**Advancing climate change research with open science**

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**Abstract**

**Accelerating the progression of climate change research warrants open science (OS). OS practices can improve research communication among scientists, public institutions and developing countries, increase collaboration potential, and facilitate rapid, robust climate change triage. By enhancing both the academic and societal impact of climate change research, OS can improve our understanding and management of climate change impacts.**

**Main text**

Open science (OS) practices enable 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). Adoption of OS practices can have wide-ranging benefits, including increased citation rates of open access (OA) publications (‘the OA citation advantage’) (Lawrence, 2001; Eysenbach, 2006), improved collaboration, reproducibility, and scientific progression through sharing of data and code (Ellison, 2010; Ram, 2013; Lowndes *et al.*, 2017), and greater public engagement (Wang *et al.*, 2015). 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.

Climate change research enhances our understanding of how global environmental change affects nature and society, from tracking declines in ecosystem function to assessing changes in food security (IPCC, 2014). Successful adaptation and mitigation of climate change impacts requires collaborations between diverse disciplines to generate robust scientific evidence. However, 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 focus on climate change issues depend upon 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 comprehensive uptake of OS principles, such as publishing OA, can advance climate change research and thereby accelerate efforts to mitigate climate change impacts. We use citation and social media metrics to underscore the benefits of publishing OA in raising the academic and societal impact of climate change research.

*Citation and social media benefits of OA*

In climate change publications 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 varies by journal impact factor. For low and very high journal impact categories, OA publications in 2016 accounted for <16%, while medium and high impact journal studies were 41% and 29% open access, respectively. More popular OA journals, such as PLoS ONE and Nature Scientific Reports, are medium to high impact, which could explain the higher proportions of OA publications in these groups.

Most researchers benefit from institutional subscriptions to various publishers to access closed publications (i.e. subscription only), yet OA publications generally have increased citation rates (Eysenbach, 2006; Wang *et al.*, 2015; McKiernan *et al.*, 2016). OA climate change studies were also cited more than closed studies in all journal impact factor groups (Fig. 2a). While these differences are small, they suggest 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).

Despite the citation benefits of OA publishing, there are barriers and competing incentives to publish closed access instead. One major barrier is the cost to publish OA and the added tradeoffs between cost and journal prestige. For example, for the few high-impact OA journals, OA costs are prohibitively expensive (e.g. Nature Communications, $5,200 USD) and authors may forego such costs and opt to submit papers to higher impact journals such as Nature or Science. However, only a small percentage (12%) of researchers tend to pay OA costs out of pocket, while the majority of costs are either covered by grants or by researcher institutions (83%) (Dallmeier-Tiessen *et al.*, 2011). Outputs and deliverables are already required by most granting agencies and are fundamental to knowledge mobilization and the progression of science; thus, OA publication costs should explicitly be included when submitting grants.

Beyond academic citation advantages, OA 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 from low, medium, and high impact journals 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 limit the uptake of current scientific knowledge by policymakers (Cvitanovic *et al.*, 2014).

*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). Climate change researchers, especially those based in developed nations, can facilitate adaptation and mitigation efforts across the globe by openly sharing their research findings and data.

The rapid 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. Successful triage requires efficient and rapid decision making (Bottrill *et al.*, 2008). By enhancing collaborations through data and code sharing, assisting the peer-review process and limiting mistakes with reproducible research (Ram, 2013; Lowndes *et al.*, 2017), and reducing publication times with preprints and OA journals (Vale, 2015), OS principles can help to minimize scientific uncertainty throughout the research process while increasing the potential for collaborations. Some institutions successfully practice open data climate science where, 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). Indeed, comprehensive open data policies have been implemented by some governments (e.g. USA; Obama, 2013) and journal groups (e.g. Nature editors, 2018), while most scientists agree that publicly-funded research should be freely available (Dallmeier-Tiessen *et al.*, 2011). 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.

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. |

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**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; bins from ‘low’ to ‘very high’ separated by the 25th, 50th, and 75th quantiles). Publications were extracted from Scopus (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.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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