a simplified approach when it comes to more commonly used software (e.g., statistical analysis), whereby authors simply choose from a list.

In the review of existing journal submissions, it became clear that it is currently not possible to identify which articles have accessible data and code quickly and efficiently. In the most part journals use data availability statements, with only 10% of the 20 journals considered not at least mentioning including a data availability statement. However, it is not possible to filter or search articles by these statements. In chemistry it has been suggested that one solution to this challenge would be to completely recast data-rich scientific journal articles into two components, a narrative and separate data component, each of which is assigned a persistent digital object identifier (Harvey et al., 2014). However perhaps a simpler solution could be the requirement for authors to choose from pre-defined categories of data availability – which as part of the editorial process is checked to be accurate. Then journals could implement a search criterion based upon if the data is accessible.

5.5 Limitations of study

The findings presented in this review are not exhaustive. There exist several limitations to the study that should be highlighted. Firstly, there are alternative ways in which the choice of journals to include could be made. The approach here, as far as possible, was designed to avoid user bias in the selection of journals, but it is recognized that the breadth of journals included covers some topics that may be considered outside of the immediate subject area of geophysics. Secondly, and related to this, the choice of search tools could impact the results. In this study searches were undertaken using tools and databases which did not require paid subscription access. Alternative subscription only search services may result in different results, for the review of existing literature. Thirdly, when reviewing journal policies, there is a component of subjectivity in the categorization of a journals requirements. As discussed above this is itself is one of the issues which publishers and journals need to tackle to avoid any ambiguity in the requirements. Fourthly, when categorizing the availability of data for an individual article, while in some cases it is very clear if data is available and accessible (e.g., DOI linked data) or not (e.g., data is confidential) there are examples where, for example the availability of the data is insufficiently described to easily assess if the data is accessible Examples of this include where a link to a website which hosts data is provided, but there are no specifics of the data used (for example, not specifying the exact time series). Overcoming this uncertainty in future studies would require attempting to download the exact dataset used in each case, which would be significant undertaking, not least as it would require some subject matter expertise across a diverse range of geophysical subjects.

6 Conclusions

Reproducibility and repeatability are important themes for the geophysics community as evidenced by the increasing number of publications identified in this review. Through examining the current policies of multiple journals which publish geophysical articles, it is identified that all too often the wording used is ambiguous and open to interpretation. If journals want to publish truly reproducible works, it will require not just a shift to using concise wording, but also for journals to enforce stricter policies. Despite this, the empirical evidence is that journals are making a concerted efforts to provide guidance on the provision of code, software, and data. For published articles it is found that there are stark differences in the availability and accessibility of both code and data. However, there is still a long way to go for geophysical research to reproducible, as shown by the findings which indicate that less than 30% of articles over the past 5 years provide enough information on the source of data to reproduce the results.

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8 Data and software availability

The data used in this study can be found at data.ncl.ac.uk at the following location 10.25405/data.ncl.21564381. There are 5 data tables included the description of each which are provided below.

- DataTable1_JournalListSciMargo – List of 100 geophysics journals used as starting point for review
- DataTable2_ExistingLiteratureReliability – Number of journal articles published, by year, with the word ‘reliability’ in the title.
- DataTable3_ExistingLiteratureReproducibility – Number of journal articles published, by year, with the word ‘reproducibility’ in the title.
- DataTable4_JournalRequirements – Summary of journal requirements categorised.
- DataTable5_PublishedArticles_Anon – Summary of availability of data and code for individual publications. We have removed any identifiable details relating to the individual journal articles sampled in this study.

The study used Publish or Perish software by Harzing, A.W. available from https://harzing.com/resources/publish-or-perish. All statistics and plots were created using Microsoft Excel.

9 Competing interests

The authors have no competing interests.

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