Mitigating climate change through reductions in greenhouse gas emissions: climate science constraints on annual global emissions targets for 2020 and 2050:

SUPPLEMENTARY MATERIAL

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These supplementary materials give more details on the key assumptions that underlay our findings. We note that the climate model assumptions used in this study are designed to be consistent with those used the UK Government-funded AVOID programme[1], though the emissions trajectories are defined differently.

Emissions Trajectory Design

Baseline Emissions: One of the most common criticisms of emissions trajectory analyses is the realism of the baseline emissions that they assume. Too lower baseline can result in stringent targets appearing to be too 'easy' to achieve, and vice versa. The scenarios generated by SiMCaP EQW (Meinshausen *et al*. 2005 and 2006) are designed to each give global emissions of 37 $GtCO_2e$ in 1990, 41 $GtCO_2e$ in 2000 and 47 $GtCO_2e$ in 2010. These historical emissions are roughly consistent with those given by the World Resources Institute (2005)[2] of 39 $GtCO_2e$ in 1990 and 42 $GtCO_2e$ in 2000. However, there are large uncertainties in historical emissions estimates (for example, the IPCC Fourth Assessment Report (IPCC 2007) gave ±4$GtCO_2e$ per year uncertainty in land-use CO_2 emissions over the 1990s). Recent estimates from the Global Carbon Project (Le Quéré *et al.* 2009) suggest that land-use change emissions are towards the upper end of current estimates (making our total carbon dioxide estimates as much as 3 $GtCO_2e$ lower in 2008). Future projections are even more uncertain. The 2010 projection used in this study is designed to be consistent with the International Energy Agency's (IEA) latest reference scenario. For example, the World Energy Outlook 2008, projected global GHG emissions of roughly 48 $GtCO_2e$ in 2010 and 55 $GtCO_2e$ in 2020 (IEA 2008) and the 2009 Outlook reduced this projection by 2 $GtCO_2e$ in 2020 as a result of the global recession (IEA 2009). Le Quéré *et al.* 2009 suggest that fossil fuel carbon emissions have been growing more rapidly than those represented in the IEA scenarios; were this trend to continue this could lead to much higher emissions in 2010. Uncertainties in the baseline will contribute to uncertainties in conclusions on 2020 and 2050 targets; for example, a higher baseline would imply stronger emissions cuts required to reach the same temperature-based target.

Emissions 'floors': The emissions floor is the level of roughly stable emissions that we would expect to see in the long-term, that is, around the end of the century. In this study, emissions stabilise at around 4 to 6 $GtCO_2e$ by 2100, with most of this coming from methane and nitrous oxide emissions. We suggest that this mainly incorporates long-term emissions from food production. This level and type of emissions is consistent with agricultural emissions today. Such an assumption is roughly consistent with many previous studies (e.g. den Elzen *et al.* 2007).

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[1] http://www.avoid.uk.net/

[2] http://cait.wri.org/

Some studies assume that emissions can be brought down even lower, through for example, carbon sequestration, and these studies would tend to give less stringent targets for 2020 and 2050. We assume that setting 2020 and 2050 targets that rely on eliminating GHG emissions completely is not a sound strategy.

The contribution of non-CO_2 gases: This study uses non-CO_2 gases generated using the SiMCaP EQW model, which generates non-CO_2 gases as part of the Equal Quantile Walk methodology (Meinshausen *et al.* 2005). Under these assumptions, the dominant emissions by 2100 are methane (CH_4) and nitrous oxide (N_20). Non-fossil fuel CO_2 emissions (i.e. land-use change) are assumed to become negative in around 2040, offsetting a portion of fossil fuel CO_2 emissions. In 2100, we see small negative net CO_2 emissions of around 0.5 $GtCO_2e$.

Aerosol Assumptions

Aerosols exert a significant net cooling influence on climate[3] (i.e. a negative radiative forcing). For example, it is estimated that, at present, the negative radiative forcing from aerosols roughly offsets the positive radiative forcing from the non-CO_2 gases, slowing the observed rate of warming. But, unlike GHGs, aerosols are very short-lived in the atmosphere; with a life time of only a few days. The effects of aerosols on climate are important, but are one of the largest sources of uncertainty in current climate projections. There are three components to this uncertainty: (1) estimating future anthropogenic emissions from aerosols; (2) estimating future natural emissions from aerosols; and (3) estimating and representing the radiative forcing effects of aerosols in models. We address each of these below:

1. *Anthropogenic Aerosol Emissions:* Global emissions of aerosols have risen roughly in line with fossil-fuel CO_2 emissions; however, since around 1970 the growth in emissions have slowed considerably as a result of the implementation of air quality legislation, a shift to lower sulphur fuels and economic transition in Eastern Europe and the Former Soviet Union (Fisher *et al.* 2007, F2007). At the same time, sulphur emissions grew rapidly in Asia; though this growth has also slowed in the last decade. Projecting future aerosol emissions requires one to anticipate trends in fossil-fuel use, as well as the aerosol emissions intensity of that activity. In additional to this, there is disagreement even on current aerosol emissions, with an uncertainty range of around 10-50% (Van Vuuren and O'Neill, 2006, VN2006). The MAGICC model includes three types of aerosols, sulphate aerosols (SO_2), fossil-fuel organic carbon and black carbon. Two different sulphate aerosol emissions intensity assumptions are used in this study; the first is based on the IPCC SRES B1 scenario (Nakicenovic *et al*. 2000); and the second, an average across simulations generated from the SiMCaP model (Meinshausen *et al.* 2006). Aerosol emissions are calculated for each GHG emission scenario by applying the aerosol intensity projection to the projected fossil-fuel related carbon emissions of the specific trajectory. Based on the analyses of VN2006, and comparing to projections reported in F2007, we conclude that our SRES B1-based scenario used might be considered a mid- to high-end aerosol emission assumption; for example, VN2006 finds that all the SRES scenarios over-predicted sulphur emissions by around 15% over the 1990-2000s compared with observation-based estimates, but the B1 scenario (a "cleaner" SRES world storyline) used here lies roughly at the mid- to high-end of non-

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[3] Different types of aerosols have different effects (e.g. sulphate aerosols are cooling, while black carbon has a warming effect), but the net effect is through to be negative.

SRES projections (towards the high-end to around 2050 then reaching the mid-range by 2100) (VN2006, F2007). The SiMCaP-based aerosol intensities lay at the low-end of current projections. In general, low-end projections reflect new information on planned sulphur legislation in developing countries, such as India and China (F2007). It should be noted that these two scenarios are not designed to span the full uncertainty range in aerosol emissions; but to provide two plausible futures. Fossil-fuel organic carbon and black carbon are assumed to scale with the sulphate aerosol emissions.

2. *Natural Aerosol Assumptions:* Natural aerosol emissions from, for example volcanoes, are assumed to be negligible in this study.
3. *Assumptions and Representation of the Effect of Aerosols on Climate:* the direct and indirect radiative forcing from aerosols is highly uncertain. For example, the IPCC Fourth Assessment Report (IPCC 2007) gave an uncertainty range of -0.9 to -0.1 Wm^{-2} for direct aerosol forcing and -1.8 to -0.3 Wm^{-2} for the indirect aerosol forcing in 2005 and rated our "Level of Scientific Understanding" of the forcings as medium/low and low respectively. This uncertainty is represented stochastically in MAGICC and the uncertainty range incorporated is roughly consistent with AR4[4].

Climate Modelling Assumptions

The advantage of the model approach used in this study is that it treats important uncertain climate assumptions, like climate sensitivity, in a probabilistic way. This is a significant advantage over a deterministic approach. However, it does not remove model dependency. It is important to recognise how the distributions of parameters relate to those of other studies.

Climate Sensitivity: There is much debate over climate sensitivity, which means that it is not currently possible to define such a distribution objectively (see Box 10.2 of Meehl *et al.* 2007). We use the distribution given by Murphy *et al.* (2004) as it incorporates information from both models and spatially explicit observations (whereas most studies include only one or the other or only global mean constraints). Comparison with the IPCC conclusions on climate sensitivity suggests that the "most likely" value of Murphy *et al.* is well aligned with current consensus, but that Murphy et al. under-predicts the likelihood of both low and high temperature outcomes relative to IPCC conclusion (this is unsurprising given that the IPCC conclusions represent a consensus over many studies). This will mean that the uncertainties in temperature given in this study will be narrower than the current consensus.

Ocean Diffusivity: The ocean diffusivity is an important determinant on the rate of warming. A distribution of ocean diffusivity was estimated by fitting a log-normal distribution to the model-derived ocean mixing rates across the range of current global climate models (Table 9.A1, Cubasch *et al.,* 2001).

Carbon Cycle Feedbacks: The uncertainty in the temperature-carbon cycle feedback amplification parameter was derived from the recent model inter-comparison study, C4MIP (Friedlingstein *et al.* 2006). Each of the model projections are treated with equal probability and no observational constraints are applied.

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[4] http://www.cgd.ucar.edu/cas/wigley/magicc/UserMan5.3.v2.pdf