AVOID 2

Can we avoid dangerous climate change?

Future temperature responses based on IPCC and other existing emissions scenarios

July 2014

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Version: 2

Reference: AVOID2 WPA.1 Report 1

Met Office

Grantham Institute Climate Change and the Environment
An institute of Imperial College London

Tyndall°Centre® for Climate Change Research

Walker Institute

Funded by

Department of Energy & Climate Change

Department for Environment Food & Rural Affairs

NERC Science of the Environment

This work was supported by AVOID 2 programme (DECC) under contract reference no. 1104872
For more information about the AVOID 2 programme visit www.avoid.uk.net

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Non-technical summary

This study re-analysed emissions data produced for the IPCC Fifth Assessment Report. It presents the spread in emissions from this dataset at 2020, 2030 and 2050 compatible with warming limits of 1.5 °C up to 4 °C. Confidence is provided in the modelling system by comparison of elements of this analysis with similar reported results from IPCC and UNEP.

The analysis is then extended by sampling different climate outcomes at pre-specified levels of emissions in 2030, giving an alternative way of viewing the IPCC database.

The final part of this assessment is to go beyond the IPCC Working Group 3 assessment by demonstrating how a key climate uncertainty (the equilibrium climate response) leads to a very large spread in the emissions compatible with different warming levels.

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Executive summary

The IPCC Fifth Assessment Report (AR5) of Working Group 3 (IPCC WG3 2014) constructed and considered over a thousand emission scenarios. These were produced using Integrated Assessment Models (IAMs) to take account of aspects of future economic and technical feasibility. Not all of the emissions scenarios are suitable for climate assessment because of the length of record or missing emissions for some radiatively active species. This assessment, and that of IPCC, is that the viable size of the dataset is around 500 emission pathways, consisting of both reference cases without explicit mitigation policy, and mitigation cases.

The aim in this AVOID2 study is to analyse this emission dataset to produce results not easily extracted from the IPCC WG3 report, and to take account of developments in climate science that were not included in the IPCC assessment of these pathways. Before doing this there is a demonstration that the AVOID2 climate modelling system is able to reproduce many aspects of the original IPCC climate calculations, when set up with suitable parameters, such as the distribution of climate sensitivity. Some differences do remain but the largest differences appear to be related to the outputs of two particular IAMs, which treat SO_2 emissions differently from the remainder of the emissions dataset. AVOID2 is currently seeking explanations from the modelling centres that ran those simulations to understand their assumptions and establish if any adjustments or normalisations were applied during the IPCC climate simulations for WG3.

Having established suitable fidelity in the AVOID2 approach three investigations were carried out focused on the questions:

- What is the distribution of emissions that leads to a particular median warming outcome?
- What is the distribution of warming outcomes for a given emissions level in, say, 2030?
- How sensitive are the results to alternative but credible assumption of equilibrium climate sensitivity?

Before answering any of these questions it is vital to recognise that the IPCC emissions dataset was not designed to optimally sample the emissions scenarios that lead to median warming levels over the range 1.5 °C to 5 °C. There is a grouping of the models around the 2 °C level, another but smaller grouping around 3.5 °C to 4.5 °C, and sparser coverage at other temperatures. Furthermore, although some delayed peaking pathways were constructed there is much less consideration of technology limitation (e.g. no CCS availability on large-scale). Further work is recommended to better sample the solution space.

Using the AVOID2 default climate model set up and focusing on the temperature warming limit relative to pre-industrial levels of 2 °C (with a small threshold either side) reveals median emissions of 48.8 $GtCO_2e$ in 2020 (10^{th} to 90^{th} spread of 42.6 to 53.7 $GtCO_2e$), and for 2030 emissions of 44.8 $GtCO_2e$ (spread 35.6 to 59.5). This is in close agreement with WG3. When focusing on higher temperature thresholds the median emissions for the 2.5 °C and 3 °C are very similar in 2020 with 51.2 and 51.7 $GtCO_2e$ respectively, and again at 2030 with 53.4 and 54.2 $GtCO_2e$. Much bigger separation is evident by 2050. This reflects the late peaking of many of the scenarios compatible with 2.5 °C, combined with a lack of sampling within the database for the temperature in the range 2.5 °C to 3.5 °C. In order to further build confidence in the AVOID2 approach the analysis was compared with the recent UNEP Emissions Gap report. Some differences are to be expected because of the different approaches and scenario choices but we find most of these to be quite small, or are explainable by the different assumptions.

An alternative way of interrogating the WG3 database is to select emissions scenarios that fall within a particular constraint, such as the emissions level in 2030 (plus or minus 0.5 $GtCO_2e$). This was done using the default climate settings, which correspond most closely to the IPCC's own analysis. Taking 44 $GtCO_2e$ as an example we found 29 compatible scenarios, with 15 of these having net carbon dioxide emissions below zero by 2100 – indicating substantial artificial carbon dioxide removal. The mean of the median warming levels for the 29 scenarios by 2100 and relative to pre-industrial conditions is 1.9 °C. The mean probabilities of limiting warming in 2100 to below 1.5 °C, 2 °C, 3 °C and 4 °C are 22 %, 51 %, 89 % and 97 %, respectively for this emissions classification.

A key part of this study was to use alternative distributions of the key climate parameter describing the long term temperature response to a doubling of CO_2, the equilibrium climate sensitivity. The IPCC Fifth Assessment WG1 report presented many different estimates of this, reported from a range of different scientific approaches. It is currently not possible to choose a single best approach so it is recommended that several of these are used in analysis of climate outcomes. The WG3 report only used one such distribution, and this choice has a major impact on the results. For example, focusing on the median emissions in 2030 for a 2 °C warming level a shift of around 15 $GtCO_2e$/yr is evident in moving from the lowest to the highest case. The spread is even greater when looking at emissions in 2050.

Future work will be able to further interrogate the WG3 emissions database. In particular it will be possible to pose questions by selecting on a range of other relevant quantities such as GDP, population, energy demand, and energy supply mix. Also it is being considered whether it would be possible to weight the results according to IAM performance metrics.

1. Introduction

A number of recent projects around the globe have produced a range of emission scenarios using integrated assessment models (IAM) to simulate economic and technically feasible futures. These include EU AMPERE and LIMITS. The IPCC Working Group 3 (WG3) has constructed a database of these existing scenarios, and this is now publically available[1]. This report details the projected climate response to these scenarios using a probabilistic tuned simple climate model approach accounting for a range of uncertainty distributions of equilibrium climate sensitivity reported in IPCC Working Group 1 (IPCC WG1 2013). This goes beyond the information that was presented by WG3.

This project exploits the methodology developed by Met Office Hadley Centre for a recent project for the UK Committee on Climate Change as part of the review of the 4th carbon budgets (Bernie *et. al.* 2013), and for the EU AMPERE project (Lowe *et. al.* 2014).

2. Method

2.1. Climate model

The modelling system used in AVOID2 samples scientific uncertainties in the climate system by sampling distributions of physical parameters which have a dominant contribution to uncertainty in climate projections. These are the equilibrium climate sensitivity (ECS), which is the long term warming response to a doubling of atmospheric CO_2; ocean diffusivity which affects how quickly heat is removed from the upper ocean, moderating the rates of atmospheric warming, and; climate-carbon cycle feedback strength which accounts for how strongly climate change affects the ability of the carbon cycle to remove CO_2 from the atmosphere. To validate the modelling system used here we have tried to match these distributions as closely as possible to those used in WG3.

The distribution of carbon cycle feedback uncertainty used by WG3 was based on C4MIP (Friedlingstein *et. al*. 2006). The modelling system used in AVOID also used a distribution based on this, so no change is made.

WG3 used an estimated distribution of ocean diffusivity based on climate models from WG1 of the IPCC Fourth Assessment Report (AR4). AVOID had been using a distribution based on the IPCC Third assessment report and so this is updated. Previous work in AVOID has shown that this would increase the median 2100 warming under a business-as-usual scenario (SRES A1B) by about 0.2 °C (Gohar *et. al.* 2011).

The default ECS distribution used is based on AR4 and is a simple combination of ECS distributions from a number of alternative lines of evidence (Rogelj *et. al*. 2012). This single distribution was used by WG3 to ensure consistency in the climate projections. For the initial validation this distribution is also adopted.

[1] IAMC IPCC Fifth Assessment Report Scenario Database, 2014, hosted by IIASA at; https://secure.iiasa.ac.at/web-apps/ene/AR5DB/dsd?Action=htmlpage&page=about#intro

2.2. IPCC Working Group 3 scenario database

The scenario data base from WG3 contains 1184 IAM scenarios from 31 different models. Where possible WG3 ran scenarios through a single climate model, MAGICC6.3 (note this is a different version to that used in this study), to establish comparability between the concentration, forcing, and climate outcome between scenarios. The aim of this was to remove the natural science uncertainty arising from use of often even more highly simplified climate model assumptions in the different integrated models.

While many scenarios in the data base are CO_2-only or provide emissions of only limited number greenhouse gas species, WG3 made climate simulations of those scenarios where it deemed the dominant greenhouse gas contributions where available. Minimum requirements to use a given scenario where the reporting for the following emissions to 2100;

- CO_2 from the fossil fuel and industry (FFI) sector
- CH_4 from FFI and land use sectors
- N_2O from FFI and land use sectors
- Sulphur emissions

In case of missing land use related CO_2 emissions the average from the representative concentration pathways (RCPs) was used. If fluorinated gas (F-gas), carbonaceous aerosols and/or nitrate emissions were missing, these were added by interpolating data from RCP2.6 and RCP8.5 on the basis of the energy related CO_2 emissions

The process resulted in 524 scenarios for which climate projections were made by WG3 and this study. Only these 524 studies are included in statements about end of century warming in the WG3 fifth assessment report. This report follows the WG3 emissions process as closely as possible for these 524 scenarios to demonstrate that, when appropriately configured, the modelling system used in AVOID2 produces climate projections that agree well with the analysis of WG3. Full details of this process are detailed in annex 2 of the WG3 report.

3. Results

3.1. Comparison with WG3 of AR5

The most basic comparison with the WG3 analysis is to examine the median end-of-century warming. Figure 1 shows that the median warming of the AVOID2 projections performed by the Met Office Hadley Centre (MOHC) compare well with those from the WG3 analysis. There are some apparent discrepancies such as clusters of scenarios around 4 °C in 2100 that have higher temperatures in the WG3 analysis than MOHC. The causes of this are examined in section 3.2.

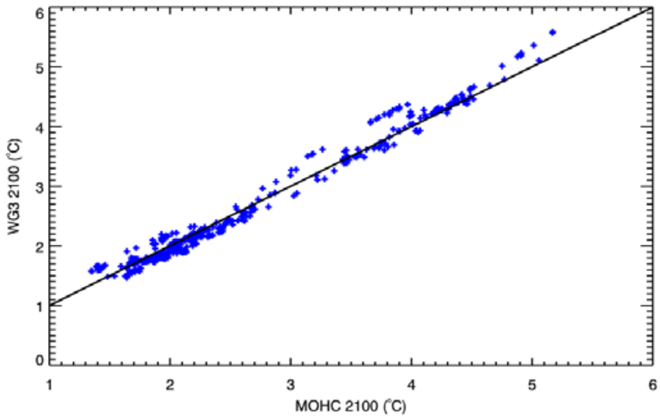

Figure 1: Median 2100 temperature projections for WG3 scenarios from the WG3 analysis and the MOHC projections of this study.

As the focus of the database is on mitigation measures, a more relevant question for validation is the extent to which emissions diagnosed as consistent with a given climate target agree in the two modelling approaches. Figure 2 shows the cumulative frequency distribution of 2020 CO_2e emissions for scenarios with a median 2100 temperature meeting with targets levels of 2 °C, 2.5 °C, 3 °C or 4 °C to within ±0.25 °C. Colours indicate the target temperature with solid lines showing the results from this study and dashed those from the MAGICC6.3 simulations from WG3.

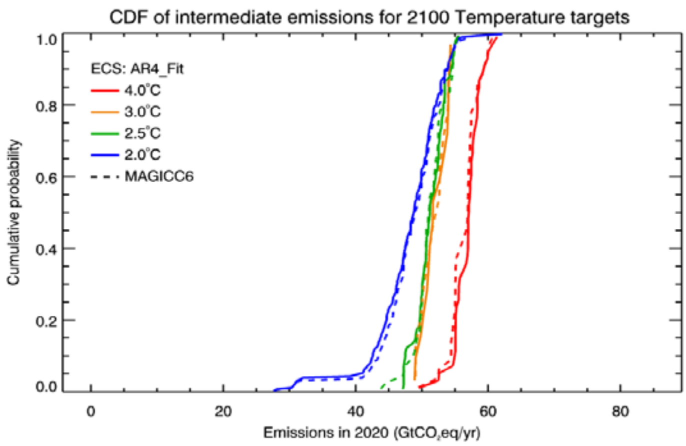

Figure 2: Cumulative frequency distributions of 2020 emissions from WG3 scenarios with median 2100 temperature projections meeting different temperature targets (colours). Those diagnosed from this study when the model is configured to match the modelling in WG3 are solid while those diagnosed directly from the WG3 projections are shown as dashed for comparison.

While there is close agreement between the two sets of projections a prominent feature of the figure 2 is that the distributions for scenarios meeting targets of 2.5 °C and 3 °C are very similar. This arises from the combination of two factors. Firstly IAM scenarios in the database are predominantly split between “Reference” scenarios with no mitigation and mitigation scenarios with median 2100 temperatures around 2 °C. This means that far more scenarios exist in the aggressive mitigation end of the spectrum around 2 °C and the business as usual end around 4 °C so the scenario space, despite the size of the WG3 database, is still quite sparse between 2.5 °C and 3.5 °C warming levels in 2100. Coupled with this it is apparent that, given the constraints on emissions reductions implied by the behaviour of the current generation of IAMs contributing to the database, 2020 emissions are a relatively weak constraint on median projected 2100 temperatures. This is illustrated in the Figure 3 where the 2020 total emissions are shown as a function of projections 2100 median temperature.

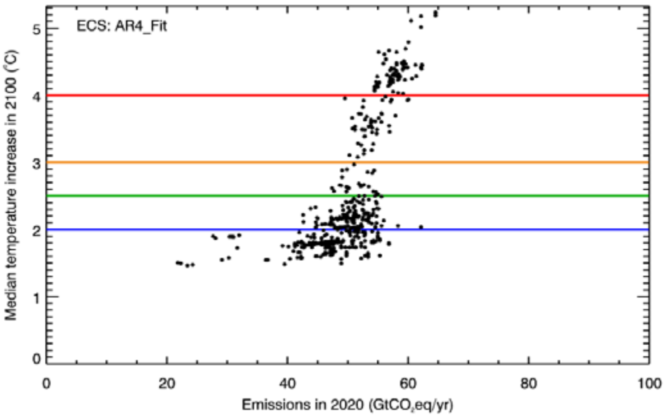

Figure 3: Median projected 2100 temperatures as a function of 2020 emissions to illustrate the scatter and relative sparsity in places of the available scenario dataset

3.2. Outstanding anomalies

While Figure 1 showed that while there is a broad agreement between the two approaches there appears to be some evidence of systematic bias with suggestion of small clusters of scenarios. On further investigation it was identified that the outliers are predominately from one of two models, either IMAGE2.4 or MERGE-ETL_2011 (Figure 4). Further to this these two models have quite atypical sulphate emissions for the WG3 database as a whole (Figure 5). MERGE-ETL_2011 uses the same sulphate emissions for all scenarios, while IMAGE2.4 has much higher emissions of sulphates than other scenarios in the data base that lead to similar levels of 2100 warming.

It is not clear as yet why the sulphate emissions from IMAGE2.4 are more than twice the level from comparable scenarios and the model team responsible has been contacted in regards to this while possible other explanations for the projections from these two models are being perused. However in the context of the broader results from the database these anomalies do not greatly detract from the overall performance of the projections and so these scenarios are included in all subsequent analysis.

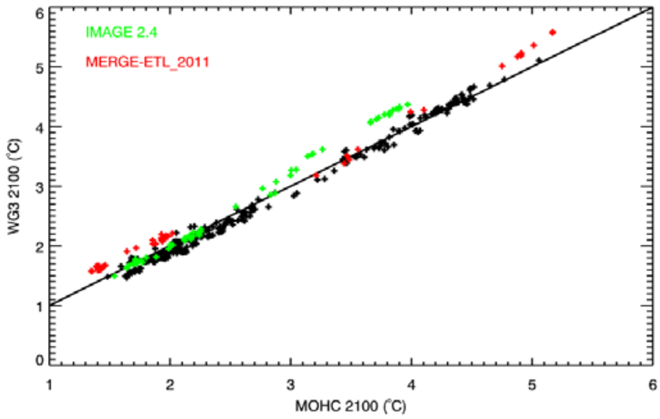

Figure 4 Median projected 2100 warming from the WG3 analysis as a function of the median 2100 warming from this study, with the scenarios from IMAGE2.4 and MERGE-ETL_2011 highlighted.

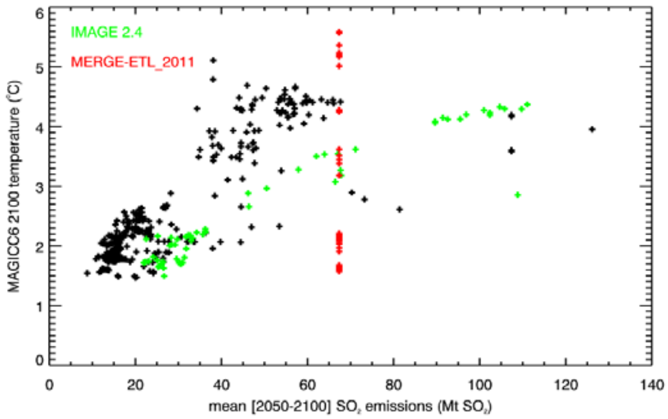

Figure 5 Median projected 2100 warming from the WG3 analysis as a function of the mean SO_2 emissions over the second half of the century. Scenarios from IMAGE2.4 and MERGE-ETL_2011 highlighted indicating atypical emissions compared to other WG3 scenarios with similar temperature outcomes.

3.3. <u>Spread of 2020 and 2030 emissions from AVOID and WG3</u>

As shown in Figure 2 there is close agreement between the two sets of projections with the median 2020 emissions consistent with 2 °C in 2100. Both studies, AVOID2 and WG3 giving a median in this case of 49 $GtCO_2e$ (43 to 54 $GtCO_2e$ 10^{th} to 90^{th} percentile range), using temperatures calculated as differences to a 1986-2005 baseline plus 0.61 °C of warming from pre-industrial as per WG3. Similar cumulative distributions for emissions in 2030 and 2050 (Figure 6) also show that the good agreement between the two sets of projections is consistent. Abridged data for Figure 2 and Figure 6 are given in Table 1.

The sparsity of the scenario database highlighted earlier also has some other consequences that are evident in Figure 2 and Figure 6 and Table 1. The low sampling of possible scenarios means that the cumulative distributions functions are not always well defined, which is evident from the lack of smoothness that might be expected from a comprehensive examination of scenario space. In the case of scenarios meeting a 2.5 °C or 3 °C target this is more evident as the emissions distributions in 2030 (and 2020) closely match. The poor sampling in these cases means that particular parts of the distributions may give counter intuitive results, for example for the median emissions in 2030 from WG3, the 2.5 °C rate is 54.42 $GtCO_2e$/yr emissions, but the 3 °C rate is lower at 53.88 $GtCO_2e$/yr. This relative sparsity present problems in drawing robust advice from the WG3 database and this issue is discussed in detail in the conclusions of this report.

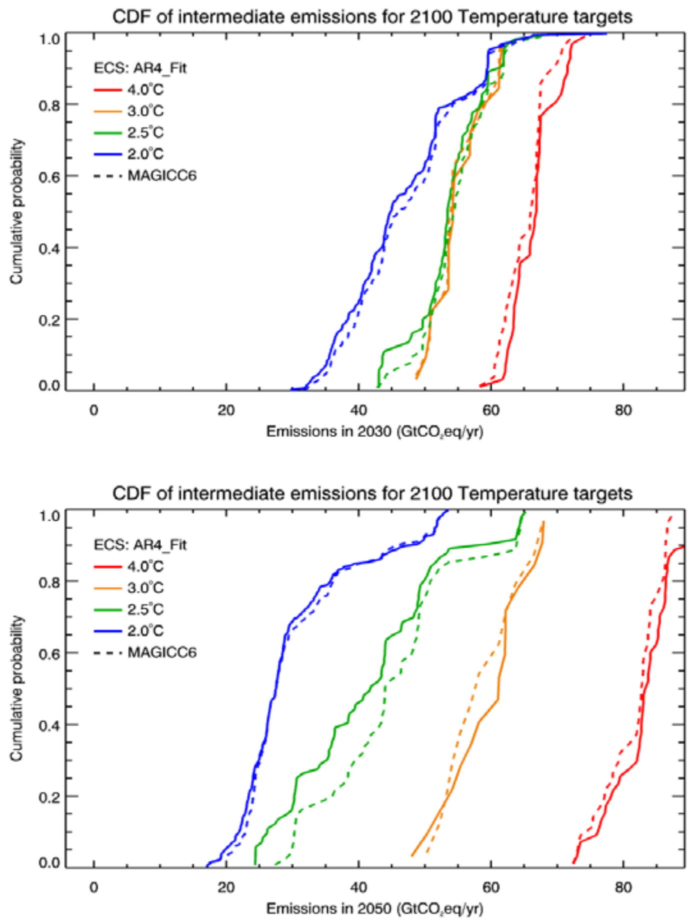

Figure 6. As Figure 2 but for emissions in 2030 (upper) and 2050 (lower).

CDF for 2020 emissions consistent with target levels in 2100 to within ±0.25 °C.								
Cumulative probability	2 °C MOHC	2 °C WG3	2.5 °C MOHC	2.5 °C WG3	3 °C MOHC	3 °C WG3	4 °C MOHC	4 °C WG3
0.1	42.59	43.44	47.50	48.73	49.13	49.05	54.95	54.44
0.2	44.67	45.56	49.69	49.77	50.14	49.76	55.11	54.81
0.3	46.27	46.66	50.07	50.15	50.85	50.34	55.64	55.08
0.4	47.49	47.58	50.66	50.63	51.17	51.21	56.97	55.78
0.5	48.77	48.95	51.21	51.06	51.65	52.13	57.09	56.97
0.6	49.92	50.04	52.09	51.88	52.77	52.69	57.44	57.08
0.7	50.95	51.11	52.65	52.48	53.66	53.21	57.73	57.30
0.8	52.15	52.59	53.24	53.38	53.99	53.97	58.38	58.06
0.9	53.67	53.97	54.42	54.66	54.19	54.14	59.34	59.34
CDF for 2030 emissions consistent with target levels in 2100 to within ±0.25 °C.								
Cumulative probability	2 °C MOHC	2 °C WG3	2.5 °C MOHC	2.5 °C WG3	3 °C MOHC	3 °C WG3	4 °C MOHC	4 °C WG3
0.1	35.60	36.29	43.68	48.56	50.23	50.10	62.43	60.97
0.2	38.42	39.65	49.79	50.92	50.83	50.86	63.44	62.16
0.3	40.93	41.99	51.63	52.24	53.56	53.44	64.13	63.21
0.4	43.54	43.85	53.01	53.30	53.61	53.56	65.88	64.27
0.5	44.82	45.96	53.43	54.42	54.22	53.88	66.86	66.00
0.6	48.60	50.10	54.36	55.58	54.69	54.24	66.92	66.83
0.7	51.24	51.62	55.67	56.95	56.82	56.53	67.33	67.10
0.8	53.77	54.22	58.37	58.60	58.95	59.16	69.39	67.39
0.9	59.45	59.53	60.92	61.89	61.29	61.21	71.56	69.26
CDF for 2050 emissions consistent with target levels in 2100 to within ±0.25 °C.								
Cumulative probability	2 °C MOHC	2 °C WG3	2.5 °C MOHC	2.5 °C WG3	3 °C MOHC	3 °C WG3	4 °C MOHC	4 °C WG3
0.1	21.93	22.97	26.19	30.31	50.51	51.68	76.13	74.27
0.2	23.39	24.06	30.29	36.04	53.58	53.24	78.15	77.16
0.3	24.96	25.06	35.18	39.47	55.82	54.27	82.04	79.30
0.4	26.20	26.24	37.81	43.29	58.07	55.82	82.71	82.22
0.5	27.53	27.57	41.76	44.02	61.13	57.58	83.29	82.70
0.6	28.50	28.60	43.98	48.07	62.08	60.30	84.07	83.26
0.7	30.89	32.12	48.32	49.10	62.20	62.08	85.50	84.04
0.8	35.73	36.07	49.82	50.85	64.81	63.97	86.40	85.89
0.9	47.80	46.00	57.91	63.84	67.61	66.88	89.75	86.40

Table 1 Sub-sampled data from the cumulative frequency distributions in Figure 2 and Figure 6 for emissions in 2020, 2030 and 2050 ($GtCO_2e/yr$) from scenarios consistent with a range of 2100 median temperature targets.

3.4. Comparison with UNEP GAP report 2013

With the modelling system used in AVOID2 shown to credibly reproduce the projections from MAGICC6.3 we can now usefully use the WG3 database to re-assess the findings of the UNEP emissions GAP report (UNEP 2013). This also used MAGICC6.3 for its climate projections, so we can extend the UNEP analysis by the inclusion of the WG3 scenarios, noting that there is significant overlap in the scenarios included.

The main difference between the UNEP scenarios and those in WG3 is that UNEP diagnosed intermediate emissions ranges only from scenarios with full period (typically from 2010) "least-cost" mitigation pathways. It did also examine other "later-action" scenarios with higher costs to assess the impact of delayed action or unavailability of particular technologies, but these scenarios were assessed and presented separately from the main analysis. Many of these later-action scenarios (from AMPERE, LIMITS, RoSE) are included in the WG3 data base. As such the analysis of UNEP provides ranges of the intermediate emissions consistent with (currently considered) cost-optimum mitigation pathways, while the use of WG3 database in its entirety would extend this to include non-optimum scenarios which are still (currently) considered plausible. These alternative scenarios are useful in consideration of sub-optimal mitigation pathways, an outcome which cannot be ruled out given recent progress toward global agreements on emissions reductions.

Data from table 3.1 of the UNEP report is shown in Table 2 along with the equivalent analysis based on WG3 scenario database using both the AVOID2 modelling system and the projections from WG3. The inclusion of results from AVOID2 and WG3 here provides additional validation of the AVOID modelling set up. The results in Table 2 are based on the use of WG3 scenarios that are a classified as "idealized" or "idealised plus supplementary measures" by WG3 (policy classifications "P1" and "P1+" respectively[2]) and so can be considered as broadly consistent with the assumptions underlying the "least-cost" scenarios examined by UNEP. This sub-selection of scenarios by policy classification reduces the size of the database to 268 scenarios. The analysis is also extended beyond comparison with UNEP by examining scenarios meeting other alternative temperature targets.

The analysis of "least-cost" type scenarios in Table 2 reports data on temperature targets of 1.5 °C, 2 °C and 2.5 °C. Three different criteria are used to assess scenarios meeting the different targets. The first of these is that of the median temperature meeting the target in 2100 to within a given tolerance. This is the same used in producing Figure 2 and Figure 6.

For comparison with UNEP two other criteria are used based on a scenario's likelihood of meeting the target. The first is those with a 50 %to 66% chance of staying below a given level of warming, and the second is a stricter criteria of needing at least a 66% chance of limiting warming to a given level. While allowing comparison with UNEP at 2 °C, these criteria can be misleading for other targets. Scenarios with at least a 66% chance of meeting a 2 °C scenario will also have at least a 66% change of meeting 2.5 °C, 3 °C or 4 °C so may produce misleading results if applied to higher target levels.

For example almost every idealised scenario in Table 2 meets targets of 3 °C and 4 °C with >66% likelihood, so these categories would reflect the database as a whole rather than

[2] Scenarios in the WG3 database were assigned values of policy classification by IPCC based on an expert judgement of the scenario definitions in the study protocols of contributing model intercomparison projects.

strictly 4 °C scenarios. These targets are therefore omitted here. Similarly this suggest s that scenarios that should be considered as “1.5 °C” have affected the results for “2 °C” scenarios when selected by a likelihood range. This would however also affect the UNEP analysis and so these scenarios are retained here for comparison.

For all cases median emissions are reported for intermediate emissions in 2020, 2030 and 2050 along with the range which is given in the format “minimum – (20th percentile – 80th percentile) – maximum”. For each case the minimum and maximum years of peak emissions are given along with the number of scenarios in each case. The UNEP numbers for 2 °C are highlighted in red.

Cost-optimum scenarios from UNEP (2013) and WG3 (Policy classification P1 and P1+)										
2100 target	Data source	Likelihood	Number of scenarios	peak year	Total 2020 emissions GtCO2eq/yr		Total 2030 emissions GtCO2eq/yr		Total 2050 emissions GtCO2eq/yr	
					Median	Range	Median	Range	Median	Range
1.5	AVOID	50% ±0.25°C	52	2010-2020	46	22-(41-47)-49	40	18-(34-43)-46	24	13-(20-27)-32
	WG3	50% ±0.25°C	52	2010-2020	45	22-(40-47)-49	38	18-(33-43)-46	23	13-(19-27)-33
	AVOID	50-66%	11	2010-2020	45	40-(41-47)-48	43	30-(38-46)-46	29	14-(25-31)-32
	WG3	50-66%	5	2010-2020	24	22-(23-44)-49	25	23-(24-36)-41	19	14-(16-21)-23
	AVOID	>66%	No matching scenarios.							
	WG3	>66%	No matching scenarios.							
2.0	AVOID	50% ±0.25°C	152	2005-2040	47	28-(44-50)-56	43	30-(36-50)-61	27	19-(24-34)-53
	WG3	50% ±0.25°C	169	2005-2040	47	28-(44-51)-56	44	30-(38-51)-61	27	19-(24-36)-53
	UNEP	**50-66%**	**66**	**2010-2020**	**46**	**24-(44-49)-53**	**41**	**32-(39-44)-55**	**28**	**21-(25-32)-44**
	AVOID	50-66%	85	2005-2040	46	32-(43-48)-56	40	30-(36-44)-61	25	19-(22-29)-51
	WG3	50-66%	59	2010-2020	46	28-(43-48)-51	40	32-(36-44)-50	27	19-(24-29)-34
	UNEP	**>66%**	**112**	**2010-2020**	**44**	**5-(38-47)-50**	**35**	**7-(32-42)-47**	**22**	**12-(18-25)-32**
	AVOID	>66%	50	2010-2020	46	22-(41-47)-49	40	18-(34-44)-46	24	13-(19-27)-32
	WG3	>66%	81	2005-2020	45	22-(41-47)-49	38	18-(34-43)-46	24	13-(21-26)-33
2.5	AVOID	50% ±0.25°C	62	2010-2040	51	47-(50-53)-55	53	43-(50-56)-63	40	24-(30-49)-65
	WG3	50% ±0.25°C	Not diagnosed by IPCC WG3							
	AVOID	50-66%	52	2010-2040	51	45-(47-52)-54	52	36-(44-54)-60	36	24-(29-44)-53
	WG3	50-66%	Not diagnosed by IPCC WG3							
	AVOID	>66%	189	2005-2040	46	22-(43-49)-56	41	18-(36-46)-61	26	13-(23-29)-51
	WG3	>66%	Not diagnosed by IPCC WG3							

Table 2 Emissions ranges for scenarios meeting different climate targets in 2100 under different criteria. Climate targets are defined either by the median 2100 temperature being within a given tolerance of the target, or by the likelihood of the 2100 temperature being under the target being 50-66% or >66%. For each criteria analysis is show for projections from WG3 and the AVOID2 projections performed for this study. Analysis taken directly from the UNEP GAP report 2013 is also shown in red, although this is only available scenarios meeting 2.0 °C with likelihood ranges of 50-66 % and >66 %. Ranges indicated are the “minimum – (20th percentile – 80th percentile) – maximum”.

Comparison of the analysis from WG3 and AVOID2 indicates a good level of agreements between the studies where there are enough scenarios to produce meaningful distributions.

There are no scenarios with projections from AVOID2 or WG3 which meet a 1.5 °C 2100 target with >66 % likelihood. At the 50-66% level there are very few matching scenarios so the cumulative frequency distribution is arguably too poorly defined to be useful and so discrepancies here are to be expected. For scenarios with a median projections within ±0.25 °C of the target there are far more matching scenarios producing a better defined cumulative frequency distribution in which there is close agreement with WG3. Median emissions from scenarios that meet a 1.5 °C target in 2100 with a ~50 % likelihood are 46, 40 and 24 $GtCO_2e$/yr in 2020, 2030 and 2050 respectively.

Scenarios meeting 2 °C in 2100 from Table 2 also include the data from UNEP for a likelihood of meeting the target of 50-66% and >66%. While the agreement between results from the WG3 projections and those from this study is again good where enough scenarios are available to usefully define a distribution, further reinforcing the credibility of the modelling systems used in AVOID2, some data differs slightly from the UNEP analysis. The UNEP data has 10-15 % lower minimum 2020 emissions from scenarios meeting the target with a likelihood of 50-66 %, while the minimum emissions for scenarios with a likelihood of meeting the target of >66 % are significantly lower in both 2020 and 2030. However, as the results from the central parts of the emissions range (20th, 50th and 80th percentiles) agree well between AVOID2, WG3 and UNEP, it seems likely that these discrepancies are a consequence of the differences in the scenario set examined by UNEP, in this case specifically the omission in the WG3 database of the most aggressive near term mitigation scenarios examined by UNEP. Similarly there are some difference in the maximum emissions.

The conclusion from analysis the WG3 database is therefore to broadly support the findings of UNEP (2013) with the caveat that both the WG3 database and the UNEP scenarios do not fully capture the possible scenarios space and that consequently the emissions ranges from all studies using them should be treated as indicative and subject to change, rather than definitive. Nevertheless, median emissions from scenarios that meet a 2.0 °C target in 2100 with a ~50 % likelihood from this study are 47, 43 and 27 $GtCO_2e$/yr in 2020, 2030 and 2050 respectively.

Temperature targets of 2.5 °C in 2100 were not considered by WG3 so there is no data for comparison with this study for this target level. Median emissions in 2020, 2030 and 2050 from these scenarios are 51, 53 and 40 $GtCO_2e$/yr respectively.

Extension of the analysis by UNEP to the WG3 data has allowed assessment of the implications of different climate targets for intermediate emissions, and different levels of stringency of these targets, that are directly relevant to discussions over global emissions reductions. However, as shown in the following section, all these results are predicated on accurate assumptions about uncertainty in the climate system.

4. Alternative estimates of equilibrium climate sensitivity (ECS)

ECS is a measure of one of the most significant uncertainties in our understanding of the climate system yet it is currently not possible to narrow the ECS to a single value. While its actual value may never be precisely determined, projections can be made with an estimated probability distribution of ECS which can provide usefully constrained advice on both future climate and levels of emissions consistent with meeting given global climate aims. However, many credible estimates of ECS uncertainty distributions exist but many have only limited overlap.

As there is no consensus over which type of approach or particular study is most robust, it is prudent to consider ECS estimates from a range of sources such as climate model output, use of the instrumental record combined with simple models, paeleoclimate data or a combination of approaches. While the combination of ECS distributions by Rogelj *et. al.*

(2012) is a good faith attempt to combine the estimates from many different studies in a even handed manor, it effectively excludes perfectly valid estimates of uncertainty in ECS by using only the combined distribution.

This study (and subsequent AVOID2 projects) examine results from a number of ECS distributions, assessing their implications for metrics such as emissions budgets and global requirements for carbon capture and storage from the WG3 database, and then provide analysis based on results from projections spanning a complete range of ECS (and for later reports, transient climate response, TCR) distributions.

As an illustration of the impact of ECS distribution choice on the emissions diagnosed as consistent with different 2100 temperature targets, Figure 7 and Figure 8 show the cumulative frequency distributions for intermediate emissions (as per Figure 2 and Figure 6) but when assuming two different ECS distributions from the IPCC AR5. The first of these (Figure 7) at the higher end of distributions and is taken directly from the ECS values diagnosed in CMIP5 (Forster *et. al.* 2013). This distribution is quite similar in terms of median and distribution width to the AR4 based ECS estimates of Rogelj *et. al.* (2012) and so the results are similar to those from the WG3 analysis in Figure 2 and Figure 6.

Figure 8 similarly shows cumulative distributions calculated from using an ECS distributions with much lower values, in this case from Aldrin *et. al.* (2012) who analyse the observational record from 1850 to 2007 for hemispheric averages of surface temperature and upper 700 m ocean heat content since 1955 in combination with a simple climate model. The typically lower values of ECS tend to lead to cooler temperatures for a given scenario as the climate's temperature response is by definition weaker. Consequently when assuming this ECS distribution, scenarios diagnosed as consistent with given 2100 temperature targets will have higher overall and intermediate emissions. The values of median, 20th and 80th percentiles of the emissions distributions in 2020, 2030 and 2050 are also given in Table 3 for these two ECS distributions and that for the AR4 based distribution examine in earlier sections. The impact on the emissions ranges is significant here with, for example, the median emissions in 2020 for 2 °C scenarios from the Aldrin *et. al.* (2012) ECS being higher than those for 3 °C when assuming the CMIP5 distribution, with significant implications for mitigation policy if unwisely taken as a sole line of evidence.

These examples from alternative ECS distributions illustrate the importance of acknowledging the uncertainty remaining in our knowledge of ECS and the extent to which consensus on attempts constrain ECS (e.g. Sherwood *et. al.* 2014) may narrow these results. While ECS remains uncertain, future AVOID2 reports and policy briefs will include information from the full range of available ECS and TCR distributions from AR5.

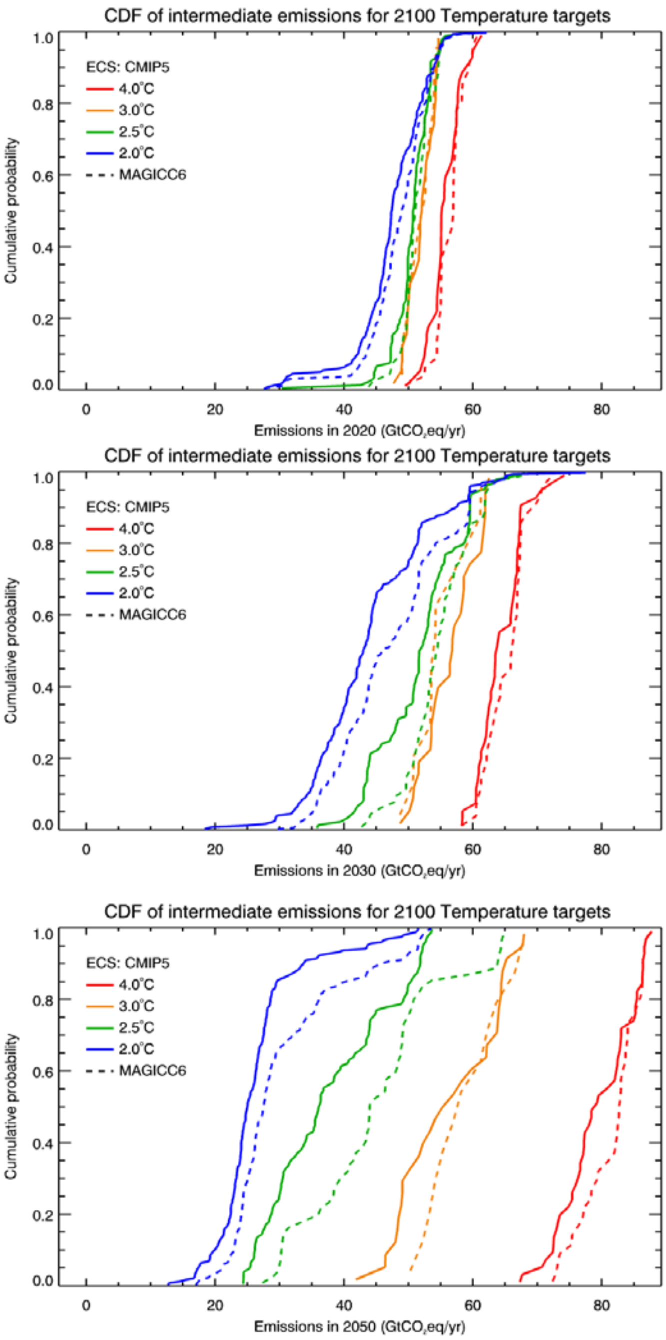

Figure 7. As Figure 2 for emissions in 2020 (upper), 2030 (middle) and 2050 (lower), but assuming the ECS distribution from CMIP5.

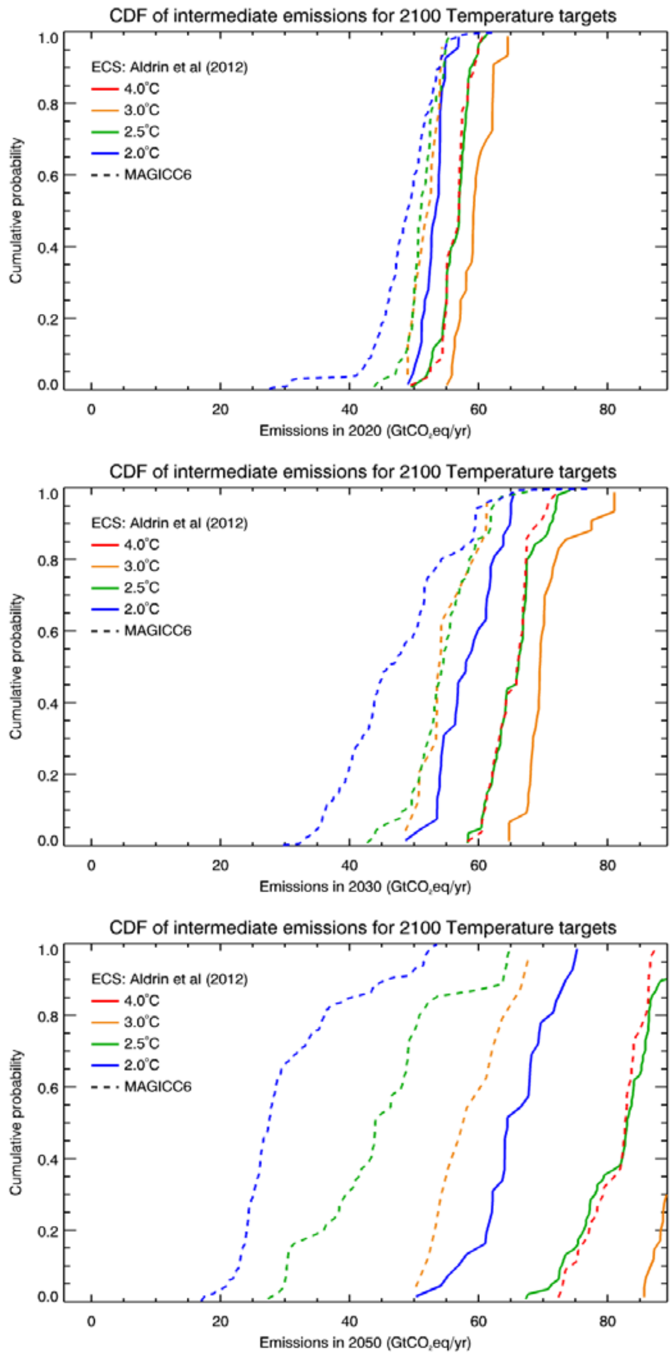

Figure 8. As Figure 2 for emissions in 2020 (upper), 2030 (middle) and 2050 (lower), but assuming and ECS distribution from Aldrin et. al. (2012)

2100 temperature	ECS distribution	2020 emissions			2030 emissions			2050 emissions		
		0.2	0.5	0.8	0.2	0.5	0.8	0.2	0.5	0.8
1.5	CMIP5	41	46	50	34	43	51	20	25	30
	AVOID	42	47	51	34	42	46	19	24	26
	Aldrin	48	51	53	44	52	57	35	46	54
2.0	CMIP5	44	47	52	36	43	51	22	25	29
	AVOID	45	49	52	38	45	54	23	28	36
	Aldrin	51	53	54	54	58	62	57	61	68
2.5	CMIP5	49	51	53	44	52	59	29	36	49
	AVOID	50	51	53	50	53	58	30	42	50
	Aldrin	55	57	58	62	66	68	68	74	77
3.0	CMIP5	50	52	54	52	57	61	49	55	64
	AVOID	50	52	54	51	54	59	54	61	65
	Aldrin	57	59	62	68	70	72	78	80	84
4.0	CMIP5	54	55	58	61	64	67	74	79	85
	AVOID	55	57	58	63	67	69	78	83	86
	Aldrin	No scenarios found.								

Table 3 Comparison of the intermediate emissions distributions for percentiles 0.2, 0.5 and 0.8 shown in Figure 7 and Figure 8 when using ECS distributions from CMIP5 and Aldrin et. al. (2012). The numbers from earlier (Figure 2) are labelled "AVOID" for comparison. Emissions numbers are in $GtCO_2e/yr$

5. Distributions of climate outcomes for a given emissions level

We have presented analysis indicating the ranges of intermediate emissions that are consistent with different temperature targets (section 3). This gives a measure the ranges of intermediate emissions that are consistent with these temperatures. Now we indicate the inverse of this, the probability of staying under a given temperature as a function of emissions, in Table 4.. In doing this it should be highlighted that there is a significant bias in the WG3 database toward 2 °C scenarios. As such selecting scenarios based upon emissions will lead to a set of scenarios with temperatures that are in many cases heavily biased toward median temperatures of 2 °C at the end of the century. As such the results presented here are a reflection of the temperature ranges from the scenarios available in the database, rather than from a set of scenarios that evenly sample all possible scenarios up to business-as-usual. It is recommended therefore that if ranges of intermediate emissions consistent with a target are a primary requirement then further consideration needs to be given to the availability of IAM results and the sampling of the WG3 database.

Figure 2 illustrates the relation of 2030 emissions in the WG3 database to the probability of exceeding thresholds from 1.5 °C to 6 °C. For each emissions level the mean and standard deviation of the probability of exceeding each level is reported for the matching scenarios. This is calculated using the AR4 ECS distribution used by WG3. As would be expected there is trend for warmer 2100 temperatures with higher 2030 emissions reflecting the generally weaker mitigation effort in such scenarios. For each 2030 emissions level in the table there are typically relatively few scenarios so distributions often sparse and the resultant scatter can lead, counter intuitively, to higher emissions levels being reported as having lower mean temperatures. Where this happens the standard deviations always overlap and so this is still a consistent set of findings, but this highlights once more that the WG3 scenario database (and the UNEP scenarios) are not a definitive set of scenarios but a sample of scenarios that are currently considered plausible.
Also included in Table 4 is the mean and standard deviation of the change in land use from 2030 to 2050. Although there is a clear assumption that emissions from land use are likely to decrease between 2030 and 2050, estimates of change in land use emissions across

scenarios at each 2030 emissions level are however poorly constrained as this is a maturing area of climate science that being actively addressed in AVOID2.

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For ALL WG3 scnearios with minimum required emissions for projections (524)																								
Variable	**Emissions**	sScenarios	Net CO2 < 0	Net CO2eq < 0	ΔLU		Temperature		P (T < 1.5 °C)		P (T < 2.0 °C)		P (T < 2.5 °C)		P (T < 3.0 °C)		P (T < 4.0 °C)		P (T < 5.0 °C)		P (T < 6.0 °C)	
Years	**2030**		2100	2100	(2050-2030)		2100 - pre.ind.		2100		2100		2100		2100		2100		2100		2100	
units	GtCO2eq				GtCO2/yr		°C		Probability		Probability		Probability		Probability		Probability		Probability		Probability	
metric		number of	number of	number of	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.	mean	std.dev.
	35	8	8	3	-1.1	3.7	1.84	0.08	0.28	0.05	0.61	0.05	0.82	0.03	0.92	0.01	0.98	0	1	0	1	0
	36	15	8	2	1.2	4.7	1.98	0.16	0.22	0.07	0.52	0.1	0.77	0.06	0.9	0.03	0.98	0.01	1	0	1	0
	37	8	8	6	-0.1	3.2	1.79	0.15	0.32	0.1	0.64	0.09	0.84	0.05	0.93	0.02	0.98	0.01	1	0	1	0
	38	12	9	6	-2.1	1.4	1.79	0.22	0.32	0.15	0.64	0.13	0.84	0.07	0.93	0.03	0.98	0.01	1	0	1	0
	39	8	7	2	-1.1	0.9	1.81	0.22	0.31	0.13	0.63	0.13	0.82	0.08	0.92	0.04	0.98	0.01	1	0	1	0
	40	16	15	4	-1.9	1.0	1.86	0.17	0.28	0.08	0.59	0.1	0.81	0.07	0.91	0.03	0.98	0.01	1	0	1	0
	41	10	10	4	-1.9	1.7	1.86	0.18	0.28	0.09	0.6	0.11	0.81	0.07	0.92	0.04	0.98	0.01	1	0	1	0
	42	19	15	14	-1.6	1.2	1.89	0.18	0.27	0.08	0.58	0.11	0.8	0.07	0.91	0.04	0.98	0.01	1	0	1	0
	43	18	11	9	-1.3	1.1	1.93	0.31	0.27	0.14	0.55	0.19	0.77	0.13	0.89	0.07	0.98	0.02	1	0.01	1	0
	44	29	15	7	-0.8	1.8	1.99	0.22	0.22	0.09	0.51	0.13	0.76	0.09	0.89	0.05	0.97	0.01	1	0	1	0
	45	13	8	5	-0.5	1.1	1.95	0.2	0.24	0.12	0.54	0.12	0.78	0.07	0.9	0.03	0.98	0.01	1	0	1	0
	46	10	7	6	-0.6	1.0	1.78	0.38	0.37	0.21	0.63	0.22	0.82	0.14	0.92	0.07	0.98	0.02	1	0	1	0
	47	4	2	1	-1.0	2.2	2.08	0.11	0.18	0.04	0.45	0.07	0.73	0.05	0.88	0.02	0.97	0	1	0	1	0
	48	9	4	3	-1.5	0.9	2.2	0.17	0.15	0.04	0.39	0.09	0.66	0.09	0.84	0.05	0.96	0.01	0.99	0.01	1	0
	49	5	4	1	-3.0	3.5	2.21	0.37	0.16	0.07	0.41	0.16	0.65	0.19	0.81	0.14	0.95	0.04	0.99	0.01	1	0
	50	12	7	1	-2.7	3.3	2.21	0.27	0.15	0.06	0.4	0.13	0.66	0.14	0.83	0.09	0.96	0.03	0.99	0.01	1	0
	51	26	15	4	-1.8	3.0	2.1	0.4	0.22	0.17	0.47	0.21	0.7	0.17	0.85	0.11	0.96	0.03	0.99	0.01	1	0
	52	24	24	9	-1.3	1.7	2.17	0.22	0.17	0.06	0.42	0.11	0.67	0.11	0.84	0.07	0.96	0.02	0.99	0.01	1	0
	53	15	6	1	-1.0	1.3	2.33	0.24	0.13	0.07	0.34	0.13	0.59	0.12	0.79	0.07	0.95	0.02	0.99	0.01	1	0
	54	18	6	1	-0.9	1.9	2.67	0.5	0.09	0.06	0.24	0.16	0.44	0.22	0.64	0.21	0.89	0.1	0.97	0.03	0.99	0.01
	55	8	2	1	-3.3	3.3	2.54	0.42	0.1	0.06	0.27	0.13	0.5	0.18	0.71	0.17	0.91	0.08	0.97	0.03	1	0.01
	56	10	4	1	-2.7	2.9	2.65	0.53	0.09	0.07	0.25	0.16	0.46	0.22	0.65	0.21	0.88	0.11	0.97	0.04	0.99	0.01
	57	8	6	2	-2.8	5.6	2.64	0.52	0.1	0.09	0.26	0.2	0.45	0.24	0.65	0.2	0.89	0.08	0.97	0.03	0.99	0.01
	58	11	6	1	-1.1	1.0	2.83	0.76	0.1	0.09	0.25	0.22	0.42	0.3	0.57	0.3	0.82	0.16	0.95	0.05	0.99	0.02
	59	18	16	11	-0.8	1.2	2.2	0.54	0.22	0.18	0.43	0.23	0.64	0.23	0.79	0.18	0.94	0.06	0.98	0.02	1	0.01
	60	19	17	9	-0.4	1.2	2.32	0.5	0.16	0.07	0.38	0.15	0.61	0.2	0.77	0.19	0.92	0.1	0.98	0.03	1	0.01

Table 4 Selected statistics of the WG3 scenarios database collated by 2030 total emissions. Each category shows; number of scenarios with given 2030 emissions; number of scenario with net negative CO_2 emissions; number of scenarios with net negative CO_2e emissions; change in CO2 emissions from land use between 2030 and 2050; temperature increase since pre-industrial; probability of temperature in 2100 remaining below given thresholds. Where appropriate each variable is reported as the mean and standard deviation of scenarios meeting the 2030 emissions level.

6. Discussion and conclusions

The modelling system which is to be used throughout AVOID2 has been shown, when suitably configured, to credibly reproduce the analysis of the IPCC WG3 scenario database. While there are some secondary issues regarding aerosols that remain to be resolved with the modelling teams responsible for two of the 31 models contributing to the database, the analysis in this report supports the use of the AVOID2 modelling framework to extend the analysis of the WG3 data base.

The WG3 database has been used to re-examine the range of intermediate emissions that are consistent with meeting a range of targets at different levels of likelihood, essentially repeating the analysis of the UNEP gap report (2013) with a different but overlapping set of scenarios. Where only "least-cost" scenarios (policy classes "P1" and "P1+") are examined from the WG3 database analysis supports the findings of UNEP for 2 °C scenarios. A significant part of the analysis here has been the extension of the UNEP analysis to determine estimates of emissions ranges from the WG3 database which are consistent with other targets at different level of stringency for climate targets.

An issue to note with the WG3 data base is that it is not designed to sample uncertainty in possible mitigation pathways and so cannot be considered as definitive for a number of reasons.

Firstly the available scenarios are not designed to densely sample the whole range of plausible mitigation pathways, instead they are a collection of solutions from independent models to particular plausible situations, such as the availability or not of particular technologies or delayed implementation of global emissions reductions pledges. As such the sampling of possible scenario space is both sparse and incomplete, with what is available reflecting aspects of the bounds of what is currently considered possible based on technological, political and economic factors.

Secondly the participating models have themselves not been designed as a set to sample uncertainty in underlying assumptions and structure of IAMs. In this sense they are an "ensemble of opportunity", analogous to the GCMs in the Coupled Model Intercomparison Projects (CMIP) that have contributed to the IPCC WG1 assessments. In the physical sciences the fact that models available for analysis were not designed to systematically sample uncertainty (implicitly assuming that independent estimates would be evenly distribution about the "truth") lead to development of systematic approaches to addressing uncertainty with the adoption of perturbed physics ensembles (Murphy *et. al.* 2004). While such an approach might be appealing for IAMs, it is unclear how tractable or appropriate a systematic assessment of uncertainty would be in this case as underlying principles are not definitive physical laws as in climate models, but an evolving understanding of the interactions encapsulated by IAM.

Whilst these aspects of IAM modelling will continue to be refined by the community over time, a significant aspect of the uncertainty in interpreting the WG3 database for policy advice is the uncertainty in the climates response to forcing. As illustrated in this report the choice of ECS distribution has a dominant effect on the emissions diagnosed as consistent with given climate targets and by considering only a single distribution WG3 may not fully reflect the uncertainty inherent to climate projections. In acknowledgment of this AVOID2 will use a complete set of ECS and TCR distributions from AR5 to constrain its projections and inform its analysis and future advice.

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Appendix A: Non-climate variables available from the WG3 scenario database

This appendix lists the non-climate related variables that are available from the WG3 database. The list is split by the class of variable with the variable name separated from the class by a forward slash. Note that not all variables are available for all scenarios.

Economy/Economy_GDP

Economy/Economy_consumption

Emissions/emissions_bc

Emissions/emissions_ch4

Emissions/emissions_co

Emissions/emissions_co2_ccs

Emissions/emissions_co2_energydemand_industry

Emissions/emissions_co2_energydemand_residentialandcommercial

Emissions/emissions_co2_energydemand_total

Emissions/emissions_co2_energydemand_transport

Emissions/emissions_co2_energysupply_electricity

Emissions/emissions_co2_energysupply_total

Emissions/emissions_co2_ffi

Emissions/emissions_co2_landuse

Emissions/emissions_co2_total

Emissions/emissions_fgases

Emissions/emissions_kyoto

Emissions/emissions_n2o

Emissions/emissions_nox

Emissions/emissions_oc

Emissions/emissions_sulfur

Energy_service/Energy_service_residential_and_commercial_floor_space

Energy_service/Energy_service_transport_freight

Energy_service/Energy_service_transport_passenger

Final_energy/Electricity

Final_energy/Gases

Final_energy/Geothermal

Final_energy/Heat

Final_energy/Hydrogen

Final_energy/Industry_Electricity

Final_energy/Industry_gases

Final_energy/Industry_heat

Final_energy/Industry_hydrogen

Final_energy/Industry_liquids

Final_energy/Industry_solids_biomass

Final_energy/Industry_solids_coal

Final_energy/Industry_solids_total

Final_energy/Industry_total

Final_energy/Liquids

Final_energy/Solar

Final_energy/Solids_Biomass_Traditional

Final_energy/Solids_Biomass_total

Final_energy/Solids_Total

Final_energy/Solids_coal

Final_energy/Total

Final_energy/residential_and_commercial_electricity

Final_energy/residential_and_commercial_gases

Final_energy/residential_and_commercial_heat

Final_energy/residential_and_commercial_hydrogen

Final_energy/residential_and_commercial_liquids

Final_energy/residential_and_commercial_solids_biomass

Final_energy/residential_and_commercial_solids_coal

Final_energy/residential_and_commercial_solids_total

Final_energy/residential_and_commercial_total

Final_energy/transport_electricity

Final_energy/transport_freight

Final_energy/transport_gases

Final_energy/transport_hydrogen

Final_energy/transport_liquids_biomass

Final_energy/transport_liquids_oil

Final_energy/transport_liquids_total

Final_energy/transport_passenger

Final_energy/transport_total

Land_cover/Land_cover

Land_cover/Land_cover_crop_land

Land_cover/Land_cover_crop_land_energy_crops

Land_cover/Land_cover_forest

Land_cover/Land_cover_other_arable_land

Land_cover/Land_cover_other_land

Land_cover/Land_cover_pasture

Policy_cost/Policy_cost_GDP_loss

Policy_cost/Policy_cost_additional_total_energy_system_cost

Policy_cost/Policy_cost_area_under_MAC_curve

Policy_cost/Policy_cost_consumption_loss

Policy_cost/Policy_cost_equilvalent_variation

Policy_cost/Policy_cost_other

Population/Population

Price/price_carbon

Primary_energy/Primary_energy

Primary_energy/Primary_energy_biomass

Primary_energy/Primary_energy_biomass_wccs

Primary_energy/Primary_energy_biomass_woccs

Primary_energy/Primary_energy_coal

Primary_energy/Primary_energy_coal_wccs

Primary_energy/Primary_energy_coal_woccs

Primary_energy/Primary_energy_fossil

Primary_energy/Primary_energy_fossil_wccs

Primary_energy/Primary_energy_fossil_woccs

Primary_energy/Primary_energy_gas

Primary_energy/Primary_energy_gas_wccs

Primary_energy/Primary_energy_gas_woccs

Primary_energy/Primary_energy_geothermal

Primary_energy/Primary_energy_hydro

Primary_energy/Primary_energy_nonbiomass_renewables

Primary_energy/Primary_energy_nuclear

Primary_energy/Primary_energy_ocean

Primary_energy/Primary_energy_oil

Primary_energy/Primary_energy_oil_wccs

Primary_energy/Primary_energy_oil_woccs

Primary_energy/Primary_energy_solar

Primary_energy/Primary_energy_wind

Secondary_energy/Electricity_Nuclear

Secondary_energy/Electricity_biomass_total

Secondary_energy/Electricity_biomass_wccs

Secondary_energy/Electricity_biomass_woccs

Secondary_energy/Electricity_coal_total

Secondary_energy/Electricity_coal_wccs

Secondary_energy/Electricity_coal_woccs

Secondary_energy/Electricity_gas_total

Secondary_energy/Electricity_gas_wccs

Secondary_energy/Electricity_gas_woccs

Secondary_energy/Electricity_geothermal

Secondary_energy/Electricity_hydro

Secondary_energy/Electricity_non-renewable_biomass

Secondary_energy/Electricity_ocean

Secondary_energy/Electricity_oil_total

Secondary_energy/Electricity_oil_wccs

Secondary_energy/Electricity_oil_woccs

Secondary_energy/Electricity_solar

Secondary_energy/Electricity_total

Secondary_energy/Electricity_wind

Secondary_energy/Gases

Secondary_energy/Heat_geothermal

Secondary_energy/Liquids_biomass

Secondary_energy/Liquids_coal_total

Secondary_energy/Liquids_coal_wccs

Secondary_energy/Liquids_coal_woccs

Secondary_energy/Liquids_fossil_total

Secondary_energy/Liquids_fossil_wccs

Secondary_energy/Liquids_fossil_woccs

Secondary_energy/Liquids_gas_total

Secondary_energy/Liquids_gas_wccs

Secondary_energy/Liquids_gas_woccs

Secondary_energy/Liquids_oil

Secondary_energy/Liquids_total

Secondary_energy/hydrogen

Secondary_energy/solids