



1 The Cloud Feedback Model Intercomparison Project (CFMIP) 2 contribution to CMIP6.

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23 Abstract

24 The primary objective of CFMIP is to inform future assessments of cloud feedbacks through improved understanding of
25 cloud-climate feedback mechanisms and better evaluation of cloud processes and cloud feedbacks in climate models.
26 However, the CFMIP approach is also increasingly being used to understand other aspects of climate change, such as
27 nonlinear change and regional changes in atmospheric circulation and precipitation. CFMIP is supporting ongoing model
28 inter-comparison activities by coordinating a hierarchy of targeted experiments for CMIP6, along with a set of cloud related
29 output diagnostics. CFMIP contributes primarily to addressing the CMIP6 questions "How does the Earth System respond to
30 forcing?" and "What are the origins and consequences of systematic model biases?" and supports the activities of the WCRP
31 Grand Challenge on Clouds, Circulation and Climate Sensitivity.

32 A compact set of Tier 1 experiments is proposed for CMIP6 to address the question: "1) What are the physical mechanisms
33 underlying the range of cloud feedbacks and cloud adjustments predicted by climate models, and which models have the most
34 credible cloud feedbacks?" Additional Tier 2 experiments are proposed to address the following questions: 2) Are cloud
35 feedbacks consistent for climate cooling and warming, and if not, why? 3) How do cloud-radiative effects impact the
36 structure, the strength and the variability of the general atmospheric circulation in present and future climates? 4) How do
37 responses in the climate system due to changes in solar forcing differ from changes due to CO₂, and is the response sensitive
38 to the sign of the forcing? 5) To what extent is regional climate change per CO₂ doubling state-dependent (nonlinear), and
39 why? 6) Are climate feedbacks during the 20th century different to those acting on long term climate change and climate
40 sensitivity? 7) How do regional climate responses (e.g. in precipitation) and their uncertainties in coupled models arise from
41 the combination of different aspects of CO₂ forcing and sea surface warming?

42 CFMIP also proposes a number of additional model outputs in the CMIP DECK, CMIP6 Historical and CMIP6 CFMIP
43 experiments, including COSP simulator outputs and process diagnostics to address the following questions: 1) How well do
44 clouds and other relevant variables simulated by models agree with observations? 2) What physical processes and
45 mechanisms are important for a credible simulation of clouds, cloud feedbacks and cloud adjustments in climate models? 3)
46 Which models have the most credible representations of processes relevant to the simulation of clouds? 4) How do clouds
47 and their changes interact with other elements of the climate system?



48 1 Introduction

49 Inter-model differences in cloud feedbacks continue to be the largest source of uncertainty in predictions of equilibrium
50 climate sensitivity (Boucher et al., 2013). Although the ranges of cloud feedbacks and climate sensitivity from
51 comprehensive climate models have not reduced in recent years, considerable progress has been made in understanding (a)
52 which types of clouds contribute most to this spread (e.g. Bony and Dufresne 2005; Webb et al., 2006; Zelinka et al., 2013),
53 (b) the role of cloud adjustments in climate sensitivity (e.g. Gregory and Webb, 2008; Andrews and Forster, 2008; Kamae
54 and Watanabe, 2012; Vial et al., 2013; Zelinka et al., 2013), (c) the processes and mechanisms which are (and are not)
55 implicated in cloud feedbacks (e.g. Rieck et al., 2012; Brient and Bony 2012; Webb and Lock 2013; Brient and Bony 2013;
56 Sherwood et al., 2014; Ringer et al., 2014; Medeiros et al., 2015; Bretherton et al., 2015; Zhao, 2015; Webb et al., 2015b), (d)
57 the inconstancy of cloud feedbacks and effective climate sensitivity (e.g. Senior and Mitchell, 2000; Williams et al., 2008;
58 Andrews et al., 2012; Geoffroy et al., 2013; Armour et al., 2013; Andrews et al., 2015), and (e) the extent to which models
59 with stronger or weaker cloud feedbacks or climate sensitivities agree with observations (e.g. Fasullo and Trenberth, 2012; Su
60 et al., 2014; Qu et al., 2014; Sherwood et al., 2014; Brient et al., 2015; Tsushima et al., 2015; Myers and Norris, 2016).
61 Additionally, our ability to evaluate model clouds using satellite data has benefited from the increasing use of satellite
62 simulators. This approach first introduced by Yu et al, 1996 for use with data from the International Satellite Cloud
63 Climatology Project (ISCCP) attempts to reproduce what a satellite would observe given the model state. Such approaches
64 enable more quantitative comparisons to the satellite record (e.g. Yu et al., 1996; Klein and Jakob, 1999; Webb et al., 2001;
65 Marchand and Ackerman, 2010; Bodas-Salcedo et al., 2011; Nam et al., 2012a; Cesana and Chepfer, 2013; Klein et al., 2013;
66 Chepfer et al., 2014). Much of our improved understanding in these areas would have been impossible without the
67 continuing investment of the scientific community in successive phases of the Coupled Model Intercomparison Project
68 (CMIP), and its co-evolution in more recent years with the Cloud Feedback Model Intercomparison Project (CFMIP).

69 CFMIP started in 2003 and its first phase (CFMIP-1) organised an intercomparison based on perpetual July SST forced Cess
70 style +2K experiments and 2xCO₂ equilibrium mixed-layer model experiments containing ISCCP simulator in parallel with
71 CMIP3 (McAvaney and Le Treut, 2003). CFMIP-1 had a substantial impact on the evaluation of clouds in models and in the
72 identification of low level cloud feedbacks as the primary cause of inter-model spread in cloud feedback, which featured
73 prominently in the fourth and fifth IPCC assessments (Randall et al., 2007; Boucher et al., 2013).

74 The subsequent objective of CFMIP-2 was to inform improved assessments of climate change cloud feedbacks by providing
75 better tools to support evaluation of clouds simulated by climate models and understanding of cloud-climate feedback
76 processes. CFMIP-2 organized further experiments as part of CMIP5 (Bony et al., 2011; Taylor et al., 2012), introducing
77 seasonally varying SST perturbation experiments for the first time, as well as fixed SST CO₂ forcing experiments to examine
78 cloud adjustments. CFMIP-2 also introduced idealized ‘aquaplanet’ experiments into the CMIP family of experiments.
79 These experiments were motivated by extensive research in the framework of the aqua-planet experiment (Neale and
80 Hoskins, 2000, Blackburn and Hoskins, 2013) and the particular finding, based on a small subset of models, that the global
81 mean cloud feedback of more realistic model configurations could be reproduced, and more easily investigated, using the
82 much simpler aqua-planet configuration (Medeiros et al., 2008). CFMIP-2 proposed the inclusion of the abrupt CO₂
83 quadrupling AOGCM experiment in the core experiment set of CMIP5, based on the approach of Gregory et al., 2004, which
84 subsequently formed the basis for equilibrium climate sensitivity estimates from AOGCMs (Andrews et al., 2012).
85 Additionally CFMIP-2 introduced satellite simulators to CMIP via the CFMIP Observation Simulator Package (COSP,
86 Bodas-Salcedo et al., 2011); not only the ISCCP simulator, but additional simulators to facilitate the quantitative evaluation
87 clouds using a new generation of active radars and lidars in space. CFMIP-2 also introduced into CMIP5 process diagnostics
88 such as temperature and humidity budget tendency terms and high frequency ‘cfSites’ outputs at 120 locations around the
89 globe. In an effort less directly connected to CMIP, CFMIP organized a joint project with the GEWEX Global Atmospheric
90 System Study (GASS) called CGILS (the CFMIP-GASS Intercomparison of LES and SCMs) to develop cloud feedback
91 intercomparison cases to assess the physical credibility of cloud feedbacks in climate models by comparing Single Column
92 Models (SCM) versions of GCMs with high resolution Large Eddy Simulations (LES) models. CFMIP-2 also developed the
93 CFMIP-OBS data portal and the CFMIP diagnostic codes catalogue. For more details, and for a full list of CFMIP related
94 publications, please refer to the CFMIP web site (<http://www.earthsystemcog.org/projects/cfmip>).

95 Studies arising from CFMIP-2 include numerous single and multi-model evaluation studies which use COSP to make
96 quantitative and fair comparisons with a range of satellite products (e.g. Nam et al., 2012; Gregory and Chepfer, 2012; Kay et
97 al., 2012; Franklin et al., 2013; Klein et al., 2013, Lin et al., 2014.). COSP has also enabled studies attributing cloud
98 feedbacks and cloud adjustments to different cloud types (e.g. Zelinka et al., 2013; Zelinka et al., 2014; Tsushima et al.,
99 2015). CFMIP-2 additionally enabled the finding that idealized ‘aquaplanet’ experiments without land, seasonal cycles or
100 Walker circulations are able to reproduce the essential differences between models’ global cloud feedbacks and cloud
101 adjustments in a substantial ensemble of models (Ringer et al., 2014; Medeiros et al., 2015). Process outputs from CFMIP
102 have also been used to develop and test physical mechanisms proposed to explain and constrain inter-model spread in cloud
103 feedbacks in the CMIP5 models (e.g. Webb and Lock, 2013; Sherwood et al., 2014; Brient et al., 2015; Webb et al., 2015a;
104 Nuijens et al., 2015a,b; Dal Gesso et al., 2015). CGILS has demonstrated a consensus in the responses of LES models to
105 climate forcings and identified shortcomings in the physical representations of cloud feedbacks in climate models (e.g.



106 Blossy et al., 2013; Zhang et al., 2013; Dal Gesso et al., 2015). The CFMIP experiments have additionally formed the basis
 107 for coordinated experiments to explore the impact of cloud radiative effects on the circulation (Stevens et al., 2012; Ferpel
 108 and Bony 2014; Crueger and Stevens 2015; Li et al., 2015; Harrop and Hartmann 2016), the impact of parametrized
 109 convection on cloud feedback (Webb et al., 2015b) and the mechanisms of negative shortwave cloud feedback in mid to high
 110 latitudes (Ceppi et al., 2015). Additionally the CFMIP experiments have, due to their idealized nature, proven useful in a
 111 number of studies not directly related to clouds, but instead analyzing the responses of regional precipitation and circulation
 112 patterns to CO₂ forcing and climate change (e.g. Bony et al., 2013; Chadwick et al., 2014; He and Soden 2015; Oueslati et al.,
 113 2016). Studies using CFMIP-2 outputs from CMIP5 remain ongoing and further results are expected to feed into future
 114 assessments of the representation of clouds and cloud feedbacks in climate models.

115 The primary goal of CFMIP is to inform improved assessments of cloud feedbacks on climate change. However, the CFMIP
 116 approach is increasingly being used to understand other aspects of climate response, such as regional circulation and
 117 precipitation changes, and non-linear changes. This involves bringing climate modelling, observational and process
 118 modelling communities closer together and providing better tools and community support for evaluation of clouds and cloud
 119 feedbacks simulated by climate models and for understanding of the mechanisms underlying them. This is achieved by:

- 120 • Coordinating model inter-comparison activities which include experimental design as well as specification of
- 121 model output diagnostics to support quantitative evaluation of modelled clouds with observations (e.g. COSP)
- 122 and in-situ measurements (e.g. cfSites) as well as process-based investigation of cloud maintenance and
- 123 feedback mechanisms (e.g. cfSites, temperature and humidity tendency terms)
- 124 • Developing and improving support infrastructure including COSP, CFMIP-OBS and the CFMIP diagnostic
- 125 codes catalogue.
- 126 • Fostering collaboration with the observational and cloud process modelling communities via annual CFMIP
- 127 meetings international funded projects.

128 CFMIP-3 touches, to differing degrees, on each of the three questions around which CMIP6 is organized (Eyring et al.,
 129 2015). With its focus on cloud feedback, CFMIP-3 is central to CMIP6's attempt to answer the question: 'How does the
 130 Earth system respond to forcing?' But as illustrated in the remainder of this document, CFMIP-3 also offers the opportunity
 131 to contribute to the other two guiding questions of CMIP6. Through its strong model evaluation component it stands to help
 132 answer the question: 'What are the origins and consequences of systematic model biases?' CFMIP-3 will also help answer the
 133 question: 'How can we assess future climate changes given climate variability, climate predictability, and uncertainties in
 134 scenarios?' For example the *amip-piForcing* experiment proposed below will support studies relating cloud variability and
 135 feedbacks on observable timescales to long term cloud feedbacks (Andrews, 2014; Gregory and Andrews, submitted).

136 The CFMIP experiments proposed for CMIP6, here referred to as CFMIP-3 are outlined below in Section 2. It is anticipated
 137 that CFMIP-3 will eventually be broader than what is described here, for instance including studies with process models, but
 138 for the purposes of this document CFMIP-3 should be considered to be synonymous with the CFMIP contribution to CMIP6.
 139 Section 3 describes the diagnostics outputs proposed for the CFMIP-3, CMIP DECK and CMIP6-Historical experiments. We
 140 provide a summary of the CFMIP-3 contribution to CMIP6 in Section 5.

141

142 2 CFMIP-3 Experiments

143 The CFMIP-3 experiments are summarised in Figure 1 and Tables 1 and 2, and are described in detail below. Following the
 144 CMIP6 design protocol, groups of experiments are motivated by science questions and are separated into Tiers 1 and 2
 145 (Eyring et al., 2015). It is a requirement for participation by modelling groups in the CFMIP-3/CMIP6 model
 146 intercomparison that all Tier 1 experiments be performed and published through the ESGF, so as to support CFMIP's Tier 1
 147 science question. Tier 2 experiments are optional, and are associated with additional science questions. Any subset of Tier
 148 2 experiments may be performed. All model output archived by CFMIP/CMIP6 is expected to be made available under the
 149 same terms as CMIP output. Most modelling groups currently release their CMIP data for unrestricted use. Our analysis
 150 plans for the CFMIP-3 experiments are summarised in Appendix A.

151 2.1 CFMIP-3 Tier 1 Experiments

152 Lead coordinator: Mark Webb

153

154 Science Question: What are the physical mechanisms underlying the range of cloud feedbacks and cloud adjustments
 155 predicted by climate models, and which of the cloud responses are the most credible?

156

157 Equilibrium climate sensitivity (ECS) can be estimated using an idealized AOGCM experiment such as the *abrupt-4xCO2*
 158 experiment in the CMIP6 DECK, at the same time statistically separating the global mean contributions from climate
 159 feedbacks and adjusted radiative forcing due to CO₂ (Gregory et al. 2004, Andrews et al., 2012). However understanding the
 160 physical processes underlying cloud feedbacks and adjustments requires diagnosis in SST forced experiments, which can



161 resolve cloud feedbacks and adjustments independently from each other and with minimal statistical noise at regional scales,
 162 while faithfully reproducing the inter-model differences in global values from the fully coupled models (Ringer et al., 2014).
 163 (The ability of these AGCM experiments to reproduce the inter-model differences in global cloud feedbacks and adjustments
 164 from coupled models indicates that they do not strongly depend on different ocean model formulations or SST biases). The
 165 CFMIP-2 *amip4xCO2* experiments in CMIP5, which quadrupled CO₂ while leaving SSTs at present day values (Bony et al.,
 166 2011), allowed the land/tropospheric adjustment process and the cloud adjustment to CO₂ to be examined in this way for the
 167 first time in the multi-model context (Kamae and Watanabe, 2012; Ringer et al., 2014; Kamae et al. 2015) in conjunction
 168 with the CMIP5 *sstClim/sstClim4xCO2* experiments which were based on climatological preindustrial SSTs (Andrews et al.,
 169 2012; Zelinka et al., 2013; Vial et al., 2013). These experiments have additionally formed the basis for more in-depth studies
 170 with individual models (e.g. Wyant et al., 2012; Kamae and Watanabe, 2013; Bretherton et al., 2014, Ogura et al., 2014).
 171 The CFMIP-2/CMIP5 *amip4K* and *amipFuture* SST perturbed atmosphere-only experiments (Bony et al., 2011) have been
 172 used to examine cloud feedbacks in greater detail, often in conjunction with CFMIP process diagnostics (e.g. Brient and
 173 Bony, 2012; Webb and Lock, 2013; Brient and Bony, 2013; Ringer et al., 2014; Bretherton et al., 2014; Lacagnina et al.,
 174 2014; Gordon and Klein, 2014; Chepfer et al., 2014; Sherwood et al., 2014; Medeiros et al., 2015; Brient et al., 2015;
 175 Tsushima et al., 2015; Bellomo and Clement, 2015; Dal Gesso et al., 2015; Webb et al., 2015a, Webb et al., 2015b, Ceppi
 176 et al., 2016). Similarly, these experiments have been used to investigate responses of regional precipitation, circulation and
 177 stability to direct radiative forcing due to increasing CO₂ concentrations and/or increases in SST (Bony et al. 2013; Ma and
 178 Xie, 2013; Huang et al., 2013; Widlansky et al., 2013; He et al., 2014; Zhou et al., 2014; Chadwick et al. 2014; Grise and
 179 Polvani, 2014; Kamae et al., 2014; Ceppi et al., 2014; Xie et al. 2015; Qu et al., 2015; Bellomo and Clement, 2015; Shaw and
 180 Voigt, 2015; Kent et al., 2015; Long et al., 2016; Chadwick, 2016).

181

182 A more idealized set of fixed SST experiments proposed by CFMIP-2 for CMIP5 (*aquaControl*, *aqua4xCO2*, and *aqua4K*)
 183 based on zonally symmetric, fixed season ‘aquaplanet’ configurations without land have been shown to reproduce the inter-
 184 model differences in global mean cloud adjustments and feedbacks from realistic experiments surprisingly effectively
 185 (Medeiros et al., 2008; Ringer et al., 2014; Medeiros et al., 2015) as well as many aspects of the zonal mean circulation
 186 response (Medeiros et al., 2015). This indicates that those features of the climate system excluded from these experiments
 187 (i.e. the ocean, land, seasonal cycle, monsoon and Walker circulations) are not central to understanding inter-model
 188 differences in global mean cloud feedbacks and adjustments, and demonstrates the value of aquaplanet experiments for
 189 investigating the origin of such differences, as well as differences in zonally averaged precipitation and circulation and their
 190 responses to climate change (e.g. Stevens et al., 2012; Bony et al., 2013; Brient and Bony, 2013; Kamae and Watanabe 2013;
 191 Oueslati and Bellon, 2013; Fermepin and Bony 2014; Qu et al., 2015; Voigt and Shaw 2015; Harrop and Hartmann, 2015;
 192 Ceppi et al., 2015). The aquaplanet experiments have the benefit not only of being less computationally expensive than
 193 alternative experiments (requiring only 5-10 years to get a robust signal); they are also much more straightforward to analyse,
 194 as their behaviour can mostly be characterized by examining zonal means, avoiding the analysis overhead of compositing
 195 which is generally required in realistic model configurations to isolate the various cloud regimes. Because for the Aqua-
 196 planet simulations it is not possible to tune the models to reproduce a known answer, these (and other idealized) experiments
 197 are particularly effective at highlighting model differences, for instance in the placement of the tropical rain bands, or in the
 198 representation of cloud changes with warming (e.g., Stevens and Bony, 2013).

199

200 The CMIP5/CFMIP-2 experiments and diagnostic outputs have thus enabled considerable progress on a number of questions.
 201 However, participation by a larger fraction of modelling groups is desired in CMIP6 to enable a more comprehensive
 202 assessment of the uncertainties across the full multi-model ensemble. Our proposal is therefore to retain the CFMIP-2/CMIP5
 203 experiments (known in CMIP5 as *amip4K*, *amip4xCO2*, *amipFuture*, *aquaControl*, *aqua4xCO2* and *aqua4K*) in Tier 1 for
 204 CFMIP/CMIP6. These are summarised in Table 1 (the names have been changed slightly compared to the CMIP5 equivalents
 205 to fit in with a wider naming convention of CMIP6). The set up for each of these experiments is described below. (For
 206 output requirements from these and other experiments please refer to Section 3).

207

208 *amip*: This is a single ensemble member of the CMIP DECK *amip* experiment which contains additional outputs which are
 209 required both for model evaluation using COSP, and for interpretation of feedbacks and adjustments in conjunction with the
 210 *amip-p4K*, *amip-4xCO2*, *amip-future4K* and *amip-m4K* experiments.

211

212 *amip-p4K* (formerly *amip4K*): The same as the *amip* DECK experiment, except that SSTs are subject to a uniform warming
 213 of 4K. This warming should be applied to the ice free ocean surface only. Sea ice and SSTs under sea ice remain the same
 214 as in the *amip* DECK experiment.

215

216 *amip-future4K* (formerly *amipFuture*): The same as the *amip* DECK experiment, except that a composite SST warming
 217 pattern derived from the CMIP3 coupled models is added to the AMIP SSTs (see Appendix C for details). As with the *amip-
 218 p4K* experiment, the warming pattern should only be applied to the ice free ocean surface, and sea ice and SSTs under sea ice
 219 should remain the same as in the *amip* DECK experiment. The warming pattern should be scaled to ensure that the global
 220 mean SST increase averaged over the ice free oceans is 4K.

221



222 *amip-4xCO2* (formerly *amip4xCO2*): The same as the *amip* experiment within the DECK, except that the CO₂ concentration
 223 seen by the radiation scheme is quadrupled. The CO₂ seen by the vegetation should be the same as in the *amip* DECK
 224 experiment. This experiment gives an indication of the adjusted radiative forcing due to CO₂ quadrupling, including
 225 stratospheric, land surface, tropospheric and cloud adjustments.

226

227 The configuration of the *aqua-control*, *aqua-p4K* and *aqua-4xCO2* experiments are unchanged compared to their equivalents
 228 in CFMIP-2/CMIP5, except that the simulation length has been extended to 10 years to improve the signal to noise ratio.
 229 Further details of their experimental set up are included in Appendix B.

230

231 We also propose to use the Tier 1 experiments as the foundation for further experiments planned in the context of the Grand
 232 Challenge on Clouds, Circulation and Climate Sensitivity (Bony et al., 2015). These will include for example sensitivity
 233 experiments to assess the impacts of different physical processes on cloud feedbacks and regional circulation/precipitation
 234 responses and also to test specifically proposed cloud feedback mechanisms (e.g. Webb et al., 2015b, Ceppi et al., 2015).
 235 Additional experiments further idealizing the aquaplanet framework to a non-rotating rotationally symmetric case are also
 236 under development (e.g. Popke et al., 2013). These will be proposed as additional Tier 2 experiments at a future time, or
 237 coordinated by CFMIP outside of CMIP6.

238 2.2 *amip* minus 4K Experiment (Tier 2)

239 Lead Coordinators: Mark Webb and Bjorn Stevens

240

241 Science Question: Are cloud feedbacks consistent for climate cooling and warming, and if not, why?

242

243 There is some evidence to suggest that cloud feedbacks might operate differently in response to cooling rather than warming.
 244 For example, Yoshimori et al., 2009 found a positive shortwave cloud feedback in a CO₂ doubling experiment with a
 245 particular GCM, but noted a tendency for it to become weaker or even negative in cooling experiments designed to replicate
 246 the climate of the last glacial maximum. They suggested that this might be related to different displacements of mixed-phase
 247 clouds in the two scenarios. For small enough changes where linearity is a good approximation, one would expect the cloud
 248 response to cooling and warming to be the same, differing only in sign, resulting in an identical cloud feedback expressed per
 249 degree of global temperature change. But for larger perturbations this symmetry of response may no longer hold. A
 250 warming or cooling of the atmosphere of equal magnitude while maintaining relative humidity will for example generate
 251 different changes in absolute humidity, and its horizontal and vertical gradients, which have been linked to cloud feedbacks
 252 (Brient and Bony, 2013; Sherwood et al., 2014), the atmospheric lapse rate and circulation which influences clouds and
 253 depends in part on the absolute humidity (Held and Soden, 2006; Qu et al., 2015) and additionally on extratropical cloud
 254 optical depth feedbacks which may be related to adiabatic cloud liquid water contents (Gordon and Klein, 2014) or phase
 255 changes that depend upon whether a given volume crosses the 0 degree isotherm in the climate change (Ceppi et al. 2015).

256

257 The configuration of the *amip-m4K* experiment will be the same as the *amip-p4K* experiment, except that the sea surface
 258 temperatures are uniformly reduced by 4K rather than increased. This cooling should be applied to the ice free ocean surface
 259 only. Sea ice and SSTs under sea ice remain the same as in the *amip* DECK experiment. This experiment will contain
 260 CFMIP COSP and process outputs so as to support the investigation of inconsistent responses of clouds to a cooling vs. a
 261 warming climate in a controlled way through comparison with the *amip-p4K* experiment. This experiment also complements
 262 the abrupt 0.5xCO₂ and the -4% solar experiments in that one can identify asymmetries in the warming/cooling response with
 263 and without interactions with the ocean. As such we hope that these experiments will provide useful synergies with
 264 Palaeoclimate Model Intercomparison Project (PMIP).

265

266 2.3 Atmosphere-only experiments without longwave cloud radiative effects. (Tier 2)

267 Lead Coordinators: Sandrine Bony and Bjorn Stevens

268

269 Science question: How do cloud-radiative effects impact the structure, the strength and the variability of the general
 270 atmospheric circulation in present and future climates?

271

272 It is increasingly recognized that clouds, and atmospheric cloud-radiative effects in particular, play a critical role in the
 273 general circulation of the atmosphere and its response to global warming or other perturbations: they have been found to
 274 modulate the structure, the position and shifts of the ITCZ (e.g. Slingo and Slingo 1988; Randall et al., 1989; Sherwood et al
 275 1994; Bergman and Hendon 2000; Hwang and Frierson, 2013; Fermepin and Bony 2014; Voigt et al., 2014; Loeb et al.,
 276 2015; Voigt and Shaw, 2015), the organisation of convection in tropical waves, Madden-Julian Oscillations and other forms
 277 of convective aggregation (e.g. Lee et al., 2001; Lin and Mapes, 2004; Bony and Emanuel, 2005; Zurovac-Jevtic et al., 2006;
 278 Crueger and Stevens, 2015; Muller and Bony, 2015), the extra-tropical circulation and the position of eddy-driven jets



279 (e.g. Ceppi et al., 2012; Ceppi et al., 2014; Grise and Polvani 2014; Li et al., 2015), and modes of interannual to decadal
280 climate variability (e.g. Bellomo et al., 2015; Rädel et al., 2016; Yuan et al., 2016). A better assessment of this role would
281 greatly help to interpret model biases (how much do biases in cloud-radiative properties contribute to biases in the structure
282 of the ITCZ, in the position and strength of the storm tracks, in the lack of intra-seasonal variability, etc) and to inter-model
283 differences in simulations of the current climate and in climate change projections (especially changes in regional
284 precipitation and extreme events). More generally, a better understanding of how clouds couple to the circulation is expected
285 to improve our ability to answer the four science questions raised by the WCRP Grand Challenge on Clouds, Circulation and
286 Climate Sensitivity (Bony et al., 2015).

287
288 These questions provided the scientific motivation for the Clouds On/Off Klima Intercomparison Experiment (COOKIE)
289 project proposed by the European consortium EUCLIPSE and CFMIP (Stevens et al., 2012). The COOKIE experiments,
290 which have been run by four to eight climate models (depending on the experiment), switched off the cloud-radiative effects
291 (clouds seen by the radiation code -and the radiation code only- were artificially made transparent) in an atmospheric model
292 forced by prescribed SSTs. By doing so, the atmospheric circulation could feel the lack of cloud-radiative heating within the
293 atmosphere, but the land surface could also feel the lack of cloud shading, which led to changes in land surface temperatures
294 and land-sea contrasts. The change in circulation between On and Off experiments resulted from both effects, obscuring to
295 some degree the mechanisms through which the atmospheric cloud-radiative effects interact with the circulation for given
296 surface boundary conditions. As the longwave cloud-radiative effects are felt mostly within the troposphere (representing
297 most of the net atmospheric cloud-radiative heating) while the shortwave effects are felt mostly at the surface (e.g. L'Ecuyer
298 and McGarragh 2010; Haynes et al., 2013), we could better isolate the role of tropospheric cloud-radiative effects on the
299 circulation by running atmosphere-only experiments in which clouds are made transparent to radiation only in the longwave.

300
301 Therefore we propose in Tier 2 a set of simple experiments similar to the *amip*, *amip-p4K*, *aqua-control* and *aqua-p4K*
302 experiments within Tier 1, but in which cloud-radiative effects are switched off in the longwave part of the radiation code.
303 These experiments will be referred to as *amip-lwoff*, *amip-p4K-lwoff*, *aqua-control-lwoff* and *aqua-p4K-lwoff*. The analysis of
304 idealized (aqua-planet) experiments will allow us to assess the robustness of the impacts found in more realistic (AMIP)
305 configurations. It will also facilitate the interpretation of the results using simple dynamical models or theories, in
306 collaboration with large-scale dynamicists (e.g. DynVar). The comparison of the inter-model spread of simulations between
307 the standard and 'lwoff' experiments for present-day and warmer climates will help to identify which aspects of the inter-
308 model spread depend on the representation of cloud-radiative effects, and which aspects do not, thus better highlighting other
309 sources of spread.

310 **2.4 Abrupt +/-4% Solar Forced AOGCM experiments (Tier 2)**

311 Lead coordinators: Chris Bretherton, Roger Marchand, Bjorn Stevens

312

313 Science Question: How do responses in the climate system due to changes in solar forcing differ from changes due to CO₂,
314 and is the response sensitive to the sign of the solar forcing?

315

316 While rapid adjustments in clouds and precipitation can easily be separated from conventional feedbacks in SST forced
317 experiments, such a separation in coupled models is complicated by various issues, including the response of the ocean on
318 decadal timescales. A number of studies have examined cloud feedbacks in coupled models subject to a solar forcing, which
319 is generally associated with much smaller global cloud and precipitation adjustment, due to a smaller atmospheric absorption
320 for a given top of atmosphere forcing (e.g. Lambert and Faull, 2007; Andrews et al., 2010), but the regional cloud and
321 precipitation changes have yet to be rigorously investigated across models. Solar forcing also differs from greenhouse
322 forcing through its different fingerprint on the vertical structure of warming (Santer et al., 2013) and small changes in the
323 radiative heating near the tropopause may project measurably on tropospheric climate (e.g., Butler et al., 2010), for instance
324 by influencing the baroclinicity in the upper troposphere and thus the storm-tracks (Bony et al., 2015).

325

326 A +4% solar experiment *abrupt-solp4p* would be analogous to the *abrupt-4xCO2* experiment but rather than changing CO₂ it
327 would abruptly increase the solar constant by four percent and keep it fixed for 150 years, resulting in a radiative forcing of a
328 similar magnitude to that due to CO₂ quadrupling. This complements the DECK *abrupt-4xCO2* experiment, tests the forcing
329 feedback framework for analyzing climate change, and would support our understanding of regional responses of the coupled
330 system with and without CO₂ adjustments. The complementary -4% abrupt solar forcing experiment (*abrupt-solm4p*) would
331 allow the examination of feedback asymmetry under climate cooling, and would also help with the interpretation of model
332 responses to geo-engineering scenarios and volcanic forcing, and of past climate signals.

333 **2.5 nonLinMIP abrupt 2xCO₂ and abrupt 0.5xCO₂ Experiments (Tier 2)**

334 Lead Coordinator: Peter Good

335



336 Science Question: To what extent is regional-scale climate change per CO₂ doubling state-dependent (nonlinear); what are
 337 the associated mechanisms; and how does this affect our understanding of climate model uncertainty?

338

339 Recent studies with individual, or a small number of climate models, have found substantial nonlinearities in regional-scale
 340 precipitation change (Good et al., 2012; Chadwick and Good, 2013), associated with robust physical mechanisms (Chadwick
 341 and Good, 2013). Significant nonlinearity has also been found in global and regional-scale warming (e.g. Colman and
 342 McAvaney, 2009; Jonko et al., 2013; Good et al., 2015) and ocean heat uptake (Bouttes et al., 2015).

343

344 To address this science question we propose two new experiments for Tier 2, abrupt 2xCO₂ and abrupt 0.5xCO₂, based on a
 345 proven analysis approach, including traceability of these experiments to transient-forcing simulations (Good et al.,
 346 submitted), to explore global and regional-scale nonlinear responses, highlighting different behaviour under business-as-usual
 347 scenarios, mitigation scenarios and palaeoclimate simulations. Additionally comparisons of the abrupt 2xCO₂ and abrupt
 348 4xCO₂ experiments will help to establish the extent to which the latter accurately estimates the equilibrium climate sensitivity
 349 to CO₂ doubling. Additional experiments (Good et al., submitted) may be proposed for Tier 2 in the future, or coordinated
 350 via CFMIP outside of CMIP6. These include 100-year extensions to *abrupt-4xCO2* and *abrupt-2xCO2*; a 1% ramp-down
 351 from the end of the *IpcI-CO2* experiment; an abrupt step-down to 1xCO₂ from year 100 of the *abrupt-4xCO2*. These would
 352 be used to explore longer-timescale responses, quantify nonlinear mechanisms more precisely and understand the reversibility
 353 of climate change.

354 2.6 Feedbacks in AMIP experiments (Tier 2)

355 Lead Coordinator: Timothy Andrews

356

357 Science question: Are climate feedbacks during the 20th century different to those acting on long term climate change?

358

359 Recent studies have shown significant time variation in climate feedbacks in response to CO₂ quadrupling (e.g. Andrews et
 360 al., 2012; Geoffroy et al., 2013; Armour et al., 2013; Andrews et al., 2015). This raises the possibility that feedbacks during
 361 the 20th century may be different to those acting on long term change, and hence has the potential to alleviate the apparent
 362 discrepancy between estimates of climate sensitivity from comprehensive climate models and from simple climate models
 363 fitted to observed warming trends (Collins et al., 2013). For example Gregory and Andrews (submitted) found that two
 364 models forced with observed monthly 20th century SST and sea-ice variations simulated effective climate sensitivities of
 365 about 2K, whereas these same models forced with patterns of long term SST change simulated effective climate sensitivities
 366 of over 3K and 4K.

367

368 The previous CFMIP-2/CMIP5 design was unable to diagnose the time-variation of feedbacks of explicit relevance to the
 369 historical period. To address this we propose an additional experiment called '*amip-piForcing*' (*amip* pre-industrial forcing)
 370 following the design of Andrews (2014) and Gregory and Andrews (submitted). This experiment is the same as the standard
 371 *amip* run (i.e. using observed monthly updating SSTs and sea-ice), but run for the period 1870-present and with constant pre-
 372 industrial forcings (i.e. all anthropogenic and natural forcing boundary conditions identical to the *piControl* run). Since the
 373 forcing constituents do not change in this experiment it readily allows a simple diagnosis of the simulated atmospheric
 374 feedbacks to observed SST and sea-ice changes, which can then be compared to feedbacks representative of long term change
 375 and climate sensitivity (e.g. from *abrupt-4xCO2* or *amip-p4K*). The experiment has the additional benefit, by differencing
 376 with the standard *amip* run that includes time-varying forcing agents, of providing detailed information on the transient
 377 effective radiative forcing and adjustments in models (Andrews, 2014). This can then be compared to the forcings diagnosed
 378 in RFMIP (who use a pre-industrial climate baseline) to test for any dependence of forcing and adjustments on the climate
 379 state. The experiment therefore complements the alternative approach of diagnosing time-varying feedbacks, which first
 380 requires estimating the forcing and adjustments (e.g. from RFMIP) and removing them from the standard *amip* experiment,
 381 since the approach here extends the time-period of the *amip* simulation and only requires a single experiment (rather than
 382 pairs) which reduces the noise. The inclusion of CFMIP process diagnostics will also enable a deeper understanding of the
 383 factors underlying forcing and feedback differences in the present and future climate.

384 2.7 Time slice experiments for understanding regional climate responses to CO₂ (Tier 2)

385 Lead Coordinators: Robin Chadwick, Hervé Douville and Christopher Skinner

386

387 Science questions:

- 388
- 389 • How do regional climate responses (e.g. of precipitation) in a coupled model arise from the combination of
 390 responses to different aspects of CO₂ forcing and sea surface warming (uniform SST warming, patterned SST
 391 warming, sea-ice change, direct CO₂ effect, plant physiological effect)?
 - 392 • Which aspects of forcing/warming are most important for causing inter-model uncertainty in regional climate
 projections?



- 393 • Can inter-model differences in regional projections be related to underlying structural or resolution differences
 394 between models through improved process understanding, and could this help us to constrain the range of regional
 395 projections?
 396 • What impact do coupled model SST biases have on regional climate projections?
 397

398 The CFMIP-2/CMIP5 set of idealised amip experiments (e.g. *amip4K*, *amipFuture*) have allowed the contribution of different
 399 aspects of SST warming and increased CO₂ concentrations to the projections of fully coupled GCMs to be examined (e.g.
 400 Bony et al., 2013; Chadwick et al., 2014; He and Soden, 2015). However the amip experiments were not designed to replicate
 401 coupled GCM responses on a regional scale, and large discrepancies exist between the two in many regions, particularly
 402 when individual models are examined instead of the ensemble mean (Chadwick, 2016). This is largely due to the choice of
 403 present-day and future SST boundary conditions used in the amip experiments, as well as missing processes such as the plant
 404 physiological response to CO₂, rather than the lack of air-sea coupling (Skinner et al., 2012).

405 We propose a new set of 7 30-year atmosphere-only time slice experiments, and one 36-year amip-style experiment, to
 406 decompose the regional responses of each model's *abrupt-4xCO2* run into separate responses to each aspect of forcing and
 407 warming (uniform SST warming, pattern SST change, sea-ice change, increased CO₂, plant physiological effect). As well as
 408 allowing regional responses in each individual model to be better understood, this set of experiments should prove especially
 409 useful for understanding the causes of model uncertainty in regional climate change.

410 The experiments are:

- 411 1) *piSST* – An AGCM experiment with monthly-varying SSTs, sea-ice, atmospheric constituents and any other necessary
 412 boundary conditions (e.g. vegetation if required) taken from a section of each model's own *piControl* run, using the 30 years
 413 of *piControl* that are parallel to years 111-140 of its *abrupt-4xCO2* run. Note that dynamic vegetation (if included in the
 414 model) should not be turned on in any of the *piSST* set of experiments;
 415 2) *piSST-pxK* – same as *piSST*, but with a global spatially and temporally uniform SST anomaly applied on top of the
 416 monthly-varying *piSST* SSTs. The magnitude of the uniform increase is taken from each model's global, climatological
 417 annual mean SST change between *abrupt-4xCO2* and *piControl* (using the mean of years 111-140 of *abrupt-4xCO2*, and the
 418 parallel 30-year section of *piControl*). Sea-ice is unchanged from *piSST* values;
 419 3) *piSST-4xCO2-rad* – same as *piSST* but CO₂ as seen by the radiation scheme is quadrupled;
 420 4) *piSST-4xCO2* – same as *piSST* but with CO₂ quadrupled, and this increase is seen by both the radiation scheme and the
 421 plant physiological effect. If a model does not include the plant physiological response to CO₂, then *piSST-4xCO2* can be
 422 omitted from the set of *piSST* experiments for that model;
 423 5) *a4SST* – same as *piSST*, but with monthly-varying SSTs taken from years 111-140 of each model's own *abrupt-4xCO2*
 424 experiment instead of from *piControl* (sea ice is unchanged from *piSST*);
 425 6) *a4SSTice* – same as *piSST*, but with monthly-varying SSTs and sea-ice taken from years 111-140 of each model's own
 426 *abrupt-4xCO2* experiment instead of from *piControl*;
 427 7) *a4SST-4xCO2* – same as *piSST*, but with monthly-varying SSTs and sea-ice taken from years 111-140 of each model's own
 428 *abrupt-4xCO2* experiment instead of from *piControl*. CO₂ is also quadrupled, and is seen by both the radiation scheme and
 429 the plant physiological effect (if included in the model). *a4SST-4xCO2* is used to establish whether a time slice experiment
 430 can adequately recreate the coupled *abrupt-4xCO2* response in each model, and then forms the basis for a decomposition
 431 using the other experiments.
 432 8) We also propose an additional amip based experiment, *amip-a4SST-4xCO2*: the same as amip, but a patterned SST
 433 anomaly is applied on top of the monthly-varying amip SSTs. This anomaly is a monthly climatology, taken from each
 434 model's own *abrupt-4xCO2* run minus *piControl* (using the mean of years 111-140 of *abrupt-4xCO2*, and the parallel 30-year
 435 section of *piControl*). CO₂ is quadrupled, and the increase in CO₂ is seen by both the radiation scheme and vegetation.
 436 Comparison of *amip-a4SST-4xCO2* and *a4SST-4xCO2* should help to illuminate the impact of SST biases on regional
 437 climate responses in each model, and how this contributes to inter-model uncertainty.
 438

439 3 CFMIP Recommended Diagnostic Outputs for CMIP experiments

440 The CFMIP-3 specific diagnostic request is designed to address the following questions: 1) How well do clouds and other
 441 relevant variables simulated by models agree with observations? 2) What physical processes and mechanisms are important
 442 for a credible simulation of clouds, cloud feedbacks and cloud adjustments in climate models? 4) Which models have the
 443 most credible representations of processes relevant to the simulation of clouds? 5) How do clouds and their changes interact
 444 with other elements of the climate system?
 445

446 The set of diagnostic outputs recommended for CFMIP-3 is based on that from CFMIP-2, with some modifications. The
 447 request outlined below is in three parts. The first part describes an updated set of CFMIP process diagnostics (based on those
 448 in CFMIP-2 which are documented at http://cmip-pcmdi.llnl.gov/cmip5/output_req.html) in terms of the various groups of
 449 variables and the experiments in which they are requested. This set was drawn up by the CFMIP committee and ratified by
 450 the modelling groups following a presentation at the 2014 CFMIP meeting. The second part describes recommendations for
 451 COSP outputs in the CFMIP-3, CMIP DECK and CMIP6 Historical experiments. The third part describes additional
 452 diagnostics requested for evaluation of mean diurnal cycle of tropical clouds and radiation. The summaries below give an
 453 overview of the diagnostic request; however the definitive and detailed specification is documented in the CMIP6 data



454 request, available at <https://earthsystemcog.org/projects/wip/CMIP6DataRequest> (Juckes et al., in preparation.) The changes
 455 in the CFMIP-3 diagnostics relative to those requested for CFMIP-2 are additionally motivated and detailed in the CFMIP
 456 CMIP6 proposal document which is available from the CFMIP website.

457

458 CMIP mandates that for participation in the CFMIP-3, modelling groups must commit to performing all of the Tier 1
 459 experiments. In recognition that sufficient resources are not available for all groups to prepare all of the CFMIP-3 specific
 460 diagnostics, these diagnostics are considered to be Tier 2, i.e., not compulsory for participation in CFMIP-3. Nonetheless,
 461 these diagnostics are extremely valuable and all groups with the capacity to do so are very strongly encouraged to provide the
 462 additionally requested CFMIP-3 specific diagnostics.

463

464 In the case where CFMIP-3 specific outputs are requested in DECK and CMIP6-Historical experiments, and modelling
 465 groups run more than one ensemble member of an experiment, we request that each set of CFMIP-3 specific outputs are
 466 submitted for one ensemble member only. Having different CFMIP variables in different ensemble members is acceptable,
 467 but submitting them all in the same ensemble member is preferable. We request that the modelling groups provide
 468 information on which CFMIP diagnostic sets are submitted in which ensemble members so that this information can be made
 469 available to those who may be analyzing the output. Our analysis plans for the CFMIP diagnostic outputs in the CMIP
 470 DECK, CMIP6 Historical and CFMIP-3 experiments, including details of the CFMIP Diagnostics Code Catalogue are
 471 summarised in Appendix A.

472 3.1 Process outputs

473 In CFMIP-2, instantaneous high frequency ‘cfSites’ outputs were requested for 120 locations in the *amip*, *amip4K*,
 474 *amipFuture* and *amip4xCO2* experiments, and for 73 locations along the Greenwich meridian in the aquaplanet experiments,
 475 to support understanding and evaluation of clouds and their interactions with convection and other processes. The 120
 476 locations include the locations of instrumented sites (ARM and CloudNet stations, Dome C, etc), the transect associated with
 477 the GCSS Pacific Cross-section Intercomparison (GPCI), past field campaigns (DYCOMS-II, NARVAL, HOPE, VOCALS,
 478 ASTEX and AMMA transects, TOGA-COARE, RICO, etc) and a number of climate regimes that contribute substantially to
 479 the inter-model spread of cloud feedbacks in climate change (Webb et al., 2015a). These outputs have so far been used to
 480 evaluate the models with in-situ measurements (e.g. Nuijens et al., 2015a, Nuijens et al., 2015b, Neggers et al., 2015), to
 481 investigate the diurnal cycle of cloud feedbacks (Webb et al., 2015a) and to compare cloud feedbacks in climate models with
 482 Single Column Models and LES outputs from CGILS (Dal Gesso et al., 2015). We have added St. Helena to the list of
 483 locations in light of upcoming field work, increasing the total number of locations to 121 for CFMIP-3. A text file containing
 484 the list of locations is available in the Supplementary Information and on the CFMIP website; these are also presented
 485 graphically in Figure 2.

486

487 For CFMIP-3 we have dispensed with the cfSites outputs in the aquaplanet experiments and in *amip-future4K*. cfSites outputs
 488 are now requested for one ensemble member of the *amip* DECK experiment, and the *amip-p4K* and *amip-4xCO2*
 489 experiments. Outputs should be provided for the full duration of each experiment. The sampling interval should be the
 490 integer multiple of the model time step that is nearest to 30 minutes and divides into 60 minutes with no remainder: e.g. 30
 491 minutes for a 30, 15 or 10 minute time step or 20 minutes for a 20 minute time step. Outputs should be instantaneous (i.e. not
 492 time means) and from nearest grid box (i.e. no spatial interpolation).

493

494 The cfSites outputs from CFMIP-3 provide instantaneous outputs of a range of quantities (including temperature and
 495 humidity tendency terms) in experiments which can be used to evaluate the present day relationships of clouds to cloud
 496 controlling factors using in situ measurements, and at the same time explore how these relationships affect cloud feedbacks
 497 and cloud adjustments. An increasing wealth of observational data with which to evaluate the models using these outputs is
 498 available or in the planning stage, for example from the Barbados Cloud Observatory (Stevens et al., 2015) the ARM
 499 Program (e.g. Wood et al., 2015; Marchand et al., 2015) or within the German national project on high-definition clouds and
 500 precipitation for climate-prediction, HD(CP)², inclusive of its observational prototype experiment (HOPE), and which has
 501 collected observations over Germany following conventions adopted for CMIP (Andrea Lammert, personal communication).

502

503 CFMIP-2 also requested cloud, temperature and humidity tendency terms from convection, radiation, dynamics etc. in the
 504 *amip*, *amip4K*, *amipFuture* and *amip4xCO2*, *aquaControl*, *aqua4xCO2* and *aqua4K* experiments, as global monthly mean
 505 outputs and high frequency outputs at fixed locations (Bony et al., 2011). Upward and downward radiative fluxes on model
 506 levels were also requested in these experiments, and for instantaneous CO₂ quadrupling in the *amip* experiment only.
 507 Temperature and humidity tendency terms in particular have been shown to be useful for understanding the roles of different
 508 parts of the model physics in cloud feedbacks and adjustments (Kamae and Watanabe 2012; Williams et al., 2013; Webb and
 509 Lock 2013; Demoto et al., 2013; Sherwood et al., 2014; Ogura et al., 2014; Brient et al., 2015) as well as in understanding
 510 clouds and circulation in the present climate (e.g. Oueslati and Bellon, 2013; Xavier et al., 2015). They have also been used to
 511 understand regional warming patterns such as polar amplification in coupled models (e.g. Yoshimori et al., 2014).

512

513 In CFMIP-3 we have dispensed with the cloud tendency terms, improved the definitions of the temperature and humidity
 514 tendency terms, and added some additional terms such as clear-sky radiative heating rates to more precisely quantify the



515 contributions of different processes to the temperature and humidity budget changes underlying cloud feedbacks and
 516 adjustments. A shortcoming of the CMIP5 protocol was that we were unable to interpret the physical feedback mechanisms
 517 in coupled model experiments due to a lack of process diagnostics. For this reason in CMIP6 we are requesting these budget
 518 terms in the DECK *abrupt-4xCO2* experiment and the pre-industrial control as well as one ensemble member of the *amip*
 519 DECK experiment, and all of the CFMIP-3 experiments listed in Sections 2.1-2.6.

520 Clustering approaches (e.g., Jakob and Tselioudis, 2003) are now commonly used for assessing the contributions of different
 521 cloud regimes (e.g. stratocumulus, trade cumulus, frontal clouds, etc) to present day biases in cloud simulations and to inter-
 522 model differences in cloud feedbacks (e.g. Williams and Webb 2009, Tsushima et al., 2013, Tsushima et al., 2015). We have
 523 also added some additional daily 2D fields to the standard package of CFMIP daily outputs to allow further investigation of
 524 feedbacks between clouds and aerosols associated with the changing hydrological cycle (aerosol loadings and cloud top
 525 effective radii/number concentrations) and a clearer diagnosis of the roles of convective and stratiform clouds (convective vs.
 526 stratiform ice and condensed water paths and cloud top effective radii/number concentrations).

527 3.2 COSP outputs

528 This section motivates and summarizes the COSP outputs requested from the DECK, and CMIP6 historical and CFMIP-3
 529 experiments as well as a corresponding set of observations.

530
 531 There is no unique definition of clouds or cloud types, neither in models nor in observations. Therefore, to compare models
 532 with observations, and even to compare models with each other, it is necessary to use a consistent definition of clouds
 533 between the model and the satellite product in question (i.e., be “definition-aware”). Further complicating matters - climate
 534 model grid boxes (typically 1 degree) are much larger than the scales over which many satellite observations are made
 535 (typically <10 km). As a result, one must downscale the climate model cloud properties to the observation scale (i.e., be
 536 “scale-aware”). The CFMIP Observation Simulator Package (COSP) enables definition-aware and scale-aware comparisons
 537 between models and multiple sets of observations by producing cloud diagnostics from model simulations that are
 538 quantitatively comparable to a variety of satellite products from ISCCP, CloudSat, CALIPSO, MODIS, MISR and Parasol
 539 (Bodas-Salcedo et al., 2011). COSP enables a more quantitative comparison of model outputs with satellite cloud products,
 540 which often sub-sample low level clouds in the presence of high level clouds due to the effects of cloud overlap and
 541 attenuation (e.g. Yu et al., 1996). COSP also provides histograms of various cloud properties as a function of height or
 542 pressure which are directly comparable with satellite products and cannot be calculated correctly from time mean model
 543 outputs. The multiple simulators within COSP allow a multi-faceted evaluation of clouds in models whereby the strengths
 544 and weaknesses of different satellite products may be considered together.

545
 546 COSP is increasingly being used not only for model intercomparison activities but as part of the model development and
 547 evaluation process by modelling groups (e.g. Marchand et al., 2009; Zhang et al., 2010; Kay et al., 2012; Franklin et al.,
 548 2013; Lacagnina and Selten, 2014; Nam et al., 2014; Williams et al., 2015, Konsta et al., 2015). Many of the standard
 549 monthly and daily COSP outputs have been shown to be valuable in the CMIP5 experiments, not only for cloud evaluation,
 550 allowing a detailed evaluation clouds and precipitation, and their interaction with radiation (e.g. Nam et al., 2012; Cesana and
 551 Chepfer, 2012; Kay et al. 2012; Klein et al., 2013; Tsushima et al., 2013; Gordon and Klein, 2014; Lin et al., 2014; Bodas-
 552 Salcedo et al., 2014; Bellomo and Clement, 2015), but also in quantifying the contributions of different cloud types to cloud
 553 feedbacks and forcing adjustments in climate change experiments (e.g. Zelinka et al., 2013; Zelinka et al., 2014; Chepfer et
 554 al., 2014; Tsushima et al., 2015). For a full list of studies that use COSP diagnostics for model evaluation and feedback
 555 analysis please refer to the ‘CFMIP publications’ section of the CFMIP website.

556
 557 Here we will give only a brief overview of the COSP request; readers interested in the complete details of the data request are
 558 referred to the Earth System CoG website (<https://earthsystemcog.org/projects/wip/CMIP6DataRequest>).

559
 560 The COSP data request for the CMIP DECK and CMIP6 has been designed to span model evaluation across different space
 561 and time scales. Monthly-mean diagnostics allow for the evaluation and intercomparison of large-scale distributions of cloud
 562 properties and their interaction with radiation. High-frequency model outputs (daily, 3-hourly) are aimed at a process-oriented
 563 evaluation (e.g. Bodas-Salcedo et al., 2012) and offer the opportunity of exploiting the synergy between multiple instruments
 564 (e.g. Konsta et al., 2015). Recent observational developments have improved our capability to retrieve cloud radiative
 565 properties. In particular, new methodologies for cloud phase identification are available for CALIPSO and MODIS, and
 566 COSP has been enhanced to provide diagnostics that are compatible with these new observational datasets (Cesana and
 567 Chepfer, 2013). These new diagnostics will help elucidate some open questions regarding the role of cloud phase in model
 568 biases (Ceppi et al., 2016; Bodas-Salcedo et al., in press).

569 Within CFMIP-3 COSP output is requested from six simulators as follows:

- 570 • ISCCP: pseudo-retrievals of cloud top pressure (CTP) and cloud optical thickness (τ) (Klein and Jakob 1999;
- 571 Webb et al., 2001).
- 572 • CloudSat: a forward model for radar reflectivity as a function of height (Haynes et al., 2007).

573



- 574 • CALIPSO (Chepfer et al., 2008; Cesana and Chepfer, 2013): forward model for lidar scattering ratio as function of
575 height, and cloud phase retrieval.
576 • MODIS: pseudo-retrievals of CTP, effective particle size and tau as function of phase (Pincus et al., 2012).
577 • MISR: pseudo-retrievals of cloud top height (CTH) and tau (Marchand and Ackerman, 2010).
578 • PARASOL: simple forward model of mono-directional reflectance (Konsta et al., 2015).
579

580 The main difference to CFMIP-2 is that output is requested from a greater number of simulators and longer periods of
581 simulated time. MISR provides more accurate retrievals of cloud-top-height for low-level and mid-level clouds, and more
582 reliable discrimination of mid-level clouds from other clouds, while MODIS provides better retrievals of high-level clouds.
583 ISCCP and MISR histograms can be combined to separate optically-thin high-level clouds into multi-layer and single-layer
584 categories (Marchand et al. 2010). Aerosol schemes are becoming more complex, with more elaborate representations of
585 cloud-aerosol interactions. This makes the evaluation of the phase partitioning an important aspect of model evaluation, and
586 height-resolved partitioning estimates from the CALIPSO simulator are included in the COSP request. Cloud phase and
587 particle size estimates from the MODIS simulator were not available in CFMIP-2 but may prove a useful complement to
588 investigate cloud-aerosol interactions by virtue of greater geographic sampling and longer time records. Many of the COSP
589 diagnostics are now requested for the entire lengths of the DECK, CMIP6 Historical and CFMIP-3 experiments to support the
590 quantification and interpretation of cloud feedbacks and cloud adjustments in a broader context. The new inclusion in this
591 COSP request of a long time series of three-dimensional cloud fractions will facilitate the comparison of cloud trends with the
592 observational record (Chepfer et al., 2014). More details of all the changes with respect to CFMIP-2 can be found in the
593 proposal of the CMIP6-Endorsed MIPs, available from the CMIP6 web site (<http://www.wcrp-climate.org/wgcm-cmip6>).
594
595

596 The COSP output is in six variable groups:

- 597
598 1) CFMIP-cfMon-sim: monthly means of ISCCP 2D diagnostics (cloud fraction, cloud albedo, and cloud top pressure),
599 ISCCP CTP-tau histogram, and CALIPSO 2D and 3D cloud fractions.
600 2) CMIP5-cfDay-2d: daily means of ISCCP and CALIPSO 2D diagnostics, and PARASOL reflectances.
601 3) cfDay-3d: daily means of ISCCP and CALIPSO 3D diagnostics.
602 4) CFMIP-cfMonExtra: monthly means of CloudSat reflectivity and CALIPSO scattering ratio histograms as function
603 of height, CALIPSO 3D cloud fractions by phase, MODIS 2D cloud fractions, MODIS CTP-tau histogram and size-
604 tau histograms by phase, MISR CTH-tau histograms, and PARASOL reflectances.
605 5) CFMIP-cfDayExtra: daily means of CALIPSO total cloud fraction, MODIS CTP-tau histogram and size-tau
606 histograms by phase, and PARASOL reflectances.
607 6) CFMIP-cf3hrSim: 3-hourly instantaneous diagnostics of ISCCP CTP-tau histograms, MISR CTH-tau histograms,
608 MODIS CTP-tau histogram and size-tau histograms by phase, CALIPSO 2D and 3D cloud fractions, CloudSat
609 reflectivity and CALIPSO scattering ratio histograms as function of height, and PARASOL reflectances.
610

611 The variable groups CFMIP-cfMon-sim and CMIP5-cfDay-2d are requested for all years in the *amip* experiment performed
612 as part of the DECK and the CMIP6-Historical experiments, and for 140 years the *piControl*, *1pctCO2*, and *abrupt-4xCO2*.
613 These are requested for one ensemble member only from these experiments. They are also requested in all of the CFMIP
614 experiments listed in Sections 2.1-2.6 above. *cfDay-3d* is requested in one ensemble member of the DECK *amip* experiment
615 and in the CFMIP *amip-p4K* and *amip-4xCO2* experiments. CFMIP-cfMonExtra and CFMIP-cfDayExtra are requested for
616 all years of one ensemble member of the *amip* DECK experiment, and CFMIP-cf3hrSim for the year 2008 only.
617

618 COSP 1.4, available via the CFMIP website (<https://www.earthsystemcog.org/projects/cfmip>), is the official version to be
619 used for CMIP6. This is a stable release that was made available well in advance of CMIP6 at the request of the modelling
620 groups. Version 2 of COSP is under active development. At the time of writing, COSP 2 is in beta testing and does not have a
621 stable release, and so is not currently permitted for production of CMIP6 data. COSP-2 may be permitted for use in CMIP6
622 along with COSP 1.4 in the future; if and when this happens details will be posted on the CFMIP website.
623

624 The CFMIP community has developed a set of observational datasets available via the CFMIP-OBS web site
625 (<http://climserv.ipsl.polytechnique.fr/cfmip-obs/>) that are defined consistently with the COSP diagnostics and the CFMIP
626 data request in terms of vertical grids and time averaging periods. These are mostly reported as monthly means although
627 some are reported at higher temporal resolution for process oriented model evaluations (e.g. Konsta et al., 2012). Table 3
628 summarizes the datasets relevant to the COSP CMIP6 data request. Some of the CFMIP-OBS datasets listed in Table 3
629 (CALIPSO, CloudSat, ISCCP, PARASOL) are also available from the ESGF as part of the obs4MIPs project (Teixeira et al.,
630 2014).
631

632 3.3 Monthly Mean Diurnal Cycle Outputs

633
634 Climate models have difficulties representing the diurnal cycle of convective clouds over land (Yang and Slingo, 2001;
635 Stratton and Stirling, 2011), but its evaluation is not possible with sun-synchronous satellites. Geostationary satellites
636 provide high-frequency sampling that can be used to evaluate model biases in the diurnal cycle of clouds and radiation (albeit



637 over a limited area). The Geostationary Earth Radiation Budget instrument (GERB; Harries et al., 2005) measures the TOA
638 radiation budget from a geostationary orbit at 0E at 15 minute frequency, which provides a unique view of tropical
639 convection over Africa. The variable group *cf1hrClimMon* requests monthly mean diurnal cycle of TOA radiative fluxes (all-
640 sky and clear sky) for the entire length of the *amip* DECK experiment. The radiative fluxes are hourly UTC means. The
641 ‘average day’ for each month of the simulation is then constructed by averaging each UTC hourly mean over the entire
642 month. These diagnostics will be directly comparable with GERB measurements.
643

644 4. Summary

645 The primary goal of CFMIP is to inform improved assessments of cloud feedbacks on climate change. This involves bringing
646 climate modelling, observational and process modelling communities closer together and providing better tools and
647 community support for understanding and evaluation of clouds and cloud feedbacks simulated by climate models. CFMIP
648 supports ongoing coordinated model inter-comparison activities by recommending experiments and model output
649 diagnostics for CMIP, designed to support the understanding and evaluation of cloud processes and cloud feedbacks in
650 models. The CFMIP approach is also increasingly being used to understand other aspects of climate change, such as
651 circulation, regional-scale precipitation and non-linear changes. CFMIP proposes a number of experiments and model outputs
652 for CMIP6, building on and extending those which were part of CMIP5.

653 A compact set of Tier 1 experiments are proposed address the question: “1) What are the physical mechanisms underlying the
654 range of cloud feedbacks and cloud adjustments predicted by climate models, and which models have the most credible cloud
655 feedbacks?” The Tier 1 experiments (*amip-p4K*, *amip-4xCO2*, *amip-future4K*, *aqua-control*, *aqua-4xCO2* and *aqua-p4K*)
656 retain the idealized experimental hierarchy of the CFMIP-2/CMIP5 experiments while building on the DECK AMIP
657 experiment. A number of Tier 2 experiments are proposed to address additional science questions. An *amip* uniform minus
658 4K experiment is proposed to address the question “2) Are cloud feedbacks consistent for climate cooling and warming, and
659 if not, why?” Atmosphere-only experiments with clouds made transparent to longwave radiation address the question “3)
660 How do cloud-radiative effects impact the structure, the strength and the variability of the general atmospheric circulation in
661 present and future climates?” Abrupt +/-4% Solar Forced AOGCM experiments are proposed for the question “4) How do
662 responses in the climate system due to changes in solar forcing differ from changes due to CO₂, and is the response sensitive
663 to the sign of the solar forcing?” abrupt 2xCO₂ and abrupt 0.5xCO₂ experiments are proposed to address the question “5) To
664 what extent is regional-scale climate change per CO₂ doubling state-dependent (nonlinear), and why?” Other experiments and
665 questions proposed include: AMIP with preindustrial forcing “6) Are climate feedbacks during the 20th century different to
666 those acting on long term climate change and climate sensitivity?”; Time slice experiments forced with SSTs from
667 preindustrial and *abrupt-4xCO2* simulations “7) How do regional climate responses (of e.g. precipitation) in a coupled model
668 arise from the combination of responses to different aspects of CO₂ forcing and warming (uniform SST warming, pattern SST
669 warming, direct CO₂ effect, plant physiological effect, sea-ice change)?”

670 The CFMIP experiments in CMIP6 will continue to include outputs from the CFMIP Observational Simulator Package
671 (COSP) to support robust scale-aware and definition-aware evaluation of modelled clouds with observations and to relate
672 cloud feedbacks to observed quantities. COSP outputs are also proposed for inclusion in the DECK and CMIP6 Historical
673 experiments. Process diagnostics including ‘cfSites’ high frequency outputs at selected locations and temperature and
674 humidity budget terms from radiation, convection, dynamics, etc. are also retained from CMIP5. These will help to address
675 the following questions: 1) How well do clouds and other relevant variables simulated by models agree with observations?
676 2) What physical processes and mechanisms are important for a credible simulation of clouds, cloud feedbacks and cloud
677 adjustments in climate models? 4) Which models have the most credible representations of processes relevant to the
678 simulation of clouds? 5) How do clouds and their changes interact with other elements of the climate system?

679 By continuing the CFMIP experiments and diagnostic outputs within CMIP6 we hope to apply the well established aspects of
680 the CFMIP approach to a larger number of climate models. Additionally we have proposed new experiments to investigate a
681 broader range of questions relating to the Grand Challenge on Clouds, Circulation and Climate Sensitivity. We hope that the
682 modelling community will participate fully in CFMIP via CMIP6 so as to maximize the relevance of our findings to future
683 assessments of climate change.

684 Code and Data Availability

685 COSP is published under and open source license via GitHub (please see the CFMIP website for details). The model output
686 from the DECK, CMIP6 historical and CFMIP-3 simulations described in this paper will be distributed through the Earth
687 System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. As in CMIP5, the model output will be freely
688 accessible through data portals after registration. In order to document CMIP6’s scientific impact and enable ongoing support
689 of CMIP, users are obligated to acknowledge CMIP6, the participating modelling groups, and the ESGF centres (see details
690 on the CMIP Panel website at <http://www.wcrp-climate.org/index.php/wgcm-cmip/about-cmip>). Further information about
691 the infrastructure supporting CMIP6, the metadata describing the model output, and the terms governing its use are provided



692 by the WGCM Infrastructure Panel (WIP) in their invited contribution to this Special Issue. Along with the data itself, the
 693 provenance of the data will be recorded, and DOIs will be assigned to collections of output so that they can be appropriately
 694 cited. This information will be made readily available so that published research results can be verified and credit can be
 695 given to the modelling groups providing the data. The WIP is coordinating and encouraging the development of the
 696 infrastructure needed to archive and deliver this information. In order to run the experiments, datasets for natural and
 697 anthropogenic forcings are required. These forcing datasets are described in separate invited contributions to this Special
 698 Issue. The forcing datasets will be made available through the ESGF with version control and DOIs assigned.

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 702 Robert Pincus and Yuying Zhang for their contributions to COSP and to CFMIP-OBS, to Dustin Swales for his
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 704 grateful to Brian Soden for producing the CMIP3 composite pattern dataset used for the CMIP5 *amipFuture* and CMIP6
 705 *amip-future4K* experiments, and to PMIP representatives Pascale Braconnot, Masa Kageyama, and Masakazu Yoshimori for
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 710 Climate Programme (GA01101).

711 **Appendix A: Analysis Plan and CFMIP Diagnostic Codes Catalogue**

712 CFMIP-2 analysis activities are ongoing and the CFMIP community is ready to analyse CFMIP-3 data at any time. We would
 713 like modelling groups to perform the proposed CFMIP-3 experiments at the same time or shortly after their DECK and
 714 CMIP6 Historical experiments. Subsequent CFMIP experiments which are not included in CMIP6 will build on the proposed
 715 DECK and CMIP6/CFMIP experiments and some will start as soon as CMIP6 DECK experiments start to become available.
 716 We envisage a succession of CFMIP related intercomparisons addressing different questions arising from the Grand
 717 Challenge spanning the duration of CMIP6.

719 We plan to scientifically analyze, evaluate and exploit the proposed experiments and diagnostic outputs, and have identified
 720 leads within CFMIP for different aspects of this activity. An overview of the proposed evaluation/analysis of the CMIP
 721 DECK, CMIP6 Historical and CFMIP CMIP6 experiments follows:

722 CFMIP will continue to exploit the CMIP DECK and CMIP6 experiments to understand and evaluate cloud processes and
 723 cloud feedbacks in climate models. The wide range of analysis activities described above in the context of CFMIP-2 will be
 724 continued in CFMIP-3 using the CMIP DECK and CMIP6 experiments, allowing the techniques developed in CFMIP-2 to
 725 be applied to an expanding number of models, including the new generation of models currently under development. These
 726 activities will include evaluation of clouds using additional simulators, investigation of cloud processes and cloud
 727 feedback/adjustment mechanisms using process outputs (cfSites, tendency terms, etc). The inclusion of COSP and budget
 728 tendency terms in additional DECK experiments (e.g. *abrupt-4xCO2*) will enable the CFMIP approach to be applied to a
 729 wider range of experimental configurations. Lead coordinator: Mark Webb.

731
 732 Analysis of the +/-4% solar forcing runs will include an evaluation of both rapid adjustments and longer-term responses on
 733 global and regional top-of-atmosphere radiative fluxes, cloud types (using ISCCP and other COSP simulators) and
 734 precipitation characteristics, as well as comparison of these responses with responses in DECK *abrupt-4xCO2* experiments.
 735 GeoMIP and SolarMIP have expressed a strong interest in these CFMIP experiments and joint analysis of these CFMIP
 736 experiments with GeoMIP and SolarMIP experiments is anticipated, specifically with the goal of determining to what degree
 737 results from abrupt solar forcing only experiments and abrupt CO₂ only experiments can be used to predict what happens
 738 when both forcings are applied simultaneously, as done in the GeoMIP experiments. Lead coordinators: Chris Bretherton,
 739 Roger Marchand and Bjorn Stevens.

740
 741 Analysis of nonlinear climate processes is discussed in detail by Good et al., 2016. This includes a method for validating
 742 traceability of abrupt CO₂ experiments to transient simulations, which is also recommended as a standard test of the DECK
 743 *abrupt-4xCO2* experiment. Analysis will primarily involve comparing the *abrupt-4xCO2*, *abrupt-2xCO2* and *abrupt-*
 744 *0p5xCO2* experiments over the same timescale. Lead coordinator: Peter Good.

745
 746 Analysis of *amip-piForcing* has already been performed in detail for two models in Andrews, 2014 and Gregory and
 747 Andrews (submitted). We propose to use this as a starting point for a multi-model analysis. Lead coordinator: Timothy
 748 Andrews.

749



750 An overview analysis of regional responses and model uncertainty in the piSST set of experiments will be carried out by the
 751 coordinators, in collaboration with members of contributing modelling groups. We anticipate that further detailed analysis on
 752 the processes at work in different regions will be carried out by a variety of research groups with interest and expertise in a
 753 particular region: for example a set of similar experiments has previously been used to examine the climate response of the
 754 West African monsoon in CCSM3 (Skinner et al., 2012). The piSST set of experiments have already been successfully run
 755 using the Met Office, NCAR and CNRM CMIP5 models. Lead Coordinators: Robin Chadwick, Hervé Douville and
 756 Christopher Skinner.

757

758 The analysis of the COOKIE experiments will be reviewed by the coordinators in collaboration with members of the
 759 contributing modelling groups. The role of longwave atmospheric cloud-radiative effects in large-scale circulations, regional
 760 precipitation patterns and the organisation of tropical convection will be investigated in the current climate and in climate
 761 change, with the aim of highlighting both robust effects and sources of uncertainties in the model responses. Lead
 762 coordinators: Sandrine Bony and Bjorn Stevens.

763

764 When analyzed together with the *amip-p4K* experiment, the *amip-m4K* experiment allows the CFMIP process diagnostics to
 765 be used to understand for asymmetries in the climate response to warming and cooling which have been noted in PMIP
 766 experiments. These might arise from cloud phase responses in middle- and high-latitude clouds or from the adiabatic cloud
 767 liquid water path response feedback which is important over land regions and which would be expected to be weaker with
 768 cooling because of the non-linearity in the Clausius-Clapeyron relation. Lead coordinators: Mark Webb and Bjorn Stevens.

769

770 The COSP data request for the *amip* DECK experiment will allow a comprehensive multi-model evaluation of clouds and
 771 radiation, following on from CMIP5 studies (e.g. Klein et al., 2013; Bodas-Salcedo et al., 2014). The COSP data request for
 772 the other experiments (e.g. *amip-p4K*, *abrupt-4xCO2*, etc.) permits evaluation of cloud feedbacks and adjustments by cloud
 773 type (Zelinka et al., 2013, Tsushima et al., 2015) or cloud trends (Chepfer et al., 2014). New COSP diagnostics have been
 774 used in single-model analyses: cloud phase diagnostics (Cesana and Chepfer, 2013); MISR simulator outputs to evaluate
 775 cloud fraction and multilayer clouds (Marchand and Ackerman, 2010); CALIPSO vertical distribution of cloud fraction for
 776 the study of cloud trends (Chepfer et al., 2014). These studies will be used as starting points for multi-model analyses. The
 777 COSP PMC co-chairs will coordinate and encourage the exploitation of these resources. Lead coordinators: Alejandro Bodas-
 778 Salcedo and Steve Klein.

779

780 Analysis of output from CFMIP and CMIP6 experiments will also be facilitated by sharing of diagnostic codes via the
 781 CFMIP Diagnostics Code Catalogue (accessible via the CFMIP website <http://www.earthsystemcog.org/projects/cfmip/>).
 782 This is a catalogue of programs written by various members of the CFMIP community, implementing a number of diagnostic
 783 approaches from published studies. These include daily cloud clustering evaluation metrics based on ISCCP and ISCCP
 784 simulator outputs (Williams and Webb, 2009, Tsushima et al., 2013), error metrics for total cloud amount, longwave and
 785 shortwave cloud properties (Klein et al., 2013), process oriented evaluation of clouds using A-train instantaneous
 786 observations (Konsta et al., 2012), quality control and low-cloud diagnostics (Nam et al., 2012; Nam and Quaas, 2012),
 787 sensitivity of low cloud cover to estimated inversion strength and SST (Qu et al., 2013) and cloud radiative kernels (Zelinka
 788 et al., 2012). Any codes which implement diagnostics which are relevant to analysing clouds, circulation and climate
 789 sensitivity in models and which are documented in peer reviewed studies are eligible for inclusion in the catalogue, and we
 790 welcome additional contributions to further support community analysis of CMIP6 outputs.

791 APPENDIX B: Aquaplanet Experimental Design

792 Aquaplanets are Earth-like planets with completely water-covered surfaces. They are often used as idealized configurations
 793 of atmospheric GCMs, and in this context the usual convention is that landmasses and topography are removed. Although
 794 many flavours of aquaplanet configurations exist, another convention is to retain as much of the atmospheric model's
 795 formulation as possible. That is, the numerical grid, dynamical core, and parameterized physics are all used just as in realistic
 796 climate simulations.

797

798 The Tier 1 aquaplanet experiments follow the same experimental design as CMIP5/CFMIP-2 (Medeiros et al., 2015). Those,
 799 in turn, were closely related to previous aquaplanet descriptions. In particular, the control configuration closely follows the
 800 AquaPlanet Experiment protocol (Blackburn and Hoskins, 2013) using a prescribed SST pattern described by Neale and
 801 Hoskins (2000). Two additional runs parallel the CFMIP-2 *amip4K* and *amip4xCO2* experiments: a uniform 4K warming and
 802 a quadrupling of atmospheric CO₂.

803

804 Here we provide the detailed experimental protocol for the three aquaplanet simulations that are part of Tier 1. We note again
 805 that these follow the APE protocol and CMIP5/CFMIP-2, and therefore largely mirror previous descriptions in Blackburn and
 806 Hoskins (2013), Williamson et al. (2012), and Medeiros et al. (2015).

807



808 Orbital parameters are set to perpetual equinox conditions. This is usually achieved by setting eccentricity and obliquity to
809 zero to define a circular orbit and insolation independent of calendar. The diurnal cycle is retained. Insolation is based on a
810 non-varying solar constant of 1365 W m^{-2} .

811
812 The SST is non-varying and zonally uniform. The longitudinal variation is specified using the “Qobs” SST pattern from
813 Neale and Hoskins (2000), given by:

$$814 \quad T(\varphi) = \begin{cases} \frac{1}{2} (2 - \sin^4 \phi - \sin^2 \phi) \delta T + T_{\min}, & \text{if } |\varphi| < \frac{\pi}{3} \\ 0, & \text{otherwise} \end{cases} \quad (\text{B1})$$

815 where φ is latitude, $\phi = \frac{\pi}{2} \frac{\varphi}{\varphi_{\max}}$, $\varphi_{\max} = \frac{\pi}{3}$, $\delta T = T_{\max} - T_{\min}$, $T_{\max} = 27^\circ\text{C}$, and $T_{\min} = 0^\circ\text{C}$.

816

817 Because results are sensitive to the specification of the SSTs, groups that use a prognostic equation for the surface skin
818 temperature are asked to set this skin temperature to the specified SST. No sea ice is prescribed, so the surface temperature is
819 spatially uniform at 0°C poleward of 60° for the control simulation.

820

821 Radiatively active trace gases are well-mixed with mixing ratios following the AMIP II recommendations: CO_2 : 348 ppmv;
822 CH_4 : 1650 ppbv; N_2O : 306 ppbv; Halocarbon yield of approximately 0.24 W m^{-2} radiative forcing. The ozone distribution is
823 the same as used in APE and CFMIP2/CMIP5, and is derived from the climatology used in AMIP II (Gates et al., 1999), and
824 is constant in time and symmetric about the equator. This ozone distribution is provided as a netCDF file which is archived
825 on the Earth System Grid and available via the DOI <http://dx.doi.org/10.5065/D61834Q6> (and also available via the CFMIP
826 website).

827

828 Aerosols are removed to the extent possible to remove aerosol-radiation interaction (aka direct effects) and aerosol-cloud
829 interaction (aka indirect effects). No external surface emissions are to be prescribed. Models requiring aerosol for cloud
830 condensation should use a constant oceanic climatology that is symmetric about the equator and zonally. Alternatively,
831 models with the capability should set the cloud droplet and crystal numbers to $100 \cdot 10^6 \text{ m}^{-3}$ and $0.1 \cdot 10^6 \text{ m}^{-3}$, respectively (as
832 in Medeiros et al., 2016).

833

834 As in APE, it is recommended that the atmospheric dry mass be adjusted to yield a global mean of 101080 Pa. It is also
835 recommended to adopt the APE recommended values for geophysical constants, as listed in Table 2 of Williamson et al.
836 (2012).

837

838 The aqua-4K experiment follows the above protocol, but with SST derived by adding 4K to Eq. B1.

839

840 The aqua-4xCO2 experiment replaces the CO_2 mixing ratio with 1392 ppmv. The SST is unchanged from the control
841 simulation (Eq. B1).

842

843 Model runs should be 10 years. We recommend discarding the initial spin up period of a few months.

844

845

846 **APPENDIX C: SST Pattern for CFMIP *amip-future4K/amipFuture* experiments**

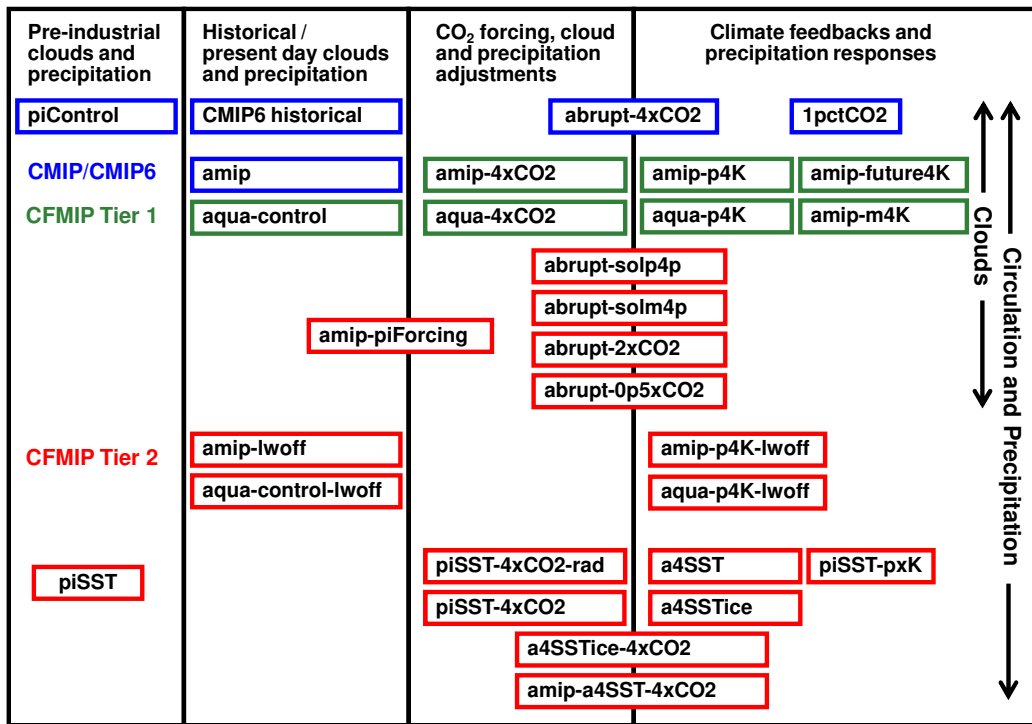
847

848 The *amip-future4K* (formerly *amipFuture*) experiment is the same as the *amip* DECK experiment, except that the SSTs are
849 subject to a composite SST warming pattern derived from the CMIP3 coupled models. The patterned SST forcing dataset is
850 available in a netcdf file called *cfmip2_4k_patterned_sst_forcing.vn1.0.nc* which is available in the supplementary
851 information for this paper, and via the CFMIP website. This is a normalised multi-model ensemble mean of the ocean
852 surface temperature response pattern (the change in ocean surface temperature (TOS) between years 0-20 and 140-160, the
853 time of CO_2 quadrupling in the 1% runs) from thirteen CMIP3 AOGCMs (cccma, cnrm, gfdlcm20, gfdlcm21, gissler,
854 inmcm3, ipsl, miroc-medres, miub, mpi, ncar-ccsm3, and ncar-pcm1.) Before computing the multi-model ensemble
855 mean, each model's TOS response was divided by its global mean and multiplied by 4. This guarantees that the pattern
856 information from all models is weighted equally and the global mean SST forcing is the same as in the uniform +4K
857 experiment.

858



859
 860

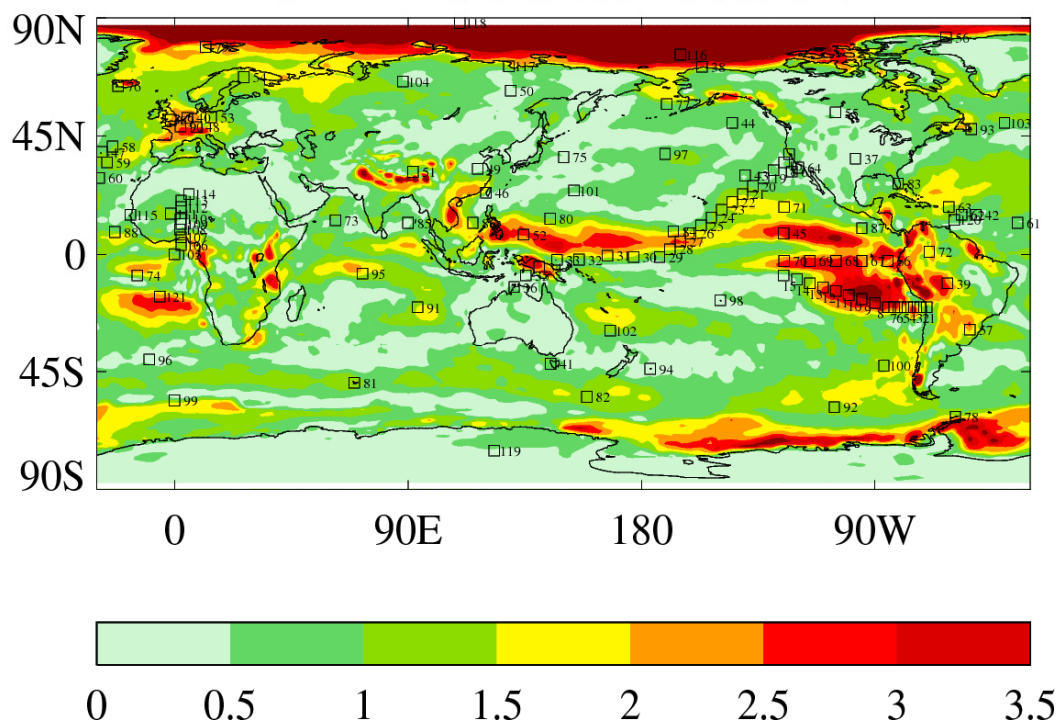


861
 862
 863
 864

Figure 1. Summary of CFMIP-3 experiments and CMIP DECK / CMIP6 experiments.



CFMIP-3 cfSites Locations



865
866
867
868

Figure 2. CFMIP-3 cfSites locations. The contours give an indication of inter-model spread in cloud feedback from the CFMIP-2 amip/amip4K experiments (please refer to Webb et al., 2015a for details).



869 **Table 1.** Summary of CFMIP Tier 1 experiments.

Experiment Name	Experiment Description / Design	Configuration	Start Year	Length
amip	This is a single ensemble member of the AMIP DECK experiment which contains additional outputs which are required for model evaluation using COSP, and as control values for model outputs in the amip-p4K, amip-4xCO2, amip-future4K and amip-m4K experiments.	Atmos- only	1979	36
amip-p4K	As CMIP5/CFMIP-2 amip4K experiment. AMIP experiment where SSTs are subject to a uniform warming of 4K.	Atmos- only	1979	36
amip-4xCO2	As CMIP5/CFMIP-2 amip4xCO2 experiment. AMIP experiment where SSTs are held at control values and the CO ₂ seen by the radiation scheme is quadrupled.	Atmos- only	1979	36
amip-future4K	As CMIP5/CFMIP-2 amipFuture experiment. AMIP experiment where SSTs are subject to a composite SST warming pattern derived from coupled models, scaled to an ice-free ocean mean of 4K.	Atmos- only	1979	36
aqua-control	Extended version of CMIP5/CFMIP-2 aquaControl experiment. Aquaplanet (no land) experiment with no seasonal cycle forced with specified zonally symmetric SSTs.	Atmos- only	1979	10
aqua-p4K	Extended version of CMIP5/CFMIP-2 aqua4K experiment. Aquaplanet experiment where SSTs are subject to a uniform warming of 4K.	Atmos- only	1979	10
aqua-4xCO2	Extended version of CMIP5/CFMIP-2 aqua4xCO2 experiment. Aquaplanet experiment where SSTs are held at control values and the CO ₂ seen by the radiation scheme is quadrupled.	Atmos- only	1979	10

870
871



872 **Table 2.** Summary of CFMIP Tier 2 experiments.

Experiment Name	Experiment Description / Design	Configuratio	Start Year	Length
amip-m4K	As amip experiment but SSTs are subject to a uniform cooling of 4K.	Atmos-only	1979	36
amip-lwoff	As amip experiment, but with cloud-radiative effects switched off in the LW radiation code.	Atmos-only	1979	36
amip-p4K-lwoff	As amip-p4K experiment, but with cloud-radiative effects switched off in the LW radiation code.	Atmos-only	1979	36
aqua-control-lwoff	As aqua-control experiment, but with cloud-radiative effects switched off in the LW radiation code.	Atmos-only	1979	10
aqua-p4K-lwoff	As aqua-p4K experiment, but with cloud-radiative effects switched off in the LW radiation code.	Atmos-only	1979	10
abrupt-solp4p	Conceptually similar to abrupt 4xCO ₂ DECK experiment, except that the solar constant rather than CO ₂ is abruptly increased by 4%.	Coupled AOGCM	1850	150
abrupt-solm4p	Same as abrupt-solp4p, except solar constant is reduced by 4% rather than increased.	Coupled AOGCM	1850	150
abrupt-2xCO ₂	Identical to the DECK abrupt4xCO ₂ , but at 2xCO ₂ .	Coupled AOGCM	1850	150
abrupt-0p5xCO ₂	Identical to the DECK abrupt4xCO ₂ , but at 0.5xCO ₂	Coupled AOGCM	1850	150
amip-piForcing	Identical to AMIP DECK experiment but from 1870-present with constant pre-industrial forcing levels (anthro & natural).	Atmos-only	1870	145
piSST	An AGCM experiment with monthly-varying SSTs, sea-ice, atmospheric constituents and any other necessary boundary conditions (e.g. vegetation if required) taken from each model's own piControl run (using the 30 years of piControl that are parallel to years 111-140 of its abrupt4xCO ₂ run). Dynamic vegetation should be turned off in all the piSST set of experiments.	Atmos-only	Year 111 of abrupt-4xCO ₂	30
piSST-pxK	Same as piSST, but with a spatially and temporally uniform SST anomaly applied on top of the monthly-varying piSST SSTs. The magnitude of the uniform increase is taken from each model's global, climatological annual mean SST change between abrupt4xCO ₂ minus piControl (using the mean of years 111-140 of abrupt4xCO ₂ , and the parallel 30-year section of piControl).	Atmos-only	Year 111 of abrupt-4xCO ₂	30
piSST-4xCO ₂ -rad	Same as piSST but CO ₂ as seen by the radiation scheme is quadrupled.	Atmos-only	Year 111 of abrupt-4xCO ₂	30
piSST-4xCO ₂	Same as piSST but CO ₂ is quadrupled. The increase in CO ₂ is seen by both the radiation scheme and vegetation.	Atmos-only	Year 111 of abrupt-4xCO ₂	30
a4SST	As piSST, but with monthly-varying SSTs taken from years 111-140 of each model's own abrupt4xCO ₂ experiment instead of from piControl. Sea-ice is unchanged from piSST.	Atmos-only	Year 111 of abrupt-4xCO ₂	30
a4SSTice	As piSST, but with monthly-varying SSTs and sea-ice taken from years 111-140 of each model's own abrupt4xCO ₂ experiment instead of from piControl.	Atmos-only	Year 111 of abrupt-4xCO ₂	30
a4SSTice-4xCO ₂	As a4SSTice, but CO ₂ is quadrupled, and the increase in CO ₂ is seen by both the radiation scheme and vegetation.	Atmos-only	Year 111 of abrupt-4xCO ₂	30
amip-a4SST-4xCO ₂	Same as amip, but a patterned SST anomaly is applied on top of the monthly-varying amip SSTs. This anomaly is a monthly climatology, taken from each model's own abrupt4xCO ₂ run minus piControl (using the mean of years 111-140 of abrupt4xCO ₂ , and the parallel 30-year section of piControl). CO ₂ is quadrupled, and the increase in CO ₂ is seen by both the radiation scheme and vegetation.	Atmos-only	1979	36

873

874

875 **Table 3.** Summary of CFMIP-OBS observational datasets available for comparison with COSP diagnostics.

876

Dataset	Years	Observables	Applications	References
CALIPSO-GOCCP	2006/06 - 2012/10	Cloud fractions: 2D and 3D by phase. Scattering ratio histograms as function of height.	Vertical distributions of clouds. Cloud phase identification.	Chepfer et al., (2010); Cesana and Chepfer, (2013)
CloudSat	2006/06 - 2010/12	Reflectivity histograms as function of height.	Vertical distributions of clouds and precipitation	Marchand et al., (2009); Zhang et al., (2010)
ISCCP	1983/07-2008/06	Cloud top pressure – cloud optical depth histograms.	Cloud radiative properties. Long time series.	Rossow and Schiffer, (1999)
MODIS	2002/07 – 2015/11	Cloud top pressure – cloud optical depth histograms. Total, liquid and ice cloud fractions. Effective radius – optical depth histograms by cloud phase.	Cloud radiative properties. Effective size, and phase information.	Pincus et al., (2012); King et al., (2003)
MISR	2000/06 – 2013/05	Cloud top height (CTH) – cloud optical depth histograms	Cloud radiative properties. Independent estimate of cloud top height.	Marchand et al., (2010)
PARASOL	2003/05 - 2012/08	Monodirectional reflectance	Cloud radiative properties.	Konsta et al., (2015)

877

878

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