Current status on the need for improved accessibility to climate change models code

Juan A. Añel[1], Michael García-Rodríguez[1,2], and Javier Rodeiro[2]

[1]EPhysLab, Ed. Campus da Auga, Campus As Lagoas, 32004, Ourense, Galicia (SPAIN)
[2]School of Computer Sciences, Campus As Lagoas, 32004, Ourense, Galicia (SPAIN)

Correspondence: Juan A. Añel (j.anhel@uvigo.es)

Abstract. Over the past few years, increasing attention has been focused on the need to publish computer code as an integral part of the research process. This has been reflected in improved policies on publication in scientific journals, including key related issues such as repositories and licensing. We explore the state-of-the-art of code availability and sharing of climate models, using as a testbed the models from the Fifth Climate Model Intercomparison Project (CMIP5), and we include some particular reflections on this case. Our results show that there are many limitations in terms of access to the codes of these climate models and that the climate modelling community needs to improve its code-sharing practice to comply with best practice in this regard, and the most recent editorial publishing policies.

Copyright statement. TEXT

1 Introduction

Reproducibility of results is essential to comply with the scientific method when performing research. This has extraordinary implications in the field of earth system models (Añel, 2019; Gramelsberger et al., 2020). Because so much scientific output today relies on the use of computers, there are new requirements in terms of the description of any experiments performed, to assure computational scientific reproducibility (CSR). This is widely known (Añel, 2011) and was recently discussed in a Sackler Colloquium on "Reproducibility of Research: Issues and Proposed Remedies" (Allison et al., 2018). CSR is a problem of high complexity.

In some cases, scientists may be unaware of some of the issues that have significant impacts on it, reaching the wrong conclusion that an experiment complies with CSR, when it is not the case, as exposed in Añel (2017). Also, a researcher could decide to use a model based on judgements that have little to do with the most appropriate from a scientific point of view, such as complying with the scientific method (Joppa et al., 2013). All this makes it necessary to consider a range of issues to comply with CSR in the process of design and use of models (Añel, 2017), and climate change models in particular. Some of them are legal aspects of software distribution and intellectual property, usually unfamiliar for researchers. Recent examples have revealed some very low levels of CSR (Allison et al., 2018; Stodden et al., 2018). Steps are being taken to improve CSR,

e.g., an increasing number of journals now have computer-code policies (Stodden et al., 2013; GMD Executive Editors, 2015; Nature, 2018), and recommendations have been made to ensure greater reproducibility of results (Wilson et al., 2017). They include to maintain appropriate documentation for the software, split the code into functions and submit it to DOI-issuing repositories, encourage the participation of external collaborators and make it easy for them to collaborate, etc.

5   The study of climate change relies heavily on the use of large computer simulations with geoscientific models of varying levels of complexity. In projects involving the intercomparison of climate models and in some research papers, it has become increasingly common to provide details of the simulations performed. These details include initial configurations, which are generally clear, accessible and formalised, in related outputs with digital object identifiers (DOIs) (e.g. Eyring et al. (2016); Morgenstern et al. (2017)). However, it is somewhat perplexing that the codes of the underlying models are not always made

10   available. At best they are shared informally, using links, repositories without any security regarding long-term availability or access, or email addresses via which it is claimed that the code will be delivered after contact. Especially in a field where heated debates occasionally arise following the publication of results, it seems odd that this core element of the research is not made more widely accessible.

There are other reasons that justify the need for access to the codes of climate models used in scientific research. One is

15   to prevent the loss of knowledge on the cycles of development of these models. Some of them nowadays rely on 'legacy' code that was written up to five decades ago, and new developers must understand why some decisions on implementation were undertaken so long ago. There is both an educational and practical dimension to this issue. In some cases, different models share sections of code, but its development remains fairly obscure (Knutti et al., 2013). It can be argued that adequate documentation of the code and the model is not necessary to prevent a potential loss of knowledge if the code used in the

20   models includes appropriate comments. But, indeed, this is not the case of the models contributing to the Fifth Climate Model Intercomparison Project (CMIP5). CMIP models are sophisticated software projects, and they need full documentation of the experiments (Pascoe et al., 2020).

Moreover, it is generally the case that climate models do not comply with what would be the ideal level of programming practice, an idea already pointed out by Wieters and Fritzsch (2018). García-Rodríguez et al. (2020) show how programmers

25   have tended to perform very poorly in this regard in particular, and the incidence of comments throughout the code of CMIP5 models is very low. Another issue related to the need for code sharing of climate models is the replicability of results. In different computing environments can also be challenging and should not be expected by default (Easterbrook, 2014), even where the same model is used (Massonnet et al., 2019).

Some informal efforts have been made to document accessibility for some climate models (Easterbrook, 2009; RealCli-

30   mate.org, 2009) and others more formally to check their quality (e.g., Pipitone and Easterbrook (2012); García-Rodríguez et al. (2020)). In light of these efforts, in this study, we intended to test the current status of accessibility to the most commonly used global climate models, in particular those that have contributed to the CMIP5. In the sections that follow, we describe our efforts to gain access to these models, the procedures we followed, and a classification of the models according to some metrics related to accessibility, and we also provide a discussion containing reflections on the state-of-the-art.

2 Methods

In our attempt to better understand the current status of CSR and the availability of climate models, we used as a testbed the models of CMIP5 (Taylor et al., 2012) given their extensive use in climate research over the last five years. These served as a vital tool for the last IPCC AR5 (IPCC, 2013), and given the ongoing development of CMIP6, groups of modellers should now be more open to sharing the code, due to the possible depreciation of the earlier version. We followed a standard procedure to obtain the code of each model. First, we checked the information available on each model in the webpage of CMIP5. Then we contacted research groups where necessary using email, without disclosure of ourselves as climate scientists to full explanation of our interest in studying the code. Our approach is detailed in the following sections.

2.1 Survey methods

Using a systematic methodology, we attempted to obtain the codes of all the climate models involved. This procedure included the first step using the web addresses for code downloading indicated on the CMIP5 webpage (https://pcmdi.llnl.gov/?cmip5/). When the code was not directly available to be downloaded, we looked for contact details (emails, on-line formularies, etc.) in the webpage. In some cases, there was an email address to contact. However, in other cases following the information in the CMIP5 website was not enough. In such cases, we searched through the internet using a search engine. We looked for institutional web pages, intending to find open repositories for the corresponding model. In a few cases, this was sufficient (see Table 1). Still, in others, we had to proceed by making contact with development teams at different levels, e.g. emails (see Appendix) (with follow-up emails two weeks after the first contact). In the case of the IPSL team after sending the email in English and failing to get a reply, we sent the second email in French, and we got an answer. For the NASA-GMAO model, we were unable to get a response from contact via email. However, we were approached by a member of the institution after a presentation during a conference. After discussing it, the development team granted us access to the model.

For those cases where we needed to establish contact via email, we provide details in the Table 1 of the different replies that we received. Michael García-Rodríguez always sent the first email from his student address (under the domain esei.uvigo.es), who had had no previous involvement in the activities of the international climate modelling community. The idea behind this was to check whether after it had become evident that the models were not available easily, institutions and researchers would then share them with someone from outside the community. In the end, to assure CSR and accessibility, details of experiments must be open to everybody, not just to peers or other scientists. A second email, equal to the first one, was sent to insist on our request. We intended to minimize the possibility of not getting a reply because of reasons such as the contact person being too busy at the moment of receiving the first email, it was unnoticed or filtered as spam. We waited for a reply for three weeks after sending the first email before sending the second. Finally, three weeks after the second email, we sent a final email, where we identified ourselves and our team, to make clear that we were indeed climate scientists, and thus to check whether we thus had a better chance of obtaining the code. Where access to the code was denied, we sent a survey with a few questions to better understand the reasons for this. All emails sent followed the same template as that given in the Appendix A.

It could be possible to look for additional contact information in the published scientific literature. However, many papers continue to be accessible only through paywalls (they are not open-access) and therefore they are not available for most of the people. Moreover, identifying the relevant person to contact from an author list requires a knowledge of the modelling groups that only a handful of experts in the field have. Also, additional contact information is available for five models from metadata included in the NetCDF files containing the results of the simulations in the CMIP5 repository. However, the ability to find and manage such data has computational requirements and needs of a knowledge that is beyond what could be considered reasonable for the general public, including part of the scientific community.

3 Results

After all attempts and several months, we successfully gained access to 10 out of 26 models (27 out of the 61 model versions or configurations) contributing to CMIP5. Table 2 provides a summary of the details of the replies obtained from these centres, teams or contacts that allowed access to the code. In terms of research centres or groups contributing to the CMIP5 project, this also represents 10 out of a possible 26. We found a strong regional bias in terms of the countries where models were made accessible. The USA, Germany and Norway stood out as the best contributors in that we obtained the code for all their models (though Norway only contributes one). Together, these three countries represent 38% of the research centres or CMIP5 models and 44% of all the versions. For France, we gained access to one of two models (three out of five versions). This analysis is relevant. We can speculate that in some cases, the decision on whether to share the code of the models, could have been influenced by national or regional regulations on software copyright, intellectual property, etc. For example, it is well known that the law in the USA, where for instance software can be patented, enables the possibility to enforce a higher level of restrictions to software sharing and distribution than in the EU (van Wendel de Joode et al., 2003; European Patent Office, 2016). However, it is the case that we have been able to get the code for 6 of the 7 models contributed by research centres from the USA and yet, for the EU we have only got 3 in 7. The fact that the models developed in the USA can count with the participation of federal employees could partially explain this result. Under the USA copyright law (U.S. Code, 1976), all the work produced by federal employees is in the public domain. Although they are not the same thing, the public domain could be considered closer to openness that lack of licensing of the models. For the case of Norway, we can speculate that the fact that NorESM has been developed using core parts of CESM1 (Knutti et al., 2013) could have facilitated openness of the code through the inheritance of licenses and copyright. In the same way, not sharing the code of the models could be due to inheritance reasons.

Figure 1 shows the percentage of models obtained from a global perspective, with specific plots for Europe and Asia. This makes it easier to visualise the rather narrow distribution of the regions on the maps and because different countries could apply different national laws in order to share the codes of the models.

In some cases, a high number of email exchanges were required over periods longer than one week to receive a reply or the code. In five cases, there was no obvious way to contact the development teams; in four cases, we received no answer at all. Seven research centres (corresponding to eighteen models) they replied that they did not share the codes of their models.

We decided to include in this final group EC-Earth, for which the code is said to be available to a given group of users. Still, in practice, the procedure to access it makes it completely unfeasible for non-members of the regular team involved in its development. In no case did we receive a response to the questionnaire sent asking for the reasons why they did not want to share the code. For the models obtained, we performed a ranking, as shown in Table 3, taking into account licensing issues and availability for reuse by third parties, among other factors. We considered the level of requirements introduced by the GPLv3 license (https://www.gnu.org/licenses/gpl-3.0.en.html) as the ideal case for a license under which the model can be shared, modified and used without restriction. This is in line with the recent updates to the policy on code availability published by Geoscientific Model Development (GMD Executive Editors, 2019). Moreover, it has been argued that it is the license that better fits to scientific projects to assure the benefits and openness of software (Morin et al., 2012).

We also addressed other issues relevant for running the models. In some ways, accessibility or ability to gain access to the code means nothing if adequate documentation for the model, a description of its components, instructions on how to compile or run it, and basic examples are not provided. This is in line with recommendations contained in the literature (Lee, 2018). The results are shown in Table 4. It can be seen that almost all the models obtained comply with all these criteria, except for NICAM.09, which only includes a 'Readme' and a 'Makefile'. For the IPSL, although the link to access the documentation does not work, it is possible to gain access to it by performing an internet search.

4 Conclusions

In this work, for cases where we obtained the code of a given model, we were not provided with a reason for the license behind it. In fact, in some cases, despite getting the code, we did not see a license explaining clearly the terms of use. Some scientists or model development groups could be worried because of issues such as legal restrictions (national or institutional) that prevent from publishing code. Also, because of potential dependencies of the model on third party proprietary software, lack of funding to maintain a public repository or violation of property rights. For all these cases, there is a clear response or solution:

- In the first case, if it is not possible to make available the code, then any result obtained with such a model should not be accepted as scientifically valid because it is impossible to verify the findings. We acknowledge that this is the case for several models widely used in scientific research nowadays, and this situation must be solved by modification of the legal precepts applied to them. Consequently, those working with such models should look for a change in the legal terms so that the model complies with the scientific method.

- If a part of the model depends on proprietary software, then it harms the possibility to distribute the whole model. Therefore again, the model does not comply with the scientific method. In this case, a good option can be to substitute the part of the model that is proprietary software with one that is free software.

- Lack of funding to maintain a software repository can not be considered a real problem. There are many options available to host the code. For example, Zenodo is free, widely adopted and assures hosting at least for the next twenty years.

- Fears about a violation of property rights usually respond more to a lack of awareness on how the law applies to software distribution than to real issues, as Añel (2017) points out. Intellectual property is usually detached of the norms that apply to the distribution of the model. Unless the developer specifically resigns to the intellectual property, it is generally retained despite if the software is made available and distributed and their contractual obligations. Indeed, under some legal frameworks, it is impossible to resign to intellectual property. The best option is always to get specialised legal advice on these matters.

It is a matter of some regret that we obtained straightforward access to just 3 of the 26 models (7 of the 61 versions) in CMIP5 and that for 16 (34 versions) we were not able to obtain the code at all. For all others, some interaction was required, from email exchanges to personal discussions at workshops. Indeed, we did not get access to the codes for more than half of all the versions used in the CMIP5 despite identifying ourselves as research peers. Therefore, we have to report the very poor status of accessibility to climate models, which could generate serious doubts for the reproducibility of the scientific results produced by them. While there is no reason to doubt the validity of the results of the study of climate change obtained using the CMIP5 models (in a similar way to findings for other disciplines (Fanelli, 2018)), we encourage all model developers to improve the availability of the codes of climate models and their CSR practices. Previous work has already shown that there is room for significant improvement in the structure of the codes of the models, which is in some cases very poor (García-Rodríguez et al., 2020), and sharing it could help to alleviate this situation. It would be desirable that future efforts on the development of climate models have into account the results here presented. In this vein, scientists starting model development from scratch, without problems with legacy code, are in a great position to care from the beginning about licensing and reproducibility, doing it in the best way possible.

It is possible to speculate that some scientists could be reluctant to share code because of perceived potential damage to their reputations because of its quality (Barnes, 2010). It can be argued that this could be related to a lack of adequate education in computer programming (Merali, 2010). This issue with the quality of the code has been raised for the case of climate models (García-Rodríguez et al., 2020). Given that many scientists have no formal training as programmers, it may be presumed that they consider that their code may not comply with the standards of excellence that they usually pursue in their primary fields of knowledge. Indeed, it has been documented that some climate scientists acknowledge that imperfections in climate models exist, and they address them through continuous improvement without paying too much attention to the common techniques of software development (Easterbrook and Johns, 2009).

Nevertheless, all scientists must believe that their code is good enough (Barnes, 2010) and that there are thus no reasons not to publish it (LeVeque, 2013). Barriers to code-sharing through licensing, imposed by, e.g., government bodies, cannot be an excuse. When contributing to scientific studies and international efforts where collaboration and trust are critical, such practice is not acceptable (Añel, 2019).

We recommend that frozen versions of the climate models later used to support the results discussed in international reports on climate change should be made accessible along with the outputs from simulations in official data portals. Also, this should apply to any other Model Intercomparison Project. It must be had into account that climate models are an essential piece in the evaluation of climate change, and not sharing them can be perceived as a weakness of the methodology used to perform such

assessments. Reproducibility could not be compromised; however, the simple fact that replicability (note that reproducibility and replicability are different concepts (ACM, 2018)) can not be achieved because of the lack of the code of the model is unfortunate. In this way, frozen versions of the models combined with cloud computing solutions and technologies such as containers can be a step forward to achieve full replicability of results in earth system modelling (Perkel, 2019; Añel et al., 2020). Also, tools to validate climate models are becoming common. Such tools use metrics to validate the outputs of the models. The ESMValTool (Righi et al., 2020) has been designed with this purpose and evaluation of the accessibility and code of the model could be integrated as a part of the process to measure the performance of the models contributing to the CMIP.

An additional reason to request an open code software policy is that several scientific gaps have been pointed out for the CMIP5 (Stouffer et al., 2017). The lack of availability of the code of the models makes it difficult to address them, as it is not possible to perform a complete evaluation of the source of discrepancies between them. As it has been shown for other fields of software development, sharing the code can help to improve the development process of climate models and their reliability (Boulanger, 2005; DoD CIO, 2009). Moreover, it would help to support the collaborative effort necessary to tackle the challenge of climate change (Easterbrook, 2010) and to do it in a way that complies better with the scientific method and the goals of scientific research (Añel, 2019). Funding should be allocated by agencies and relevant bodies to support such efforts. Notwithstanding that the whole framework of science faces challenges related to CSR, at the same time presents opportunities for improvement in such a sensitive field as climate science.

Code and data availability. There is no code or data relevant to this paper.

Figure 1. Geographical map with the number of the models obtained for each country: a) worldwide; b) Europe (EC-Earth is only included in the worldwide view because it is developed as a consortium of sixteen European countries); c) Asia. Green colours and fractions represent the obtained models from the total.
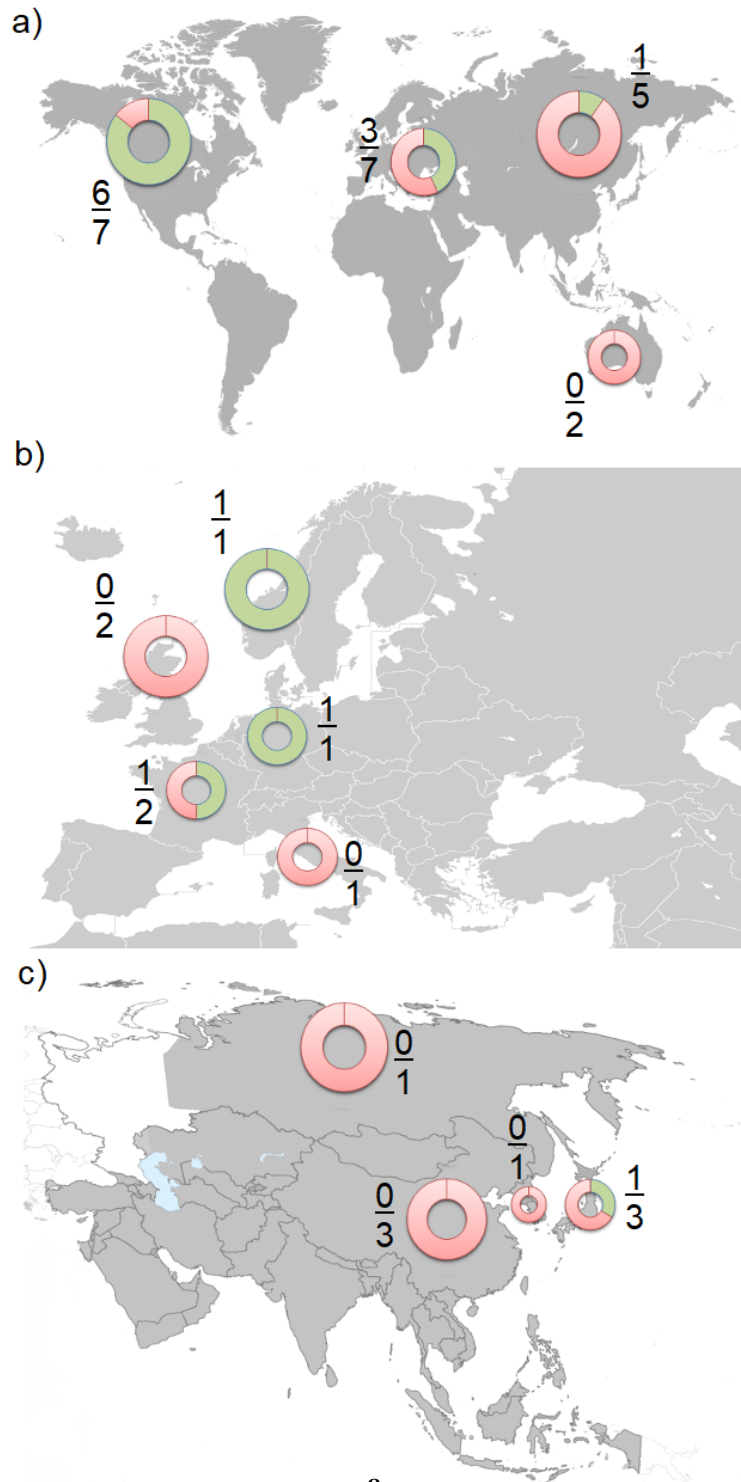
Table 1: CMIP5 model list, research centre responsible for each one and details on the procedure for accessing their code. Email 3 is not listed because we did not receive any answer to them.

Modeling center	Model	Free download	Answer Email 1	Answer Email 2	Comments/Answer
BCC	BCC-CSM1.1	No	-	-	No email or contact phone is available.
	BCC-CSM1.1(m)	No			
CCCma	CanAM4	No	Yes		The code is not shared.
	CanCM4	No			
	CanESM2	No			
CMCC	CMCC-CESM	No	No	No	No answer.
	CMCC-CM	No			
	CMCC-CMS	No			
CNRM-CERFACS	CNRM-CM5	No	No	Yes	The code is not shared.
	CNRM-CM5-2	No			
COLA and NCEP	CFSv2-2011	Yes	-	-	Code available from the official web site.
CSIRO-BOM	ACCESS1.0	No	Yes		The code is not shared.
	ACCESS1.3	No			
CSIRO-QCCCE	CSIRO-Mk3.6.0	No	-	-	No email or contact phone is available.
EC-EARTH	EC-EARTH	No	-	-	The code is not shared.
FIO	FIO-ESM	No	No	No	No answer.
GCESS	BNU-ESM	No	No	No	No answer.
INM	INM-CM4	No	-	-	No email or contact phone is available.
IPSL	IPSL-CM5A-LR	Yes	Yes		Available after email exchange.
	IPSL-CM5A-MR	Yes			
	IPSL-CM5B-LR	Yes			
LASG-CESS	FGOALS-g2	No	No	No	No answer.
LASG-IAP	FGOALS-gl	No	-	-	No email or contact phone is available.
	FGOALS-s2	No			
MIROC	MIROC4h	No	Yes		The code is not shared.
	MIROC5	No			
	MIROC-ESM	No			
	MIROC-ESM-CHEM	No			
MOHC	HadCM3	No	No	Yes	The code is not shared.

	HadCM3Q	No			
	HadGEM2-A	No			
	HadGEM2-CC	No			
	HadGEM2-ES	No			
MPI-M	MPI-ESM-LR	Yes			
	MPI-ESM-MR	Yes	Yes	-	Available after email exchange.
	MPI-ESM-P	Yes			
MRI	MRI-AGCM3.2H	No			
	MRI-AGCM3.2S	No			
	MRI-ESM1	No	-	-	No email or contact phone is available.
	MRI-CGCM3	No			
NASA-GISS	GISS-E2-H	Yes			
	GISS-E2-H-CC	Yes			
	GISS-E2-R	Yes	No	No	Available after email exchange.
	GISS-E2-R-CC	Yes			
NASA-GMAO	GEOS-5	Yes	No	No	Available after meeting during a workshop.
NCAR	CCSM4	Yes	-	-	Code available from the official web site.
NCC	NorESM1-M	Yes	Yes		Available after email exchange.
	NorESM1-ME	Yes			
NICAM	NICAM.09	No	No	Yes	Available after email exchange.
NIMR/KMA	HadGEM2-AO	No	No	Yes	The code is not shared.
NOAA-GFDL	GFDL-CM2.1	Yes			
	GFDL-CM3	Yes			
	GFDL-ESM2G	Yes			
	GFDL-ESM2M	Yes	Yes	Yes	Available after email exchange.
	GFDL-HIRAM-C180	Yes			
	GFDL-HIRAM-C360	Yes			
NSF-DOE-NCAR	CESM1(BGC)	Yes			
	CESM1(CAM5)	Yes			
	CESM1(CAM5.1,FV2)	Yes	-	-	Code available from the official web site.
	CESM1(FASTCHEM)	Yes			
	CESM1(WACCM)	Yes			

Table 2: Summary of reasons behind granting us access to the source code of the models.

Modeling center	Model	Process and reasons to access to the code
COLA and NCEP	CFSv2-2011	A tarball with the source code can be easily accessed from the official web site explaining what the code does and how the climate model works.
IPSL	IPSL-CM5A-LR	M. García-Rodríguez identified himself and explained via email the purposes of this research. After a meeting of the developing team and additonal details on this research we were granted access to a tarball with the source code.
	IPSL-CM5A-MR	
	IPSL-CM5B-LR	
MPI-M	MPI-ESM-LR	The access to a tarball with the source code was granted after registration as an user via a web page and approval, without any extra communication or reasoning.
	MPI-ESM-MR	
	MPI-ESM-P	
NASA-GISS	GISS-E2-H	After two weeks, we received the answer to our email. They have provided us directly with a link in which a tarball with the source code can be accessed with the snapshots of the model.
	GISS-E2-H-CC	
	GISS-E2-R	
	GISS-E2-R-CC	
NASA-GMAO	GEOS-5	Initially, they did not answer the emails that were sent to them. After a presentation during a workshop Dr Añel was approached by one of the members of the team and we were put in contact with one of the coders. By contacting this person we obtained access, available as 4073 files in directories retrieved using 'wget'.
NCAR	CCSM4	The code of the model is available through a web page. The dowload proccess is open to anyone but it is hard. Each file of the model has to be individually retrieved (2247 files in total, each in its respective sub-directory).
NCC	NorESM1-M	First, we received a reply stating that the code of the model is not shared with anyone outside the NorESM-community, asking if we really needed it. After identifying ourselves and explaining our research, we were granted access to a tarball after registering as users in the 'noresm wiki'.
	NorESM1-ME	
NICAM	NICAM.09	Initially, they asked us questions about the purpose of achieving the code. Then, explaining the objectives of the project, they have given us access to a tarball with the code after registering in the nicam user group.
NOAA-GFDL	GFDL-CM2.1	We were granted access to a tarball with the source code in reply to our first request via email.
	GFDL-CM3	
	GFDL-ESM2G	
	GFDL-ESM2M	
	GFDL-HIRAM-C180	

	GFDL-HIRAM-C360	
NSF-DOE-NCAR	CESM1(BGC)	We had to register to access the Community Earth System Model. After that, we were able to download a tarball with the source code.
	CESM1(CAM5)	
	CESM1(CAM5.1,FVV2)	
	CESM1(FASTCHEM)	
	CESM1(WACCM)	

Table 3: CMIP5 models with code obtained and scores of reproducibility. Maximum value of three filled stars is given to those models it is possible to access through the internet without restriction, with a license that allows full testing and evaluation of the model. The score was reduced by one star when failing for each one of the following criteria: if in order to gain access to the model we had to contact a research centre or development group, to sign license agreements, or if we gained access only after identifying ourselves as scientists undertaking climate research and according to the rights to evaluate and use the model as granted by the license (if applicable). A not-filled star means that the license of the model does not allow modification of the code.

Institution	Model	Score
Cola & NCEP	CFSv-2011	★★☆
IPSL	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR	★★
MPI-M	MPI-ESM-LR MPI-ESM-MR MPI-ESM-P	★
NASA GISS	GISS-E2-H GISS-E2-H-CC GISS-E2-R GISS-E2-R-CC	★☆
NASA GMAO	GEOS-5	★☆
NCAR	CCSM4	★★★
NCC	NorESM1-M NorESM1-ME	★★
NICAM	NICAM.09	★
NOAA GFDL	GFDL-CM2.1 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GFDL-HIRAM-C180 GFDL-HIRAM-C360	★★
NSF-DOE-NCAR	CESM1(BGC) CESM1(CAM5) CESM1(CAM5.1 FV2) CESM1(FASTCHEM) CESM1(WACCM)	★★★

Table 4: Availability of detailed information provided with the source code of the models in order to run them. 'Documentation' refers to full documentation of the model (for IPSL models a web address/link was included to access the documentation but it did not work). 'Readme' corresponds to a file containing basic explanations on the files part of the model and basic instructions. 'Basic example' refers to whether an example to explain the model is included. 'Dependencies' refers to the basic information on libraries, compilers or any other software and its version needed to run the model. 'Makefile' refers to the existence of a single file that manages all the process of compilation and model run.

Modeling center	Model	Documentation	ReadMe	Basic example	Depencencies listed	Makefile
COLA and NCEP	CFSv2-2011	yes	yes	yes	yes	yes
IPSL	IPSL-CM5A-LR	no*	yes	yes	yes	yes
	IPSL-CM5A-MR					
	IPSL-CM5B-LR					
MPI-M	MPI-ESM-LR	yes	yes	yes	yes	yes
	MPI-ESM-MR					
	MPI-ESM-P					
NASA-GISS	GISS-E2-H	yes	yes	yes	yes	yes
	GISS-E2-H-CC					
	GISS-E2-R					
	GISS-E2-R-CC					
NASA-GMAO	GEOS-5	yes	yes	yes	no	yes
NCAR	CCSM4	yes	yes	no	yes	yes
NCC	NorESM1-M	yes	yes	yes	yes	yes
	NorESM1-ME					
NICAM	NICAM.09	no	yes	no	no	yes
NOAA-GFDL	GFDL-CM2.1	yes	yes	yes	yes	yes
	GFDL-CM3					
	GFDL-ESM2G					
	GFDL-ESM2M					
	GFDL-HIRAM-C180					
	GFDL-HIRAM-C360					
NSF-DOE-NCAR	CESM1(BGC)	yes	yes	yes	yes	yes
	CESM1(CAM5)					
	CESM1(CAM5.1,FVV2)					
	CESM1(FASTCHEM)					

	CESM1(WACCM)					

Appendix A: Templates of emails used to contact the model development teams

A1 First email

Dear Sir/Madame,

my name is Michael García Rodríguez and I am an MSc Student at the EPhysLab in the Universidade de Vigo, Spain (http://ephyslab.uvigo.es). I am developing my MSc Thesis on the study of qualitative issues of climate models, mostly re-
5   lated to scientific reproducibility and copyright issues.

In order to do it, I have focused my research project on the study of the models that contributed to the last CMIP5 report. For it, I am trying to get access to the code of all the models that reported results of this effort.

Therefore I would like kindly request access to the code of your model, $MODEL-NAME$, namely the version that you used to produce CMIP5 results. Therefore, could you say me how could I get access to it?

10   Many thanks in advance.

Best regards,

Michael García Rodríguez

EPhysLab

Universidade de Vigo

15   http://ephyslab.uvigo.es

========================

A2 Third email

Dear Sir/Madame,

We are not trying to understand the code but some way to make qualitative measurements of the code most the focus of copy-
20   right use and scientific reproducibility, focusing on how easy it is to get access to the code of the models. Size and complexity of the code is not a problem from my point of view. What you describe is similar to how other models are but for example, the CESM team has provided a tarball file maybe you can do something similar. We are not going to try to understand the physics of the code. If the amount of work is so great that in fact, you can not to deal with it, could you explain me why? It would be of great help, in case of not being able to get the code of the model, know the answer. Please, if it's possible, mark with a cross
25   one or more answers on below:

[ ] Because of restrictions imposed by the institution/s where the model is developed

[ ] Copyright issues (please, if you mark this choice, could you send me a copy of the licenses?)

[ ] Development team policy

[ ] Legal restrictions of your country

30   [ ] Others reasons (please specify):

____-

In this case, I will be able to write down the reasons why I was not allowed access to the code and I could document it in my MSc Thesis on the study of qualitative issues of climate models.

thank you for your time, I really appreciate it.

Best regards,

Michael García Rodríguez

EPhysLab

Universidade de Vigo

http://ephyslab.uvigo.es

========================

Author contributions. All the authors participated in the design of the study and writting of the text. MGR and JAA made the attemps to get access to the code of climate models.

Competing interests. We do not have competing interest.

Acknowledgements. This research was partially supported by the ZEXMOD Project of the Goverment of Spain (CGL2015-71575-P) and the European Regional Development Fund (ERDF). Juan A. Añel is supported by a 'Ramón y Cajal' Grant funded by the Government of Spain (RYC-2013-14560). We would like to thank to Didier Roche, Julia Hargreaves, Rolf Sander, Richard Neale and two anonymous referees for useful comments to improve this paper.

References

ACM: Artifact Review and Badging, Tech. rep., https://www.acm.org/publications/policies/artifact-review-badging, 2018.

Allison, D., Shiffrin, R., and Stodden, V.: Reproducibility of research: Issues and proposed remedies, Proc. Nat. Ac. Sci., 115, 2561–2562, https://doi.org/10.1073/pnas.1802324115, 2018.

Añel, J. A.: The importance of reviewing the code, Communications of the ACM, 54, 40–41, https://doi.org/10.1145/1941487.1941502, 2011.

Añel, J. A.: Comment on 'Most computational hydrology is not reproducible, so is it really science?' by Hutton et al., Water Resour. Res., 53, 2572–2574, https://doi.org/10.1002/2016WR020190, 2017.

Añel, J. A.: Reflections on the Scientific Method at the beginning of the twenty-first century, Contemp. Phys., 60, 60–62, https://doi.org/10.1080/00107514.2019.1579863, 2019.

Añel, J. A., Montes, D. P., and Rodeiro Iglesias, J.: Cloud and Serverless Computing for Scientists, Springer, https://doi.org/10.1007/978-3-030-41784-0, 2020.

Barnes, N.: Publish your computer code: it is good enough, Nature, 467, 753, https://doi.org/10.1038/467753a, 2010.

Boulanger, A.: Open-source versus proprietary software: Is one more reliable and secure than other?, IBM Syst. J., 44, 239–248, https://doi.org/10.1147/sj.442.0239, 2005.

DoD CIO: Clarifying Guidance Regarding Open Source Software (OSS), Tech. rep., 2009.

Easterbrook, S. M.: https://www.easterbrook.ca/steve/2009/06/getting-the-source-code-for-climate-models, 2009.

Easterbrook, S. M.: Climate change: a grand software challenge, FoSER '10: Proceedings of the FSE/SDP workshop on Future of software engineering research, pp. 99–104, https://doi.org/10.1145/1882362.1882383, 2010.

Easterbrook, S. M.: Open code for open science?, Nat. Geosci., 7, 779–781, https://doi.org/10.1038/ngeo2283, 2014.

Easterbrook, S. M. and Johns, T.: Engineering the Software for Understanding Climate Change, Comput. Sci. Eng., 11, 65–74, https://doi.org/10.1109/MCSE.2009.193, 2009.

European Patent Office: European Patent Convention, 2016.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Mod. Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

Fanelli, D.: Opinion: Is science really facing a reproducibility crisis, and do we need it to?, Proc. Nat. Ac. Sci., 115, 2628–2631, https://doi.org/10.1073/pnas.1708272114, 2018.

García-Rodríguez, M., Añel, J. A., Foujols, M.-A., and Rodeiro, J.: FortranAnalyser: a software tool to assess Fortran code quality, submitted to SoftwareX, http://fortrananalyser.ephyslab.uvigo.es/, 2020.

GMD Executive Editors: Editorial: The publication of geoscientific model developments v1.1, Geosci. Mod. Dev., 8, 3487–3495, https://doi.org/10.5194/gmd-8-3487-2015, 2015.

GMD Executive Editors: Editorial: The publication of geoscientific model developments v1.2, Geosci. Mod. Dev., 12, 2215–2225, https://doi.org/10.5194/gmd-12-2215-2019, 2019.

Gramelsberger, G., Lenhard, J., and Parker, W.: Philosophical Perspectives on Earth System Modeling: Truth, Adequacy, and Understanding, J. Adv. Model. Earth Syst., 12, e2019MS001 720, 2020.

IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Joppa, L. N., McInerny, G., Harper, R., Salido, L., Takeda, K., O'Hara, K., Gavaghan, D., and Emmot, S.: Troubling Trends in Scientific Software Use, Science, 340, 814–815, https://doi.org/10.1126/science.1231535, 2013.

Knutti, R., Masson, D., and Gettelman, A.: Climate model genealogy: Generation CMIP5 and how we got there, Geophys. Res. Lett., 40, 1194–1199, https://doi.org/10.1002/grl.50256, 2013.

Lee, B. D.: Ten simple rules for documenting scientific software, PLoS Comput. Biol., 14, e1006 561, https://doi.org/10.1371/journal.pcbi.1006561, 2018.

LeVeque, R. J.: Top Ten Reasons To Not Share Your Code (and why you should anyway), SIAM News, 46, 7–8, 2013.

Massonnet, F., Ménégoz, M., Acosta, M., Yepes-Arbós, X., Exarchou, E., and Doblas-Reyes, F. J.: Replicability of the EC-Earth3 Earth System Model under a change in computing environment (in review), Geosci. Mod. Dev. Discuss., https://doi.org/10.5194/gmd-2019-91, 2019.

Merali, Z.: Computational science: ...Error, Nature, 467, 775–777, https://doi.org/10.1038/467775a, 2010.

Morgenstern, O., Hegglin, M. I., Rozanov, E., O'Connor, F. M., Abraham, N. L., Akiyoshi, H., Archibald, A. T., Bekki, S., Butchart, N., Chipperfield, M. P., Deushi, M., Dhomse, S. S., Garcia, R. R., Hardiman, S. C., Horowitz, L. W., Jöckel, P., Josse, B., Kinnison, D., Lin, M., Mancini, E., Manyin, M. E., Marchand, M., Marécal, V., Michou, M., Oman, L. D., Pitari, G., Plummer, D. A., Revell, L. E., Saint-Martin, D., Schofield, R., Stenke, A., Stone, K., Sudo, K., Tanaka, T. Y., Tilmes, S., Yamashita, Y., Yoshida, K., and Zeng, G.: Review of the global models used within phase 1 of the Chemistry–Climate Model Initiative (CCMI) , Geosci. Mod. Dev., 10, 639–671, https://doi.org/10.5194/gmd-10-639-2017, 2017.

Morin, A., Urban, J., and Sliz, P.: A Quick Guide to Software Licensing for the Scientist-Programmer, PLoS Comput. Biol., 8, e1002 598, https://doi.org/10.1371/journal.pcbi.1002598, 2012.

Nature: Does your code stand up to scrutiny?, Nature, 555, https://doi.org/10.1038/d41586-018-02741-4, 2018.

Pascoe, C., Lawrence, B., Guilyardi, E., Juckes, M., and Taylor, K. E.: Designing and Documenting Experiments in CMIP6, Geosci. Mod. Dev., https://doi.org/10.5194/gmd-2019-98, 2020.

Perkel, J. M.: Containers in the Cloud, Nature, 575, 247–248, https://doi.org/10.1038/d41586-019-03366-x, 2019.

Pipitone, J. and Easterbrook, S.: Assessing climate model software quality: a defect density analysis of three models, Geosci. Mod. Dev., 5, 1009–1022, https://doi.org/10.5194/gmd-5-1009-2012, 2012.

RealClimate.org: http://www.realclimate.org/index.php/data-sources, 2009.

Righi, M., Andela, B., Eyring, V., Lauer, A., Predoi, V., Schlund, M., Vegas-Regidor, J., Bock, L., Brötz, B., de Mora, L., Diblen, F., Dreyer, L., Drost, N., Earnshaw, P., Hassler, B., Koldunov, N., Little, B., Loosveldt Tomas, S., and Zimmermann, K.: ESMValTool v2.0 – Technical overview , Geosci. Mod. Dev., https://doi.org/https://doi.org/10.5194/gmd-2019-226, 2020.

Stodden, V., Guo, P., and Ma, Z.: Toward Reproducible Computational Research: An Empirical Analysis of Data and Code Policy Adoption by Journals, PLoS ONE, 8, e67 111, https://doi.org/10.1371/journal.pone.0067111, 2013.

Stodden, V., Seiler, J., and Ma, Z.: An empirical analysis of journal policy effectiveness for computational reproducibility, Proc. Nat. Ac. Sci., 115, 2584–2589, https://doi.org/10.1073/pnas.1708290115, 2018.

Stouffer, R., Eyring, V., Meehl, G., Bony, S., Senior, C., Stevens, B., and Taylor, K.: CMIP5 Scientific Gaps and Recommendations for CMIP6 , Bull. Amer. Meteorol. Soc., 98, 95–105, https://doi.org/10.1175/BAMS-D-15-00013.1, 2017.

Taylor, K., Stouffer, R., and Meehl, G.: An Overview of CMIP5 and the Experiment Design, Bull. Amer. Meteorol. Soc., pp. 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

U.S. Code: 17 U.S. Code § Section 105. Subject matter of copyright: United States Government works, 1976.

van Wendel de Joode, R., de Bruijn, J. A., and van Eeten, M. J. G.: Protecting the Virtual Commons, T.M.C. Asser Press, 2003.

Wieters, N. and Fritzsch, B.: Opportunities and limitations of software project management in geoscience and climate modelling, Adv.
Geosci., 45, 383–387, https://doi.org/10.5194/adgeo-45-383-2018, 2018.

Wilson, G., Bryan, J., Cranston, K., Kitzes, J., Nederbragt, L., and Teal, T.: Good enough practices in scientific computing, PLoS Comput. Biol., 13, e1005 510, https://doi.org/10.1371/journal.pcbi.1005510, 2017.