**Advancing climate change research with open science**

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**Abstract**

**Effective climate change science requires interdisciplinary research that is rapidly conducted and widely disseminated. We argue that these goals can be achieved by adopting open science (OS) practices. Citations and Altmetrics indicate that open access studies receive more citations and are communicated more widely in news media and policy documents, suggesting that OS has the potential to improve research communication among scientists and public institutions. Opening data and code will increase collaboration opportunities and facilitate climate change triage. By enhancing both the academic and societal impact of climate change research, OS can facilitate mitigation and adaptation efforts for the most vulnerable regions of the world.**

**Main text**

Climate change research aims to understand global environmental change and how it will impact nature and society. The broad scope of climate change impacts means that successful adaptation and mitigation efforts will require an unprecedented collaboration effort that unites diverse disciplines and is able to rapidly respond to evolving climate issues (IPCC, 2014). However, to achieve this, climate change research practices need updating: key research findings remain behind journal paywalls, while scientific progress can be impeded by low levels of reproducibility and transparency (Ellison, 2010; Morueta-Holme *et al.*, 2018), individual data ownership (Hampton *et al.*, 2015), and inefficient research workflows (Lowndes *et al.*, 2017). Furthermore, the level of public interest and policy on climate change issues rely on fast communication of academic research to public institutions, yet the societal impact of climate change studies likely differs according to their public availability and exposure. Here, we argue that by adopting open science (OS) principles, scientists can advance climate change research and accelerate efforts to mitigate impacts; especially for highly vulnerable developing regions of the world where research capacity is limited. Using citation and social media metrics, we underscore the benefits of OS in raising the academic and societal impact of climate change research.

OS enables rapid and robust collaborative research, which can be critical for fast-moving interdisciplinary fields such as climate change. OS principles aim to improve reproducibility and transparency throughout the research process by openly sharing data, code, and papers (Hampton *et al.*, 2015; McKiernan *et al.*, 2016). OS practices can have wide-ranging benefits specific to climate change research, including improved collaboration, reproducibility, and scientific progression through sharing of data and code (Ellison, 2010; Ram, 2013; Lowndes *et al.*, 2017), greater public engagement (Wang *et al.*, 2015), and increased citation rates of open access (OA) publications (‘the OA citation advantage’) (Lawrence, 2001; Eysenbach, 2006). OS has transformed research practices of entire disciplines (e.g. preprints in mathematics, open genome data in genetics; Nielsen, 2011), but the transition to OS for climate change research is incomplete.

*Citation and social media benefits of OA*

In publications containing ‘climat\* change’ in their title, abstract or keywords and published between 2007-2016 (www.scopus.com), OA studies increased substantially, accounting for only 4% in 2007 and increasing to 26% in 2016 (Fig. 1). However, this varied by journal impact factor (IF; see Fig. 1 caption). For low and very high impact categories, OA publications in 2016 accounted for <16%, while medium and high impact studies were 41% and 29% open access, respectively. More popular OA journals, such as PLoS ONE and Nature Scientific Reports comprise 72% of OA publications and 21% of all publications in the medium impact group, which could explain the higher proportions of OA publications in these groups. These patterns show that the OA citation advantage also applies to climate change publications (Fig. 2a) (Eysenbach, 2006; Wang *et al.*, 2015; McKiernan *et al.*, 2016), which suggests that OA publications can lead to earlier and increased citations, and thus accelerate scientific progression by building upon existing science at a faster rate (Eysenbach, 2006; Lowndes *et al.*, 2017).

Beyond academic citation advantages, OA climate change research can have a greater societal impact when studies are communicated to non-academic audiences by mainstream news and social media, as well as utilized by policymakers (Wang *et al.*, 2015; Bornmann *et al.*, 2016). In ‘mentions’ of climate change studies in online news sources, Twitter feeds, and policy documents (www.altmetric.com), we show that OA studies in journals < 2.7 IF were communicated more frequently (Fig. 2b-d), likely due to those studies being accessible to non-academic audiences. Although media reporting was higher for closed studies in the highest impact journals, those studies are often promoted with academic press releases. Indeed, given that the highest impact journals are largely closed access (e.g. *Nature*, *Science*), these patterns indicate that most highly-reported research is kept behind paywalls, likely limiting public understanding and engagement of academic knowledge (Parker, 2013).Beyond mainstream media, higher Twitter activity for OA studies—irrespective of impact factor—supports a longstanding perception that open research is more widely disseminated and discussed online (Darling *et al.*, 2013; Wang *et al.*, 2015). Overall, policy documents also cited OA studies more often than closed (Fig. 2d), supporting evidence that subscription-only publishing models can limit the uptake of current scientific knowledge by policymakers (Cvitanovic *et al.*, 2014). Policy uptake of OA studies did decrease with increasing IF,

*OS facilitates communication, collaboration and triage*

Our results show that OA facilitates both academic and non-academic communication of climate change, which may be especially important for developing nations. Most climate change research is published through institutes within the developed world (McSweeney, 2015), yet the greatest impacts will be observed in some of the least developed and most vulnerable regions of the world (e.g. IPCC, 2014; Blasiak *et al.*, 2017). Additionally, inability to access subscription-only publications may inhibit science-based policy in developing countries. For example, inaccessibility of primary research has contributed to low citation rates in policy plans for tropical marine protected areas, implying that environmental management may fall behind current scientific knowledge (Cvitanovic *et al.*, 2014).

Successful triage requires efficient and rapid decision making (Bottrill *et al.*, 2008). The pace of climate change combined with a need to address societal and ecological impacts with limited resources make aspects of climate change research, such as biological conservation, triage disciplines. OS principles can help to minimize scientific uncertainty throughout the research process while increasing the potential for collaborations through data and code sharing, assisting the peer-review process with fully-reproducible manuscripts (Ram, 2013; Lowndes *et al.*, 2017), and reducing publication times with preprints and OA journals (Vale, 2015), Most scientists agree that publicly-funded research should be freely available (Dallmeier-Tiessen *et al.*, 2011) and several institutions have successfully implemented open data climate science. For instance, research on climate-driven thermal bleaching events in coral reef ecosystems has benefited hugely from open access to NOAA’s large-scale monitoring data (e.g. NOAA CoralWatch; Harris *et al.*, 2017). Comprehensive open data policies have also been implemented by some governments (e.g. USA; Obama, 2013) and journal groups (e.g. Nature editors, 2018). These examples demonstrate the success and importance of adopting open data principles; comprehensive uptake of these and other OS practices will substantially enhance application of academic research to climate change issues.

Despite the clear benefits of OS in enhancing research output and communication to stakeholders, closed publishing, fear of being ‘scooped’, and data ownership are considerable barriers to OS uptake (Nosek *et al.*, 2015). Research outputs—usually publications—are already required by most granting agencies, and grants and institutions typically cover OA costs (Dallmeier-Tiessen *et al.*, 2011). Furthermore, most climate change research is funded by developed countries, yet focus on climate issues in developing countries that may lack the institutional capacity for journal subscriptions (van Helden, 2012; McSweeney, 2015). Thus, to incentive OS climate change research, funding bodies might require grant holders to openly publish datasets, papers and code, and mandate active dissemination of climate change findings to stakeholders rather than passive dissemination by publication.

Scientists across disciplines have argued, convincingly, for improving research practices by adopting OS principles (Hampton *et al.*, 2015; Nosek *et al.*, 2015; McKiernan *et al.*, 2016). We extend these arguments to show that adoption of OS practices, such as OA publications, OS workflows, and sharing data, can also improve the academic and societal impact of climate change research. Given that global efforts to combat climate change impacts will require rapid, robust research and dissemination among academics, policymakers and the public, climate change research is in need of strong OS stewardship.

**Table 1. Recommendations to advance climate change research with open science tools.**

|  |  |  |
| --- | --- | --- |
| **Open science practice** | **Benefits** | **Application to climate change**  **research** |
| *Publish open access* | Increase uptake of primary research by public institutions (government and policy) | Limited uptake of scientific knowledge by policymakers (Cvitanovic *et al.*, 2014) may be addressed with open access (Fig. 2d) |
| Improve access to science by developing countries, thus enhancing climate change adaptation and mitigation efforts | Developing countries, which are most at risk to climate change impacts (IPCC, 2014), can access up-to-date climate research |
| Improve public communication of scientific evidence, thus raising public understanding of science | Prior knowledge of climate change causes are correlated to heightened concern (Shi *et al.*, 2016) |
|  |  |  |
| *Adopt reproducible and transparent research workflows* | Increase efficiency of research and robustness of findings | Progression of open science data tools and practices for increased transparency (Lowndes *et al.*, 2017) |
|  |  |  |
| *Archive data, code, and preprints* | Greater sharing of data, code, and ideas will stimulate more collaborative and interdisciplinary research | Journals publishing climate change research should adopt transparency policies (Nosek *et al.*, 2015)  Standardized metadata reporting will facilitate literature comparisons and meta-analyses (Morueta-Holme *et al.*, 2018)  Openly-available environmental monitoring datasets have been critical sources of information (e.g. NOAA's SST product; Reynolds *et al.*, 2002)  Open science workflows facilitate large collaborations (e.g. GitHub, Open Science Framework) (Ram, 2013; Wilson *et al.*, 2014) |
| Data availability will advance practices of 'climate change triage' | Climate change triage that supports long-term values of multiple stakeholders (e.g. scientists, Indigenous communities, government, industry) (Wheeler *et al.*, 2016) will require integration of diverse datasets from multiple disciplines  Access to open datasets at global and local scales facilitates conservation triage of coral reefs (Harris *et al.*, 2017) |
| Fast release of ideas and improved research before peer-review | Archiving pre- and post-prints on open access repositories such as arXiv, biorXiv, and MarXiv. |

../Documents/git_repos/open-climate-change/figures/Figure1.pdf

**Figure 1. Increasing prevalence of open access (OA) climate studies published between 2007-2016.** Proportional increase in OA climate change publications (black line) and across four journal impact factor categories (coloured lines; binned by the 25th, 50th, and 75th quantiles). Publications were extracted from Scopus ([www.scopus.com](http://www.scopus.com/)) for articles and reviews published between 2007-2016 containing the term “climat\* change” in title, abstract, or keywords. We further restricted publications to those journals with >200 total citation records (i.e. journals which regularly published climate change research, n = 116). Impact factors are 3-year weighted citation rates (SCImago Journal Rankings; www.scimagojr.com) and range from 0.14 to 18.13.

**../Documents/git_repos/open-climate-change/figures/Figure2_vert.pdf**

**Figure 2. Citations, communication, and media influence of closed and open access climate change studies published between 2007-2016.** Points are predicted mean number of citations (a), news mentions (b), twitter mentions (c), and policy mentions (d) in four impact factor categories, controlling for effects of publication year and journal on citations/mentions. Dashed lines are mean citations/mentions controlling for impact factor, year and journal. Citations were extracted from Scopus for the same studies in Figure 1. News, twitter and policy mentions were extracted from Altmetric (www.almetric.com) for study DOIs in Figure 1. Citations and mentions were averaged for each journal in each year, and fitted to linear mixed effects models with journal impact factor bin (4 bins represented by the 25th, 50th, and 75th quantiles) and access (open/closed) as fixed effects and year and journal as random intercepts. Citations were log10 transformed for normality and presented on a log10 scale; Altmetric models were fitted with Poisson distributions. All analyses were conducted in R 3.4.4 (R Core Team, 2018).

**Code and Data availability**

Journal citations and mentions were extracted from Scopus (www.scopus.com) and Altmetric (www.altmetric.com). We provide our queried search terms and R coding scripts at [github.com/travistai2/open-science-cc](http://www.github.com/travistai2/open-science-cc)

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**Author contributions**

TT conceived the idea. Both authors contributed equally to data analysis and writing.

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**Conflict of interest statement**

The authors declare no competing financial or non-financial conflicts of interest

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