

1 **nonlinMIP contribution to CMIP6: model intercomparison**  
2 **project for nonlinear mechanisms - physical basis,**  
3 **experimental design and analysis principles (v1.0)**

4

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**Abstract**

nonlinMIP provides experiments that account for state-dependent regional and global climate responses. The experiments have two main applications: 1) to focus understanding of responses to CO<sub>2</sub> forcing on states relevant to specific policy or scientific questions (e.g. change under low-forcing scenarios, the benefits of mitigation, or from past cold climates to the present-day); or 2) to understand the state-dependence (nonlinearity) of climate change – i.e. why doubling the forcing may not double the response. State dependence (nonlinearity) of responses can be large at regional scales, with important implications for understanding mechanisms and for GCM emulation techniques (e.g. energy balance models and pattern-scaling methods). However, these processes are hard to explore using traditional experiments, explaining why they have had little attention in previous studies. Some single model studies have established novel analysis principles and some physical mechanisms. There is now a need to explore robustness and uncertainty in such mechanisms across a range of models (point 2 above), and more broadly, to focus work on understanding the response to CO<sub>2</sub> on climate states relevant to specific policy/science questions (point 1).

nonlinMIP addresses this using a simple, small set of CO<sub>2</sub>-forced experiments that are able to separate linear and non-linear mechanisms cleanly, with a good signal/noise ratio – while being demonstrably traceable to realistic transient scenarios. The design builds on the CMIP5 and CMIP6 DECK protocols, and is centred around a suite of instantaneous atmospheric CO<sub>2</sub> change experiments, with a ramp-up-ramp-down experiment to test traceability to gradual forcing scenarios. In all cases the models are intended to be used with CO<sub>2</sub> concentrations rather than CO<sub>2</sub> emissions as the input. The understanding gained will help interpret the spread in policy-relevant scenario projections.

Here we outline the basic physical principles behind nonlinMIP, and the method of establishing traceability from abruptCO<sub>2</sub> to gradual forcing experiments, before detailing the experimental design and finally some analysis principles. The test of traceability from abruptCO<sub>2</sub> to transient experiments is recommended as a standard analysis within the CMIP5 and CMIP6 DECK protocols.

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### 3 **1 Introduction**

4 Robust climate impacts assessments require, at regional scales, understanding of physical  
5 mechanisms of climate change in GCM projections. A further, pragmatic requirement for  
6 impacts assessments is the ability to emulate (using fast but simplified climate models) GCM  
7 behaviour for a much larger range of policy-relevant scenarios than may be evaluated using  
8 GCMs directly. These two requirements may be combined into a single question: what is the  
9 simplest conceptual framework, for a given well defined model application, that has  
10 quantitative predictive power and captures the key mechanisms behind GCM scenario  
11 projections?

12

13 Often, a choice has been to assume some form of linearity. In studies of the global energy  
14 balance, linearity is often assumed in the form of a constant climate feedback parameter. This  
15 parameter may be used to quantify feedbacks in different models (e.g. Zelinka et al., 2013) or,  
16 in emulation methods, to parameterise global energy balance models (e.g. Huntingford and  
17 Cox, 2000). In understanding or emulating regional patterns of climate change, it is often  
18 assumed explicitly that regional climate change is roughly proportional to global mean  
19 warming. In emulation work, this is termed 'pattern scaling' (Santer et al., 1990; Mitchell,  
20 2003; Ishizaki et al., 2012; Tebaldi and Arblaster, 2014), but this assumption may also be  
21 applied implicitly in understanding mechanisms. Often, physical mechanisms are studied for a  
22 single period of a single forcing scenario or in a single high-forcing experiment such as  
23 abrupt4xCO<sub>2</sub> (implicitly assuming that the understanding is relevant for other periods or  
24 scenarios). The use of pattern-scaling is prevalent in studies of climate impacts.

25

26 While these approximations appear to work well under many circumstances, significant  
27 limitations are increasingly being revealed in such assumptions. These are of two types:  
28 different timescales of response, and non-linear responses. In discussing this, a complication  
29 arises in that different linearity assumptions exist. Henceforth we define 'linear' as meaning  
30 'consistent with linear systems theory' - i.e. responses that are linear in model forcing (i.e.

1 where doubling the forcing doubles the response). This is different from assuming that  
2 regional climate change is proportional to global mean warming – as in pattern scaling.

3

4 Even in a linear system (where responses are linear in forcing), the relationship between two  
5 system outputs (e.g. between global-mean temperature and regional sea surface temperature -  
6 SST) will in general not be linear. This is due to different timescales of response in different  
7 locations and/or variables (section 3.1). Examples include lagged surface ocean warming due  
8 to a connection with the deeper ocean (Manabe et al., 1990;Williams et al., 2008;Held et al.,  
9 2010;Chadwick et al., 2013;Andrews and Ringer, 2014) or the direct response of precipitation  
10 to forcings (Mitchell et al., 1987;Allen and Ingram, 2002;Andrews et al., 2010;Bala et al.,  
11 2010;Bony et al., 2014). One (generally false, but potentially acceptable) assumption of  
12 pattern scaling, then, is that regional climate responds over the same timescale as global-mean  
13 temperature. Different timescales of response are especially important in understanding and  
14 predicting behaviour under mitigation and geoengineering scenarios (or over very long  
15 timescales).

16

17 Non-linear system responses (e.g. Schaller et al., 2013) are more complex to quantify,  
18 understand and predict than those of linear systems (section 3.2). Some examples have been  
19 known for some time, such as changing feedbacks through retreating snow/sea-ice or  
20 increasing water vapour (Hansen et al., 2005;Colman and McAvaney, 2009;Jonko et al.,  
21 2013;Meraner et al., 2013). Some paleoclimate evidence supports the idea that climate  
22 sensitivity increases with warming (Caballero and Huber, 2013;Shaffer et al., 2016), which is  
23 important for the risk of high-end global warming (Bloch-Johnson et al., 2015). The nonlinear  
24 behaviour of the Atlantic Meridional Overturning Circulation is another example (Hofmann  
25 and Rahmstorf, 2009;Ishizaki et al., 2012). More recently, substantial non-linear precipitation  
26 responses have been demonstrated in spatial patterns of regional precipitation change in two  
27 Hadley Centre climate models with different atmospheric formulations (Good et al.,  
28 2012;Chadwick and Good, 2013). This is largely due to simultaneous changes in pairs of  
29 known robust pseudo-linear mechanisms (Chadwick and Good, 2013). Regional warming has  
30 been shown to be different for a first and second CO<sub>2</sub> doubling, with implications primarily  
31 for impact assessment models or studies combining linear energy balance models with pattern  
32 scaling (Good et al., 2015). Non-linearity has also been demonstrated in the response under

1 idealised geoengineering scenarios, of ocean heat uptake, sea-level rise, and regional climate  
2 patterns, with different behaviour found when forcings are decreasing than when they are  
3 increasing (Bouttes et al., 2013;Schaller et al., 2014;Bouttes et al., 2015).

4

5 Investigation of these mechanisms at regional scales has been constrained by the type of  
6 GCM experiment typically analysed. Most previous analyses (e.g. Solomon et al., 2007) have  
7 used results from transient forcing experiments, where forcing changes steadily through the  
8 experiment. There are three main problems with this approach. First, information about  
9 different timescales of response is masked. This is because the GCM response at any given  
10 time in a transient forcing experiment is a mixture of different timescales of response (Li and  
11 Jarvis, 2009;Held et al., 2010;Good et al., 2013), including short-timescale responses (e.g.  
12 ocean mixed layer response from forcing change over the previous few years) through long-  
13 timescale behaviour (including deeper ocean responses from forcing changes multiple  
14 decades to centuries earlier). Secondly, in transient forcing experiments, non-linear behaviour  
15 is hard to separate from linear mechanisms. For example, in an experiment where CO<sub>2</sub> is  
16 increased by 1% per year for 140 years ('1pctCO<sub>2</sub>'), we might find different spatial patterns at  
17 year 70 (at 2xCO<sub>2</sub>) than at year 140 (at 4xCO<sub>2</sub>). This could be due to nonlinear mechanisms  
18 (due to the different forcing level and associated different climate state). However, it could  
19 also be due to linear mechanisms: year 140 follows 140 years of forcing increase, so includes  
20 responses over longer response timescales than at year 70 (only 70 years of forcing increase).  
21 Thirdly, signal/noise ratios of regional climate change can be relatively poor in such  
22 experiments.

23

24 These three issues may be addressed by the use of idealised abruptCO<sub>2</sub> GCM experiments: an  
25 experiment where CO<sub>2</sub> forcing is instantaneously changed, then held constant. The  
26 simplified forcing in such experiments simplifies the understanding of physical mechanisms  
27 of response. In these abrupt CO<sub>2</sub> experiments, responses over different timescales (fast and  
28 slow responses) are separated from each other. Further, responses at different forcing levels  
29 may be directly compared, e.g. by comparing the response in abrupt2xCO<sub>2</sub> and abrupt4xCO<sub>2</sub>  
30 experiments over the same timescale - both have identical forcing time histories, apart from  
31 the larger forcing magnitude in abrupt4xCO<sub>2</sub>. Thirdly, high signal/noise is possible: averages  
32 may be taken over periods of 100 years or more (after the initial ocean mixed layer

1 adjustment, change is gradual in such experiments). Recent work (Good et al., 2012;Good et  
2 al., 2013;Zelinka et al., 2013;Bouttes et al., 2015;Good et al., 2015) has established that these  
3 experiments contain global and regional-scale information quantitatively traceable to more  
4 policy-relevant transient experiments - and equivalently, that they form the basis for fast  
5 simple climate model projections traceable to the GCMs. In other studies (e.g. Frolicher et  
6 al., 2014), pulse experiments have been used to separate different timescales of response  
7 (where forcing is abruptly increased, then abruptly returned to the control state). We use  
8 abruptCO2 experiments because they offer greater signal/noise in the change signal  
9 (important for regional-scale studies); and also for consistency with the CMIP6 DECK  
10 abrupt4xCO2 experiment.

11

12 The CMIP5 abrupt4xCO2 experiments have thus been used widely: including quantifying  
13 GCM forcing and feedback behaviour (Gregory et al., 2004;Zelinka et al., 2013), and for  
14 traceable emulation of GCM projections of global-mean temperature and heat uptake (Good  
15 et al., 2013;Stott et al., 2013). Abrupt4xCO2 is also part of the CMIP6 DECK protocol  
16 (Meehl et al., 2014).

17

18 NonlinMIP builds on the CMIP5 and CMIP6 DECK designs to explore non-linear responses  
19 (via additional abruptCO2 experiments at different forcing levels). It also explores responses  
20 over slightly longer timescales - extending the CMIP5 abrupt4xCO2 experiment by 100 years.

21

## 22 **2 Relating abruptCO2 to gradual forcing scenarios: the step-response model**

23 In using the highly-idealised abruptCO2 experiments, it is essential that their physical  
24 relevance (traceability) to more realistic gradual forcing experiments is determined. We  
25 cannot a priori reject the possibility that some GCMs could respond unrealistically to the  
26 abrupt forcing change. A key tool here is the step-response model (described below). This  
27 (Hasselmann et al., 1993) is a response-function method, which aims to predict the GCM  
28 response to any given transient-forcing experiment, using the GCM response to an abruptCO2  
29 experiment. Such a prediction may be compared with the GCM transient-forcing simulation,  
30 as part of a traceability assessment (discussed in detail in section 5).

31

1 Once some confidence is established in traceability of the abruptCO2 experiments to  
2 transient-forcing scenarios, the step-response model has other roles: to explore the  
3 implications, for different forcing scenarios, of physical understanding gleaned from  
4 abruptCO2 experiments; to help separate linear and nonlinear mechanisms (section 5); and  
5 potentially as a basis for GCM emulation. The method description below also serves to  
6 illustrate the assumptions of linear system theory.

7

8 The step-response model represents the evolution of radiative forcing in a scenario  
9 experiment by a series of step changes in radiative forcing (with one step taken at the  
10 beginning of each year). The method makes two linear assumptions. First, the response to  
11 each annual forcing step is estimated by linearly scaling the response in a CO<sub>2</sub> step  
12 experiment according to the magnitude of radiative forcing change. Second, the response  $y_i$  at  
13 year  $i$  of a scenario experiment is estimated as a sum of responses to all previous annual  
14 forcing changes (see Figure 1 of Good et al., 2013 for an illustration):

15

$$16 \quad y_i = \sum_{j=0}^i w_{i-j} x_j \quad (1a)$$

17

18 where  $x_j$  is the response of the same variable in year  $j$  of the CO<sub>2</sub> step experiment.  $w_{i-j}$  scales  
19 down the response from the step experiment ( $x_j$ ) to match the annual change in radiative  
20 forcing during year  $i-j$  of the scenario (denoted  $\Delta F_{i-j}$ ):

21

$$22 \quad w_{i-j} = \frac{\Delta F_{i-j}}{\Delta F_s} \quad (1b)$$

23

24 where  $\Delta F_s$  is the radiative forcing change in the CO<sub>2</sub> step experiment. All quantities are  
25 expressed as anomalies with respect to a constant-forcing control experiment.

26

1 This approach can in principle be applied at any spatial scale for any variable for which the  
2 assumptions are plausible (e.g. Chadwick et al., 2013).

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4

### 5 **3 Linear and non-linear mechanisms, and the relevance of abruptCO2** 6 **experiments**

7 Here we discuss further, with examples, the distinction between linear and nonlinear  
8 mechanisms, when they are important, and the relevance of abruptCO2 experiments.

#### 9 **3.1 Linear mechanisms: different timescales of response**

10 Even in a linear system, regional climate change per K of global warming will evolve during  
11 a scenario simulation. This happens because different parts of the climate system have  
12 different timescales of response to forcing change.

13

14 This may be due to different effective heat capacities. For example, the ocean mixed layer  
15 responds much faster than the deeper ocean, simply due to a thinner column of water (Li and  
16 Jarvis, 2009). However, some areas of the ocean surface (e.g. the Southern Ocean and south-  
17 east subtropical Pacific) show lagged warming, due to a greater connection (via upwelling or  
18 mixing) with the deeper ocean (e.g. Manabe et al., 1990; Williams et al., 2008). The dynamics  
19 of the ocean circulation and vegetation may also have their own inherent timescales (e.g.  
20 vegetation change may lag global warming by years to hundreds of years, Jones et al., 2009).  
21 At the other extreme, some responses to CO2 forcing are much faster than global warming:  
22 such as the direct response of global mean precipitation to forcings (Mitchell et al.,  
23 1987; Allen and Ingram, 2002; Andrews et al., 2010) and the physiological response of  
24 vegetation to CO2 (Field et al., 1995).

25

26 In a linear system, patterns of change per K of global warming are sensitive to the forcing  
27 history. For example in Figure 1, a scenario is illustrated where forcing is ramped up, then  
28 stabilized. Three periods are highlighted, which may have different patterns of change per K  
29 of global warming, due to different forcing histories: at the leftmost point, faster responses



1 will be relatively more important, whereas at the right, the slower responses have had some  
2 time to catch up. A key example is the different responses of global-mean warming and  
3 global-mean sea level rise under RCP2.6, as shown in Figures SPM.7 and SPM.9 of the IPCC  
4 Fifth Assessment Report (IPCC, 2013). Under RCP2.6, global-mean warming ceases after  
5 2050, when radiative forcing is approximately stabilised (corresponding qualitatively to the  
6 period when the black line is horizontal in Figure 1). In contrast, sea-level rise continues at  
7 roughly the same rate throughout the century. Therefore, in RCP2.6, the sea-level rise per K  
8 of global warming increases after 2050. This is largely because the timescale of deep ocean  
9 heat uptake is much longer than that of ocean mixed-layer warming.

10

11 By design, abruptCO2 experiments separate GCM responses with different timescales (i.e.  
12 separating faster responses from slower responses): the response of a given variable in year Y  
13 of the experiment corresponds to the response of that variable over the timescale Y. This is  
14 used, for example, (Gregory et al., 2004) to estimate radiative forcing and feedback  
15 parameters for GCMs: plotting radiative flux anomalies against global mean warming can  
16 separate 'fast' and 'slow' responses. For example, the top-of-atmosphere outgoing shortwave  
17 flux shows a rapid initial change before the global mean temperature has had time to respond.

## 18 **3.2 Non-linear responses**

19 Nonlinear mechanisms arise for a variety of reasons. Often, however, it is useful to describe  
20 them as state-dependent feedbacks. For example, the snow-albedo and sea-ice albedo  
21 feedbacks becomes small at high or low snow depth (Hall, 2004;Eisenman, 2012). Soil  
22 moisture–temperature feedbacks can also be state-dependent (Seneviratne et al.,  
23 2006;Seneviratne et al., 2010): feedback is small when soil moisture is saturated, or so low  
24 that moisture is tightly bound to the soil (in both regimes, evaporation is insensitive to change  
25 in soil moisture). Sometimes, nonlinear mechanisms may be better viewed as simultaneous  
26 changes in pairs of properties. For example, convective precipitation is broadly a product of  
27 moisture content and dynamics (Chadwick et al., 2012;Chadwick and Good, 2013;Bony et al.,  
28 2014;Oueslati et al., 2016). Both moisture content and atmospheric dynamics respond to CO2  
29 forcing, so in general we might expect convective precipitation to have a nonlinear response  
30 to CO2 forcing. In addition, the Clausius Clapeyron equation introduces some nonlinearity in

1 the increase of specific humidity with warming. Of course, more complex nonlinear responses  
2 exist, such as for the Atlantic Meridional Overturning Circulation.

3

4 In contrast to linear mechanisms, nonlinear mechanisms are sensitive to the magnitude of  
5 forcing. For example, the two points highlighted in Figure 2 may have different patterns of  
6 change per K of global warming, due to nonlinear mechanisms. In contrast, linear  
7 mechanisms would cause no difference in the patterns of change per K of global warming  
8 between the two points in Figure 2, because the two scenarios have the same forcing history  
9 apart from a constant scaling factor.

10

11 An example is the snow/ice albedo feedback, which tends to change in magnitude with  
12 increased global temperature, due to declining snow and ice cover, and the remaining snow  
13 and ice being in areas of lower solar insolation (Colman and McAvaney, 2009).

14

15 AbruptCO<sub>2</sub> experiments may be used to separate nonlinear from linear mechanisms. This can  
16 be done by comparing the responses at the same timescale in different abruptCO<sub>2</sub>  
17 experiments. Figure 3 compares abrupt2xCO<sub>2</sub> and abrupt4xCO<sub>2</sub> experiments over years 50-  
18 149. A 'doubling difference' is defined (Good et al., 2015), measuring the difference in  
19 response to the first and second CO<sub>2</sub> doublings. In most current simple climate models (e.g.  
20 Meinshausen et al., 2011), the radiative forcing from each successive CO<sub>2</sub> doubling is  
21 assumed identical (because forcing is approximately linear in log[CO<sub>2</sub>], Myhre et al., 1998).  
22 With this assumption, a linear system would have zero doubling difference everywhere.  
23 Therefore, the doubling difference is used as a measure of nonlinearity. The question of  
24 which abruptCO<sub>2</sub> experiments to compare, and over which timescale, is discussed in section  
25 5.

26

27 In some GCMs, the forcing per CO<sub>2</sub> doubling has been shown to vary with CO<sub>2</sub> (Colman and  
28 McAvaney, 2009;Jonko et al., 2013). However, this variation depends on the specific  
29 definition of forcing used (Jonko et al., 2013). Currently this is folded into our definition of  
30 nonlinearity. If a robust definition of this forcing variation becomes available in future, it

1 could be used to scale out any difference in forcing between pairs of abruptCO2 experiments,  
2 to calculate an 'adjusted doubling difference'.  
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#### 5 **4 Experimental design**

6 nonlinMIP is composed of a set of abruptCO2 experiments (the primary tools), plus a CO2-  
7 forced transient experiment. AbruptCO2 experiments are driven by changes in atmospheric  
8 CO2 concentration: CO2 is abruptly changed, then held constant. These build on the CMIP5  
9 and CMIP6 DECK protocols (the required runs from these are detailed in Table 1). The  
10 additional nonlinMIP runs (Table 2) are assigned three priority levels. Three options for  
11 participation are: 1) only the 'essential' simulation; 2) all 'high priority' plus the 'essential'  
12 simulations; or, preferably, 3) all simulations. The experiments in Table 1 are required in all  
13 cases. All experiments must be initialized from the same year of a pre-industrial control  
14 experiment, except for abrupt4xto1x (see Table 2). A typical analysis procedure is outlined in  
15 section 5.

16

17 The nonlinMIP design is presently limited to CO2 forcing, although the same principles could  
18 be applied to other forcings.

19

#### 20 **5 Basic analysis principles**

21 This section outlines the applications and general principles behind analysis of nonlinMIP  
22 results. First, some general applications are introduced, before giving more detail on how one  
23 particular application (quantifying and understanding nonlinear change) may be analysed.

24

25 The addition of the abrupt2xCO2 experiment to the standard DECK abrupt4xCO2 permits  
26 quantifying and understanding climate change due to CO2 for three main applications:

27 1) under global warming approximately comparable to that envisaged by the Paris  
28 agreement. (quantified by abrupt2xCO2 – pre-industrial control)

1 2) climate change approximately comparable to that avoided by mitigation (quantified by  
2 abrupt4xCO<sub>2</sub> - abrupt2xCO<sub>2</sub>).

3 3) nonlinear change (the difference between 2 and 1).

4

5 Applications 1 and 2 are expected to be of the widest interest to the community, as they could  
6 be analysed using the same methods as have already been used extensively to study the  
7 response in the CMIP5 abrupt4xCO<sub>2</sub> experiment, but for climate states more relevant to the  
8 policy questions outlined in 1) and 2). Useful signal/noise should be possible because ~100  
9 year means may be analysed (e.g. over years 50-149, where climate is relatively stable as it  
10 follows the initial ocean mixed layer warming). Application 3 is more specialised, and is  
11 discussed in more detail below.

12

13 The abrupt0.5xCO<sub>2</sub> experiment permits analogous work, extending the relevance to colder  
14 past climates, and exploring one aspect of how past change may differ from future change. It  
15 also allows nonlinear mechanisms to be studied with greater signal/noise:

16

17 4) change under past cold climates (abrupt0.5xCO<sub>2</sub> - piControl).

18 5) nonlinear change: as 3, but with larger signal/noise ( [abrupt4xco<sub>2</sub> - abrupt2xco<sub>2</sub>] –  
19 [piControl - abrupt0.5xCO<sub>2</sub>] ).

20

21 In quantifying nonlinear change (applications 3 or 5 above), the primary idea is to find where  
22 the step-response model (section 2) breaks: since the step-response model is based on a linear  
23 assumption, this amounts to detecting non-linear responses.

24

25 The aim is to focus subsequent analysis. If non-linearities in a quantity of interest are found  
26 to be small, then analysis may focus on understanding different timescales of response from a  
27 single abruptCO<sub>2</sub> experiment: linearity means that the physical response (over a useful range  
28 of CO<sub>2</sub> concentrations) is captured by a single abruptCO<sub>2</sub> experiment. This represents a  
29 considerable simplification. If, on the other hand, non-linearities are found to be important,

1 the focus shifts to understanding the different responses in different abruptCO<sub>2</sub> experiments.  
2 The choice of which abruptCO<sub>2</sub> experiments to focus on, and over which timescales, is  
3 discussed below.

4

## 5 **5.1 First step: check basic traceability of abrupt4xCO<sub>2</sub> to the transient-forced** 6 **response near 4xCO<sub>2</sub>**

7 The test described here is recommended as a routine analysis of the CMIP6 DECK  
8 experiments (even if nonlinMIP experiments are not performed). The aim is to confirm  
9 whether the abruptCO<sub>2</sub> experiments contain realistic physical responses in the variables of  
10 interest (as previously done for global-mean temperature and heat uptake for a range of  
11 CMIP5 models (Good et al., 2013), for regional-scale warming and ocean heat uptake  
12 (Bouttes et al., 2015; Good et al., 2015) and for other global-mean quantities for HadCM3  
13 (Good et al., 2011). This also, rules out the most pathological non-linearities (e.g. if the  
14 response to an abrupt CO<sub>2</sub> change in a given GCM was unrealistic). Although this test has  
15 been done for a range of models and variables, traceability cannot be assumed to hold for all  
16 models and variables.

17

18 The linear step-response model should first be used with the abrupt4xCO<sub>2</sub> response, to  
19 predict the response near year 140 of the 1pctCO<sub>2</sub> experiment (i.e. near 4xCO<sub>2</sub>). This  
20 prediction is then compared with the actual GCM 1pctCO<sub>2</sub> result. This should first be done  
21 for global mean temperature: this assessment has previously been performed for a range of  
22 CMIP5 models (Good et al., 2013), giving an idea of the level of accuracy expected. If the  
23 abruptCO<sub>2</sub> response is fundamentally unrealistic, it is likely to show up in the global  
24 temperature change. This approach may then be repeated for spatial patterns of warming, and  
25 then for the quantities of interest. Abrupt4xCO<sub>2</sub> is used here as it has larger signal/noise than  
26 abrupt2xCO<sub>2</sub>, yet is representative of forcing levels in a business-as-usual scenario by 2100.  
27 However, the tests may also be repeated using abrupt2xCO<sub>2</sub> – but compared with year 70 of  
28 the 1pctCO<sub>2</sub> experiment (i.e. at 2xCO<sub>2</sub>).

29

1 The step-response model emulation under these conditions should perform well for most  
2 cases: the state at year 140 of the 1pctCO<sub>2</sub> experiment is very similar to that of abrupt4xCO<sub>2</sub>  
3 (same forcing, similar global-mean temperature), so errors from non-linear mechanisms  
4 should be minimal. If large errors are found, this may imply caution about the use of  
5 abruptCO<sub>2</sub> experiments for these variables, or perhaps point to novel non-linear mechanisms  
6 that may be understood by further analysis.

## 8 **5.2 Second step: characterising nonlinear responses**

9 Having established some level of confidence in the abruptCO<sub>2</sub> physical response, the second  
10 step is to look for nonlinear responses. This first involves repeating the tests from step 1  
11 above, but for different parts of the 1pctCO<sub>2</sub> and 1pctCO<sub>2</sub> ramp-down experiments, and  
12 using different abruptCO<sub>2</sub> experiments for the step-response model.

13  
14 An example is given in Figure 4 (but for different transient-forcing experiments). This shows  
15 results for global-mean precipitation in the HadCM3 GCM (Good et al., 2012), under an  
16 idealised simulation where forcing is ramped up at a constant rate for 70 years, then ramped  
17 down at the same rate for 70 years. Here, the step-response model prediction using  
18 abrupt4xCO<sub>2</sub> (red curves) is only close to the actual GCM simulation (black) where the  
19 transient-forced simulation is near to 4xCO<sub>2</sub> (i.e. near year 70). Similarly, the prediction  
20 using abrupt2xCO<sub>2</sub> (blue curves) works only near 2xCO<sub>2</sub> (near years 35 or 105). Otherwise,  
21 quite large errors are seen, and the predictions with abrupt2xCO<sub>2</sub> and abrupt4xCO<sub>2</sub> are quite  
22 different from each other. This implies that there are large non-linearities in the global-mean  
23 precipitation response in this GCM, and that they may be studied by comparing the responses  
24 in the abrupt2xCO<sub>2</sub> and abrupt4xCO<sub>2</sub> experiments.

25  
26 Having identified some non-linear response, and highlighted two or more abruptCO<sub>2</sub>  
27 experiments to compare (in the previous example, abrupt2xCO<sub>2</sub> and abrupt4xCO<sub>2</sub>), the non-  
28 linear mechanisms may be studied in detail by comparing the responses in the different  
29 abruptCO<sub>2</sub> experiments over the same timescale (e.g. via the doubling difference, as in Figure  
30 3). This allows (Good et al., 2012; Chadwick and Good, 2013; Good et al., 2015) non-linear

1 mechanisms to be separated from linear mechanisms (not possible in a transient-forcing  
2 experiment). It is expected that analysis will focus on the 100-year period over years 40-139  
3 of the experiments (the relatively stable period after the initial ocean mixed-layer warming).

4  
5 In the same spirit as other CMIP5 and CMIP6 idealised experiments, nonlinMIP will help  
6 understand nonlinear mechanisms by isolating the signal of nonlinear mechanisms more  
7 effectively. This occurs in two ways: first, by using simplified forcing compared to the time-  
8 dependent, RCP projections (the latter feature multiple forcings of evolving strength). The  
9 simplified forcing means that alternative mechanisms (from different forcing agents or linear  
10 mechanisms) may be ruled out by design. Secondly, contamination of the signal from internal  
11 variability may be reduced, as averages of around 100 years are possible.

12  
13 The magnitude of internal variability may also be estimated at the different levels of CO<sub>2</sub>  
14 forcing. This could be used to help explore changes in variability with warming (Seneviratne  
15 et al., 2006;Screen, 2014), and to assess significance of any signal of nonlinear change in the  
16 time mean climate. Internal variability could be estimated from years 40-139 of the  
17 experiments (after the initial warming of the ocean mixed layer), after removing a fitted linear  
18 trend.

## 19 20 **6 Conclusions**

21  
22 These experiments can help improve climate science and consequent policy advice in a  
23 number of ways. The focus is on understanding mechanisms (given the idealised nature of  
24 the experiments). A further application, however, is that energy balance models could be  
25 tuned to the different experiments, to explore the importance, for projections, of state-  
26 dependence of feedback parameters (Hansen et al., 2005;Colman and McAvaney,  
27 2009;Caballero and Huber, 2013). Also, if certain regions are found to show strongly  
28 nonlinear behaviour in these experiments, this could help focus assessment of impact tools  
29 like pattern-scaling or time-shifting (e.g. Herger et al., 2015).

1 Of probably widest interest is the fact that the additional experiments will allow  
2 understanding work to focus on climate states more directly relevant to discrete policy/science  
3 questions (the benefits of mitigation; impacts of scenarios consistent with the Paris  
4 agreement; or understanding past cold climates; see start of section 5). These questions may  
5 show important differences, due to state-dependence (nonlinearity) of mechanisms, but for  
6 many cases the nature of the nonlinearity may not need to be assessed. A classical example is  
7 the snow-albedo feedback: the strength of this would be different in a warm versus a cold  
8 world (due to different baseline snow cover), but if the focus is on understanding the warm  
9 world, the first priority is to study experiments representative of the warm world (with the  
10 correct climate state).

11

12 There is also a need to quantify and understand, at regional scales, nonlinear mechanisms of  
13 climate change: that is, do the above science/policy questions give significantly different  
14 answers (e.g. different patterns of rainfall change), and why? This is difficult to do using  
15 transient model experiments alone, for two reasons: contamination due to different timescales  
16 of response, and noise from internal variability.

17

18 This paper outlines the basic physical principles behind the nonlinMIP design, and the method  
19 of establishing traceability from abruptCO<sub>2</sub> to gradual forcing experiments, before detailing  
20 the experimental design and finally some general analysis principles that should apply to most  
21 studies based on this dataset.

22

23

24

## 25 **7 Data availability**

26

27 Results will be made available as part of the CFMIP project, within the sixth model  
28 intercomparison project, CMIP6.

29



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1 Table 1. List of CMIP5/CMIP6 DECK experiments required by nonlinMIP.

Experiment	Description	Role
piControl	Pre-industrial control experiment	
Abrupt4xCO2	CO2 abruptly quadrupled, then held constant for 150 years.	Separate different timescales of response.
1pctCO2	CO2 increased at 1% per year for 140 years (i.e. as CMIP5 1pctCO2 experiment), then decreased by 1% per year for 140 years (i.e. returning to pre-industrial conditions).	To test traceability of the abruptCO2 experiments to more realistic transient-forcing conditions. Adding the ramp-down phase explores physics relevant to mitigation and geo-engineering scenarios.

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- 1 Table 2. NonlinMIP experimental design. Three options are: only the ‘essential’ simulation;
- 2 all ‘high priority’ plus the ‘essential’ simulations; or, all simulations. The experiments in
- 3 Table 1 are required in all cases.

Experiment (priority)	Description	Role
Abrupt2xCO2 (essential)	As abrupt4xCO2 (see Table 1), but at double pre-industrial CO2 concentration.	To diagnose non-linear responses (in combination with abrupt4xCO2).  Assess climate response and (if appropriate) make climate projections with the step-response model at forcing levels more relevant to mid- or low-forcing scenarios.
Abrupt0.5xCO2 (essential)	As abrupt4xCO2 (see Table 1), but at half pre-industrial CO2 concentration	To diagnose non-linear responses (in combination with abrupt4xCO2 and abrupt2xCO2). Offers greater signal/noise for regional precipitation change than if just abrupt2xCO2 was used. Also relevant to paleoclimate studies.
Extend both abrupt2xCO2 and abrupt4xCO2 by 100 years (high priority)		Permit improved signal/noise in diagnosing some regional-scale non-linear responses  Explore longer timescale responses than in CMIP5 experiment. Permit step-response model scenario simulations from 1850-2100

		<p>Allow traceability tests (via the step-response model) against most of the 1pctCO<sub>2</sub> ramp-up-ramp-down experiment.</p> <p>Provide a baseline control for the abrupt4xto1x experiment.</p>
1pctCO <sub>2</sub> ramp-down (medium priority)	<p>Initialised from the end of 1pctCO<sub>2</sub>. CO<sub>2</sub> is decreased by 1% per year for 140 years (i.e. returning to pre-industrial conditions).</p>	<p>To test traceability of the abruptCO<sub>2</sub> experiments to more realistic transient-forcing conditions. Adding the ramp-down phase explores a much wider range of physical responses, providing a sterner test of traceability. Relevant also to mitigation and geo-engineering scenarios, and offers a sterner test of.</p>
Abrupt4xto1x (medium priority)	<p>Initialised from year 100 of abrupt4xCO<sub>2</sub>, CO<sub>2</sub> is abruptly returned to pre-industrial levels, then held constant for 150 years.</p>	<p>Quantify non-linearities over a larger range of CO<sub>2</sub> (quantifies responses at 1xCO<sub>2</sub>).</p> <p>Assess non-linearities that may be associated with the direction of forcing change.</p>
Abrupt8xCO <sub>2</sub> (medium priority)	<p>As abrupt4xCO<sub>2</sub>, but at 8x pre-industrial CO<sub>2</sub> concentration. Only 150 years required here.</p>	<p>Quantify non-linearities over a larger range of CO<sub>2</sub>.</p>

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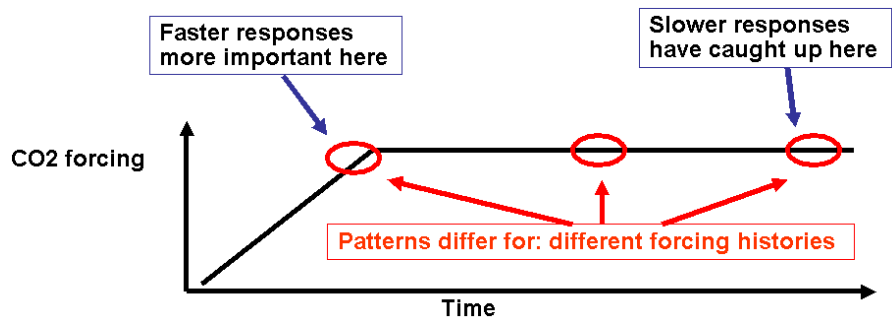


Figure 1. Schematic illustrating a situation where linear mechanisms can cause climate patterns to evolve. This represents a scenario where global-mean radiative forcing (black line) is ramped up, then stabilised. At the time indicated by the left red oval, responses with shorter timescales are relatively important, due to the recent increase in forcing. At the time marked by the right-hand oval, forcing has been stabilised for an extended period, so the responses with longer timescales (such as sea-level rise) have had more time to respond to the initial forcing increase.

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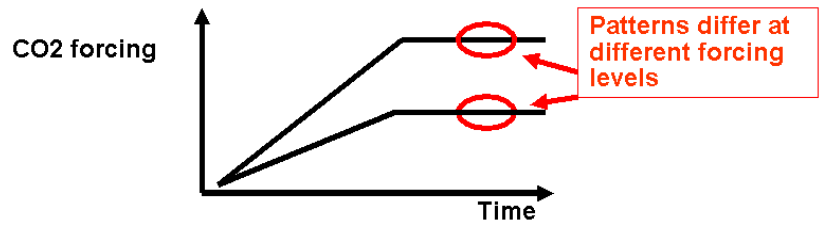
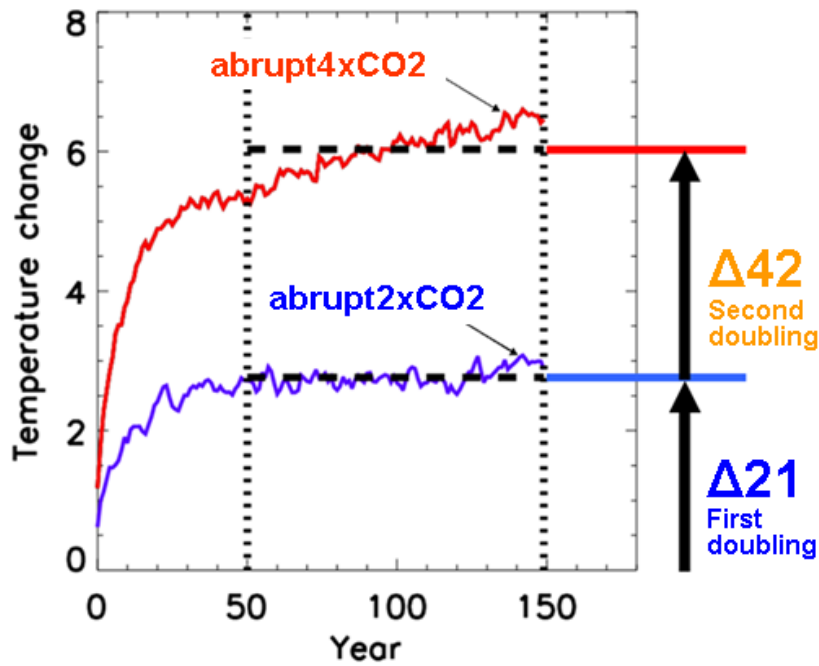


Figure 2. Schematic illustrating the point that nonlinear mechanisms can cause climate patterns to differ at different forcing (and hence global temperature) levels. This represents two different scenarios, whose forcing timeseries is identical apart from a constant scale factor (the higher forcing scenario has about twice the forcing of the lower scenario).



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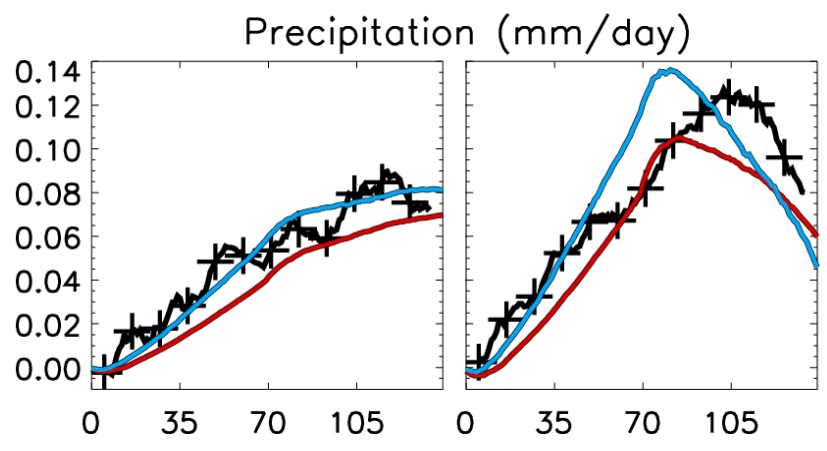
Figure 3. Defining the ‘doubling difference’. The red and blue lines show illustrative time-series of a variable (in this example, global-mean temperature from HadGEM2-ES) from the abrupt4xCO2 and abrupt2xCO2 experiments. Doubling difference =  $\Delta 42 - \Delta 21$  (the difference in response between the first and second CO2 doublings. This is defined for a specific timescale after the abrupt CO2 change – in this example, it is for means over years 50-149.

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5 Figure 4. Finding nonlinear responses in transient forcing experiments. (figure from Good et  
6 al., 2012). Time-series of global-mean precipitation change under two experiments. Left:  
7 where CO<sub>2</sub> is increased by 1% per year, then stabilised at 2x pre-industrial levels. Right:  
8 where CO<sub>2</sub> is increased by 2% per year for 70 years, then decreased by 2% per year for 70  
9 years. Black: GCM. Red: step-response model using the abrupt4xCO<sub>2</sub> response. Blue: the  
10 abrupt2xCO<sub>2</sub> response.

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