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# Contraction and convergence: an assessment of the *CCOptions* model

**Alice Bows · Kevin Anderson**

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**Abstract** Well before President Putin ratified the Kyoto Protocol, the debate had begun as to the appropriate form of any post-Kyoto agreement. Amongst the emission reduction regimes being considered is that of *Contraction and Convergence* ; conceived by Global Commons Institute (GCI) as a practical interpretation of the philosophy that "every adult on the planet has an equal right to emit greenhouse gases". To support the *Contraction and Convergence* regime, the GCI have developed a computer model, *CCOptions*, to correlate $CO_2$ stabilisation levels with global, regional and national carbon reduction targets. This paper analyses the model, concluding that, whilst the aim of *CCOptions* is laudable, the application of the model in its current form is unnecessarily ambitious and as a consequence potentially misleading to all but the well-informed user.

## 1 Introduction

Even before Russia signed the Protocol, debate had begun as to the form, scale and responsibilities of any post-Kyoto emission-reduction strategies. Whatever the form such strategies may take, significant reductions will not be possible without adequate commitment from all the high-emission nations, including the USA. The central complaint of the US Federal Government is that the Kyoto agreement exempts much of the world, including major population centres such as China and India, from compliance. Consequently, they see it as unfairly harmful to the US economy and therefore are unlikely to commit to any post-Kyoto agreement that does not require early participation by industrialising as well as industrialised nations.

A. Bows (✉) · K. Anderson
Tyndall Centre for Climate Change Research, University of Manchester,
MACE Pariser Building, P. O. Box 88, Manchester, M60 1QD, UK
e-mail: alice.bows@manchester.ac.uk

One framework designed to respond to this inclusivity issue, is to establish permissible global carbon emissions and to apportion these to all nation states according to a particular and agreed set of rules designed to maintain temperatures within agreed bounds. In doing so, all nations are required to design a carbon emission strategy tailored to their particular circumstances, in the knowledge that other nations are doing likewise. An emission reduction regime requiring all nations to set targets from the start of the process, and that has gained some popularity over recent years, is the Global Common's Institute (GCI) Contraction and Convergence regime (Meyer 2000). The GCI was founded in 1990 with a "Focus on the protection of the global commons of the global climate system". Since 1996, the GCI has encouraged awareness of the Contraction and Convergence regime as, so they contend, a practical interpretation of the philosophical principle that "every adult on the planet has an equal right to emit greenhouse gases". Contraction and Convergence is claimed to provide an international and equitable framework for arresting global anthropogenic emissions, with all nations working together to establish and achieve an overall yearly emissions target – contraction. Moreover, all nations converge towards equal per-capita emissions by a specified year – convergence. By simultaneously contracting and converging, this mechanism requires all nations to impose targets from the outset (Cameron and Evans 2003), although for some nations this target may permit increases in emissions in the early years.

Whatever international framework may exist, the majority of high-emitting nations will necessarily be required to make substantial cuts to their carbon emissions if $CO_2$ concentrations are to be stabilised at a level that avoids global temperature increases of more than 2°C.[1] Although it may be argued that the particular circumstances of different nations could lead to a requirement for differing emissions regimes, the GCI fear that any allowance made for such differences will create unacceptable delays in negotiating an agreement. As stabilising the $CO_2$ concentration at or lower than 550 ppmv demands a reduction strategy that is initiated as a matter of urgency, the GCI consider the simplicity of the Contraction and Convergence approach to be a benefit rather than a deficiency.

In light of the growing support for Contraction and Convergence, the GCI have produced a spreadsheet model, *CCOptions*,[2] to enable policy-makers to investigate what impact varying the contraction and convergence years and $CO_2$ stabilisation levels has on global carbon budgets and national emission targets. Given widespread endorsements of the regime from the Royal Commission on Environmental Pollution (RCEP 2000) and EU Parliament (COMM 2005), to the African Group of Nations and the German Advisory Council on Global Change (Grassl et al. 2003), it is appropriate to assess the GCI's downloadable model, particularly as it is specifically aimed at policy-makers. This paper therefore begins by outlining the central features of and claims for the *CCOptions* model, before proceeding to analyse how well the tool achieves its goals. In particular, the appropriateness or otherwise

[1]Both the UK and the EU have a commitment to 2°C as essentially representing the threshold between dangerous and acceptable climate change. See, for example (DEFRA 2006), Climate Change: The UK Programme 2006, the documentation accompanying the UK's 2006 Energy Review (DTI 2006), the 2003 Energy White Paper (DTI 2003) and much of the EU's literature on climate change, particularly that associated with the European Council.

[2]The model and accompanying documentation is available at http://www.gci.org.uk.

of the inclusion within the latest version of *CCOptions* of carbon-cycle feedbacks is addressed. The paper goes on to discuss the uncertainties associated with the model approach and draws conclusions regarding the model's credibility, robustness and its usefulness to policy-makers in quantifying the Contraction and Convergence principle.

## 2 The *CCOptions* model

### 2.1 The model purpose

Many science-based climate models, varying in internal complexity, are available to scientists and policy-makers. At one end of the spectrum, relatively simple and one-dimensional 'energy balance models', at the other, 'multi-dimensional global circulation models' (GCMs) representing the fluid dynamics, thermodynamics, chemistry and radiative effects within and between the atmosphere, oceans and biosphere. *CCOptions* is not within this spectrum of climate models and should not be confused with a scientifically-based modelling approach; it attempts neither to model the atmosphere, nor predict future climate. Instead, *CCOptions* uses the outputs and data from the UK's Hadley Centre GCM (e.g. HADCM3) and, to a lesser extent, from the IPCC reports, to generate a global $CO_2$ budget, apportioning this budget between nations to form national emissions trajectories. Although *CCOptions* does not profess to model $CO_2$ concentrations resulting from a particular emission trajectory, or indeed the consequential temperature response, the user could be forgiven for assuming this to be so.

The strengths of the *CCOptions* model as a policy tool arise ostensibly from its ability to embed adequately the best climate science data and to apportion subsequent global emissions between nations in accordance with the contraction and convergence regime. The model is intended for use by, amongst others, moderately informed policy-makers, enabling them to develop and investigate national emissions trajectories for each year up until 2200 and based on a range of atmospheric $CO_2$ concentrations and the distribution of the global population between nations. The discussion of the *CCOptions* model within this paper addresses both the benefits and limitations of the model in relation to its ability to interpret the climate science, apportion emissions and provide a useful policy tool. The discussion is initially divided into two subsections, *contraction* and *convergence*.

### 2.2 The contraction process

#### *2.2.1 Description*

The contraction process calculates the maximum amount of carbon that can be emitted in each year from the start year up to 2200; this annual value being referred to as the global carbon budget. Calculating this budget is divided into two stages (see Fig. 1). The first calculates the budget between the start date and the contraction year (the year in which this target is attained) by solving an equation of the form:

$$z_y = k + ly + my^2 + ny^3 + py^4 \tag{1}$$

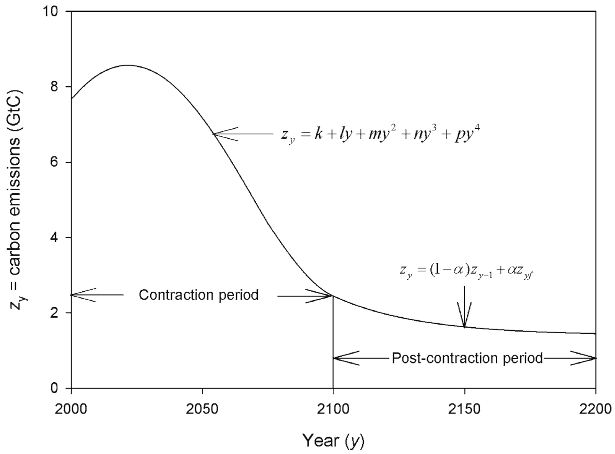


**Fig. 1** An example contraction profile, with a contraction year of 2100, a contraction target of 2.5 giga tonnes of carbon (GtC) and a 2200 carbon value of 1.8 GtC

where $z_y$ represents the carbon emissions in year $y$ and $k$, $l$, $m$, $n$ and $p$ are coefficients. The second stage of the contraction process produces the post-contraction trajectory, in which emissions gradually decline year on year according to the equation

$$z_{y+1} = (1 - \alpha)\, z_y + \alpha z_{yf} \tag{2}$$

where $\alpha$ is a smoothing factor and $z_{yf}$ is a second carbon target – the global carbon budget value in 2200. $z_{yf}$ is obtained from the user-defined $CO_2$ concentration target in parts per million by volume (ppmv) and is based on the emission-concentration relationship within IPCC documentation (Houghton et al. 1996). When coupled, these equations are intended to produce emission scenario trajectories broadly similar in form to the WRE scenarios (Wigley et al. 1996), with global emissions initially rising, before continuously declining (contraction).

### *2.2.2 Analysis*

Given *CCOptions* is a policy-oriented tool, it is likely many users will have a limited knowledge and understanding of the facts and figures relating to $CO_2$ emissions. However, in addition to simple inputs such as the start year and emissions in that start year, the model requires the user to know and understand a range of relatively advanced input parameters, including the appropriate range of cumulative $CO_2$ emissions between 1990 and 2100 associated with a particular $CO_2$ concentration; emissions growth rate in the start year; the contraction year and the carbon emissions in that year (the contraction target); and the emissions decline rate in the contraction year. These parameters are used subsequently to solve sets of simultaneous equations that provide the variables $k$, $l$, $m$, $n$ and $p$. Although the model does provide a series of 'standard' experiments, giving some guidance of choosing appropriate parameters, it is ultimately up to the user to undergo a process of iterative model runs in seeking a specially defined output.

Another potentially significant drawback of *CCOptions* for all but the less well-informed user, arises from their being required to input both the cumulative emissions value and the contraction target values, with the model subsequently calculating the emission trajectory using the separate equations (1) and (2). If the user-defined contraction target is too low for a particular model run, the emissions

**Table 1** Total anthropogenic cumulative totals for 1991–2100 (GtC) (Houghton et al. 1996)

| Stabilisation level (ppmv) | Lower bound | Upper bound |
|---|---|---|
| 450 | 630 | 650 |
| 550 | 870 | 990 |
| 650 | 1,030 | 1,190 |
| 750 | 1,200 | 1,300 |

trajectory will fall towards the contraction target, before rising during the post-contraction phase to reach the 2200 emission value $z_{yf}$. If the contraction target chosen is too high for a particular model run, the emissions trajectory will dip prior to the contraction date before rising to pass through the contraction value in order to satisfy the cumulative $CO_2$ amount. Whilst a well informed user may understand such model outputs as a practical constraint of the model, less well informed users would likely be confused. This could be avoided if the model, rather than the user, determined one or both of the values.

Given the importance of the cumulative carbon emissions over the time in question, it would be desirable for the model documentation to give a range of suggested cumulative emission values relating to particular stabilisation levels. This was the case with the original version of the model, where a range of cumulative emissions values for 450, 550, 650 and 750 ppmv, taken directly from data published by the IPCC (Houghton et al. 1996), were provided (Table 1).[3] However, since the *CCOptions* model has been updated to include carbon-cycle feedback results, the earlier cumulative values are no longer valid and updated values have not been provided.

*2.2.2.1 The role and impact of carbon-cycle feedbacks* The atmospheric concentration of $CO_2$ depends not only on the quantity of $CO_2$ emitted into the atmosphere (natural and anthropogenic), but also on changes in the strength of carbon sinks within the ocean and biosphere. As the atmospheric concentration of $CO_2$ increases, so there is an initial and net increase in the take-up of $CO_2$ from the atmosphere by vegetation (carbon fertilisation). Changes in temperature and rainfall induced by increased $CO_2$ affect both the absorptive capacity of natural sinks and the geographical distribution of vegetation and hence its ability to store $CO_2$ (Jones et al. 2006). Indeed, an increasing temperature speeds up the rate of decomposition of carbon and hence decreases storage capacity of the land.

The complicated and interactive nature of these effects leads to uncertainties with regard to the size of carbon-cycle feedbacks (Cranmer et al. 2001; Cox et al. 2006). The results of dynamic global vegetation models used to estimate the carbon storage potential of soil and vegetation differ considerably from model to model (Friedlingstein et al. 2006). Although a substantial body of research predicts further temperature increases to cause the land carbon sink to cease and become a source of carbon (Eggleston et al. 1998; White et al. 1999; Cox et al. 2000, 2006; Lenton 2000; Friedlingstein et al. 2001; Zeng et al. 2004) there exists at least one study that suggests a persistent though reducing carbon sink (Cranmer et al. 2001). Nevertheless, all models agree that a global mean temperature increase will reduce the biosphere's ability to store anthropogenic carbon emissions.

[3]The range, as opposed to a single value, arises from the different emissions scenarios used within those GCMs providing output for the IPCC.

The implications of carbon-cycle feedbacks for climate policy are profound. To achieve a desired $CO_2$ stabilisation level, the cumulative $CO_2$ emissions are more influential than the emission pathway taken (Matthews 2005, 2006b; Jones et al. 2006). These cumulative emissions are highly dependent on carbon-cycle feedbacks which in themselves are dependent on climate sensitivity. In a recent model inter-comparison of the impact of carbon-cycle feedbacks, it was concluded that these feedbacks reduce the available global emission budget for a particular $CO_2$ concentration, compared with non-feedback baselines (Friedlingstein et al. 2006; IPCC 2007). This is an extremely important result and should be considered when developing climate policies.

One of the models included by both Friedlingstein's inter-comparison and the latest IPCC Assessment Report (IPCC 2007) (hereafter AR4), was the Hadley Centre's coupled climate-carbon cycle model. Running such a model is very intensive in terms of computation time, therefore to study the impact of carbon-cycle feedbacks on global carbon budgets for a number of stabilisation scenarios, researchers use a simple climate carbon-cycle model in which feedbacks from vegetation, soils and the ocean are included to reproduce the results of the Hadley Centre coupled climate-carbon-cycle model.[4] From this, estimates of the emissions required to stabilise the $CO_2$ concentration can be made (Jones et al. 2006) and the reduction in permissible emissions, due to carbon-cycle feedbacks, calculated for particular $CO_2$ stabilisation levels. For example, according to the Jones study (based on the WRE 450 ppmv and 550 ppmv profiles and hereafter referred to as JNS), a target stabilisation concentration of 550 ppmv $CO_2$ requires the cumulative emission value from 1991 to 2100 to be around 800 GtC when allowing for carbon-cycle feedbacks, but over 1,000 GtC when feedbacks are *not* included.[5]

It is JNS carbon-cycle feedbacks that the latest version of *CCOptions* attempts to replicate. However, not only does embedding dynamic global vegetation models add substantial complexity to already complex models (Lenton and Huntingford 2003), but the 'summary for policy-makers' document issued by the IPCC (AR4) identifies a range of feedback values. Consequently, it may be argued that replicating a single model is too constraining. Certainly, in light of these additional model outputs, it would appear wise that *CCOptions* be revisited to incorporate the range of cumulative values. However, the use of a single set of model results does not necessarily negate the value of *CCOptions*. The JNS estimates of cumulative values sit in the AR4 450 ppmv $CO_2$ range and can therefore be regarded as a reasonable indicator of the mid-range impact of feedbacks on cumulative emission.[6] There is clearly a consensus emerging that all calculations for $CO_2$ stabilisation levels should be revised to include the dynamic evolution of vegetation and its influence on global carbon. The inclusion within *CCOptions* of results from a single feedback study for each stabilisation concentration, though perhaps too constraining, does provide

[4]The full GCM was run for 450ppmv and 550ppmv WRE first to ensure that the simple model gives the same answers.

[5]Compare these figures to those presented in Table 1.

[6]Within the AR4 Summary for Policy-makers, the ranges are provided for 450 and 1,000 ppmv only.

policy-makers with scientifically more rigorous cumulative emission budgets and emission trajectories that can be related subsequently to temperature targets.

*2.2.2.2 Assessing CCOptions: replicating JNS* To quantify how well the *CCOptions* model replicates JNS *with* feedbacks, the cumulative emissions output from *CCOptions* and JNS, for stabilising $CO_2$ emissions at 450 ppmv and 550 ppmv, are compared (including the *without* feedback values).

For a 450 ppmv stabilisation level, Fig. 2 illustrates the JNS cumulative totals and emission trajectories, with and without feedbacks.

*CCOptions* can produce emission profiles that peak lower than the JNS profiles, and as a consequence, decline less steeply to conserve the cumulative emissions over the period. It is these differences that contribute to the relatively small variations in the concentration profile calculated by *CCOptions*. The emission profiles produced are political rather than scientific in nature, therefore, although the JNS and *CCOptions* trajectories differ, the important observation is that they both incorporate the same cumulative carbon emissions. For policy purposes therefore, the profile produced by *CCOptions* for the 450 ppmv level represents an adequate emission scenario that can be apportioned between nations. National emission trajectories will then depend on the policy-maker's choice of convergence date and contraction level of emissions.

The same analysis is conducted for a 550 ppmv stabilisation level and the results illustrated in Fig. 3. In this case the $CO_2$ concentration derived from the *CCOptions with* feedbacks model overshoots the 550 ppmv target level, and stabilises around 575 ppmv. In other words, the *CCOptions* model produces a lower cumulative carbon total to stabilise emissions at 550 ppmv than does JNS, and consequently overestimates the emissions cuts required of individual nations. According to *CCOptions with* feedback, stabilising $CO_2$ concentrations at 550 ppmv requires cumulative carbon emissions between 1990 and 2100 of around 700–730 GtC rather than the 800 GtC suggested by JNS.

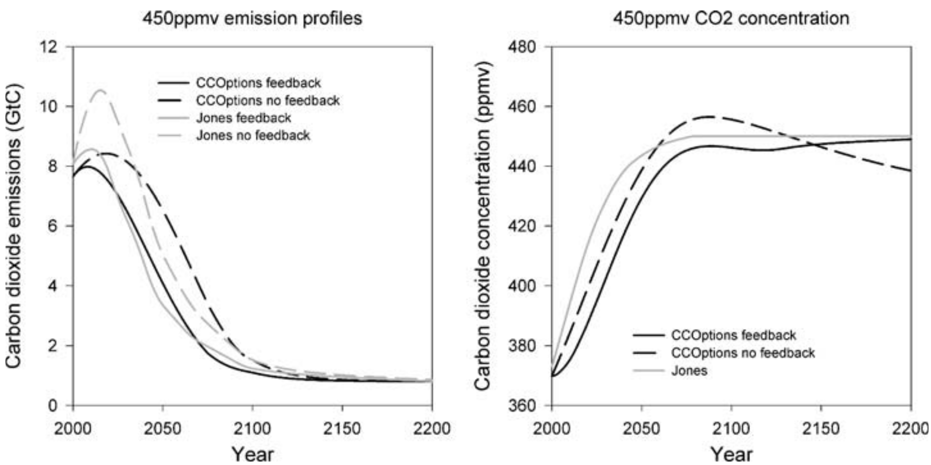


**Fig. 2** Comparison of emission profiles and $CO_2$ stabilisation levels of CCOptions with Jones et al. profiles for 450 ppmv stabilisation

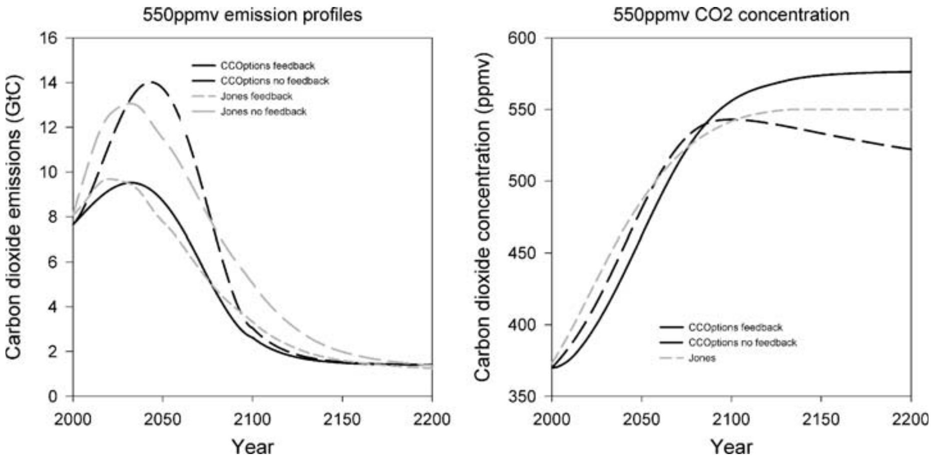


**Fig. 3** Comparison of emission profiles and $CO_2$ stabilisation levels of CCOptions with Jones et al. profiles for 550 ppmv stabilisation

Conversely, the *CCOptions* model *without* feedback, based on JNS *without* feedback data, overestimates the cumulative emissions associated with a 550 ppmv stabilisation. The overestimate correlates with a *CCOptions* outputting a maximum concentration of 543 ppmv declining to 522 ppmv by 2200, rather than stabilising at 550 ppmv.

What is evident from comparing *CCOptions* with JNS, is that the difference becomes more marked the higher the target $CO_2$ concentration, with *CCOptions* better reflecting JNS for 450 ppmv and below than it does for 550 ppmv and above. This problem would, at least in part, be reduced if *CCOptions* used a range of GCM outputs.

*2.2.2.3 Model regression equations* To further investigate why *CCOptions* better reproduces $CO_2$ concentrations and, to a lesser extent, temperature for 450 ppmv than it does for 550 ppmv, the equations underpinning the concentration and temperature relationships within *CCOptions* are assessed.

The *CCOptions* model produces two $CO_2$ concentration trajectories based, primarily, on JNS data including and excluding carbon-cycle feedbacks. The trajectories use least squares minimisation to attempt to reproduce the scientifically-derived JNS concentration-emissions relationship (Houghton et al. 1996; Jones et al. 2006). The *without* carbon-cycle feedback results, are based on a regression equation of the form:

$$C_y = C_{y-1} + 0.04\left[A_0\left(y - A_1\right) + A_2 z_y + A_3 C_{y-1}^2\right] \tag{3}$$

where:

- $C_y$ is the concentration in year $y$
- $z_y$ represents global emissions in year $y$ (including the contribution from deforestation)
- $A_i (i = 0,1,2,3)$ are constants determined by regression to fit the curve to that of both IPCC and JNS.

The *with* feedback relationship uses a similar regression equation to Eq. 3 for years up to and including 2130 (Eq. 3a) and a slightly modified version beyond 2130 (Eq. 3b):

Up to and including 2130

$$C_y = C_{y-1} + 0.04\Big[B_0 + B_1\sqrt{(y-y_0)} + B_2\left(z_{y-25} + z_y\right) + B_3\left(C_{y-1} - 270\right) + B_4\left(C_{y-25} - 270\right)^2\Big] \quad (3a)$$

Beyond 2130:

$$C_y = C_{y-1} + 0.04\Big[B_0 + B_1\sqrt{130} + B_2\left(z_{y-25} + z_y\right) + B_3\left(C_{y-1} - 270\right) + B_4\left(C_{y-25} - 270\right)^2\Big] \quad (3b)$$

where $B_i(i = 0,1,2,3,4)$ represents the constants required to reproduce the desired emission-concentration relationship.

It is again important to note that these equations are not physically or mechanistically based, but rather are simple statistical regressions designed to fit existing climate model data. The division of the equation into two parts is a consequence of Eq. 3a not adequately fitting the JNS data beyond, approximately, 2130. As the overall equation (Eqs. 3a and 3b) maintains the same coefficients for each different stabilisation level, the subsequent curves represent some JNS outputs much better than others.

According to the *CCOptions* documentation, experiments carried out with the model are limited to stabilising $CO_2$ between 350 ppmv and 750 ppmv. This again stems from the equations being statistically rather than physically-based. Whilst it could be argued that this range is unnecessarily constrained, it is sufficiently wide to encompass the concentration spectrum associated with the commonly cited 2°C rise above pre-industrial levels. Moreover, the upper end (750 ppmv) extends beyond the range currently being considered, at least openly, by policy-makers. However, as outlined earlier, at the higher concentrations the model increasingly diverges from the scientific output on which it is based.

*CCOptions* also attempts to provide temperature responses to different concentrations, based on a 2.5°C climate sensitivity and using a similar regression, rather than scientific, approach to that used for the $CO_2$ concentration calculations.

The first stage in estimating the temperature profile is to apply a time lag to the $CO_2$ concentration data:

$$C_{\text{smoothed}} = \beta C_y\,(1-\beta)\,C_{\text{smoothed}-25y} \quad (4)$$

where:

- $C_{\text{smoothed}}$ is the time-lagged concentration
- $\beta$ is a smoothing coefficient
- $C_y$ the concentration in year $y$.

The temperature is subsequently calculated for a given year and $CO_2$ concentration from the equation:

$$T_y = D_0 + D_1 y + D_2 C_y + D_3 \sqrt{C_y} + D_4 C_{y\text{smoothed}} + D_5 \sqrt{C_{y\text{smoothed}}} \qquad (5)$$

Where $T_y$ is the temperature in year $y$, and $D_i$ ($i$ = 0, 1, 2, 3, 4) are regression coefficients.

Whilst the adoption of a single climate sensitivity value limits the usefulness of the temperature correlation, the choice of 2.5°C is more worrying, given it is not the value used by the results of the climate model on which *CCOptions* is based (JNS uses a climate sensitivity of 3°C). Moreover, using a physically or mechanistically based temperature equation, as opposed to a simple regression, would arguably provide a more valuable output. In general, if the model were to offer a range of climate sensitivities policy-makers would have the opportunity to understand the range of cumulative $CO_2$ values and corresponding temperature profiles.

## 2.3 The convergence process

Having calculated the annual global carbon emissions budget, the model proceeds with the 'convergence' process, whereby national emissions converge on an equal per-capita value by a particular user-defined 'convergence year' ($y_c$). From this year onwards, whilst the global carbon budget gradually reduces, national emissions continue to be estimated on an equal per-capita basis. Within the model, the path towards convergence obeys a linear relationship that takes into account each nation's share of the global population and each nation's share of global emissions in the start year. The share of each nation's emissions in a particular year $y$ is calculated using the equation:

$$S_y = \frac{S_0 (y_c - y) + P_c (y - y_0)}{y_c - y_0} \qquad (6)$$

where:

- $S_y$ is the share of a nation's emissions in year $y$
- $S_0$ is that nation's share of emissions in the start year ($y_0$)
- $P_c$ is the predicted population share of a nation in the convergence year
- $y_c$ is the convergence year.

Each nation's share of global emissions, from the convergence year onwards, is equal to their share of the world's population.

An important model assumption is the stabilisation of population at a chosen year between 2000 and 2050. The purpose of this 'cut-off population date' is to reduce any incentive for a particular nation to increase their population and thereby their emissions allocation (each nation's emissions targets being based on their population). Clearly the appropriateness of adopting a population stabilisation date is open to argument, however given that population forecasts only exist up to 2050, the GCI consider maintaining a constant global population beyond 2050 an acceptable and appropriate simplification. One constraint is that the population cut-off year must be before or coincident with the convergence year, otherwise the equal per-capita values for each nation will not be equal after the convergence year.

## 2.4 Data uncertainty

Fundamental to the model is a comprehensive list of all nations' respective population and $CO_2$ emissions. Gathering such data is a non-trivial exercise due, for example, to national boundary changes and poor $CO_2$ accounting. The nations that are used in the latest version of *CCOptions* are those included in the $CO_2$ Information Analysis Centre's (CDIAC) 2003 listing.

### *2.4.1 $CO_2$ data*

The $CO_2$ data for all nations is taken from the CDIAC database (CDIAC 2004) giving values in million tonnes of carbon for each year between 1800 and 1999. The model includes a nation labelled 'other' to which the difference between the CDIAC's estimate of total global emissions, and the sum total of all the nations' emissions is allocated.

Despite the $CO_2$ data originating from CDIAC, comparing current CDIAC data with that used in the *CCOptions* model highlights some unexpected discrepancies. Whilst the majority of figures between 1979 and 1995 match exactly, many values prior to 1979 differ by, typically, 1 to 2%, but in some cases by more than 50%. Some of the differences between the CDIAC and *CCOptions* data, particularly the larger discrepancies, can be explained by manipulation of CDIAC data by the model writers to account for situations where nations split and merge, such has recently occurred in the Baltic States. Although it was not possible to obtain the detail of these manipulations, it is recent and future emission trajectories that are of importance when setting policy targets, and *CCOptions* data for 1990–2000 match exactly those of CDIAC.

Whilst CDIAC data is the best source available, it nevertheless is subject to the uncertainties that arise from the data collection and manipulation techniques employed by each nation. The accuracy of data collected varies between nations. Overall, uncertainties in global carbon dioxide emissions from energy and industrial processes are thought to be in the region of −6% to +10%.[7] Despite these uncertainties, the current *CCOptions* model would clearly benefit from being updated regularly with the most recent dataset.

### *2.4.2 Population data*

The population data used in *CCOptions* is taken from the UN median population figures and forecasts (United Nations 2002) and lists annual values for each nation between 1950 and 2050. Whilst the UN data is available in five-year intervals, the *CCOptions* model uses only the values at 2000, 2015, 2025 and 2050 with all interim values interpolated. Given the UN provides a low, medium and high variant result for each country in each year, and the interpolated values within the *CCOptions* model lie well within the UN's range, the uncertainties due to data manipulation are minimal in comparison to the full range of data available. Therefore, the GCI approach provides a reasonable approximation to the UN's figures and is suitable for policy purposes. However, the model should use available data rather than

[7] Personal communication with Greg Marland of CDIAC.

interpolated figures for those years for which data is published. Furthermore, it may be beneficial if the range of low, medium and high variant population figures were incorporated within the model to illustrate the implications for national emission splits of different population assumptions.

## 3 Discussion

### 3.1 Model comparison

The paper has, thus far, described and analysed specific factors of the *CCOptions* model, highlighting its particular strengths and weaknesses. Based on this analysis, the question remains as to whether, overall, *CCOptions* is a useful policy tool or not. In making this assessment it is beneficial to compare *CCOptions* with other similar climate policy tools. Two such examples are the FAIR model (Den Elzen and Lucas 2003) and the Java Climate Model (Matthews 2006a). Both models offer the user the opportunity to converge towards equal per capita emissions by a chosen date, with the Java model, being web-based, removing the need for any specific computing requirements other than web access. On the other hand, *CCOptions* is written in Excel which, despite perhaps appearing visually unsophisticated, does allow the user to access and modify the model data and, by ensuring the workings and calculations remain visible, offers a substantial degree of user flexibility.

The fact that the relationships between emissions and temperatures within both the Java and FAIR models are physically-based rather than use simple regression formulae is an important advantage over *CCOptions*. This serves to provide the user with more confidence as to the reliability and robustness of the outputs generated by both Java and FAIR over those from *CCOptions*.

*CCOptions* can be downloaded in two versions; one calculates the carbon budget for individual nations, while the other groups nations together into regions. Whilst neither version gives the user the facility to choose to output the results in a graphical format for a particular nation, national emission trajectories can be easily extracted from the tabulated data. This is less easily achieved from the graphical outputs of the FAIR model, which allows the user to download data only for the USA and China; all other nations being considered within larger regional entities. The Java model (version 5) does allow the user to see and manipulate national data. However, version 5 is clearly for the expert user. The older, less complex versions of the Java model, which are more likely to be downloaded by policy-makers, do not allow this level of interaction with the model. Being able to output national emission data from a simple model such as *CCOptions* gives it a particular appeal for policy-makers, and allows the user to assess directly the implications for specific nations.

An important facet of any climate model is the manner in which it considers climate sensitivity. *CCOptions* runs with a single model-specified climate sensitivity and consequently the uncertainties in the correlation between emission trajectories (and hence cumulative emissions) and temperature are not fully explored by *CCOptions*. Moreover, the climate sensitivity used by *CCOptions* is different from the Hadley model on which *CCOptions* is ultimately based. Within the Java Climate Model, it is possible for the user to set the climate sensitivity and view the impact on emission trajectories, with accompanying on-line documentation giving useful guidance as to impact and meaning of different climate sensitivities. *CCOptions* would benefit significantly from this greater flexibility, whilst at the same time it could have the default setting matching Hadley's climate sensitivity.

With the IPCC now providing cumulative emission values from model runs with carbon-cycle feedbacks, their inclusion within *CCOptions* is appropriate and timely, particularly given their significant implications for climate policy. The Java and FAIR models also include carbon-cycle feedbacks, but unlike the FAIR and *CCOptions* models, the Java model allows the user to specify three key parameters relating to land and ocean $CO_2$ absorption – the ocean eddy diffusion, the carbon fertilisation factor and the temperature respiration feedback. However, whilst such manipulation may be of benefit to users well-versed in climate modelling, it is unlikely that even moderately well informed policy-makers would be in a position to decide as to the appropriateness or otherwise of different sets of feedback parameters. It is possible to compare the impact of including carbon-cycle feedbacks within the *CCOptions* model with its treatment within the Java model. *CCOptions* is based on the carbon-cycle studies carried out by Jones et al. (2006), whereas the Java model bases its carbon-cycle interactions on the version of the Bern model, used in the IPCC's second assessment report. Within the major model intercomparison study, the Bern model output provides mid-range values, whereas the reduction in available carbon-cycle budget generated by Jones et al. (2006) lies towards the lower end of the range (Friedlingstein et al. 2006). In other words, the cumulative emissions associated with those profiles generated by *CCOptions* lie towards the lower end of the recently published IPCC cumulative emission range (IPCC 2007, summary for policy-makers, page 16).

A further and significant difference between *CCOptions* and both the FAIR and Java models is that whilst FAIR and Java have been developed for the Kyoto basket of six greenhouse gases ($CO_2$e), *CCOptions* considers $CO_2$ only. There are merits and drawbacks to both approaches. The inclusion of all six gases is more comprehensive and provides a closer correlation between 'equivalent' concentrations and temperature. By contrast, the $CO_2$-only route arguably recognises the substantial difference between mitigating $CO_2$ and mitigating the other greenhouse gases. Ideally, the merits of both approaches would be available if the models were able to perform runs for both $CO_2$ and $CO_2$e.

Within *CCOptions*, FAIR and Java, the opportunity for attributing bunker fuels and deforestation between nations is either neglected or not adequately considered. *CCOptions*, the only model that permits national attribution, assumes both bunker fuels and deforestation emissions to be world overheads, with an additional quantity of carbon simply added to the global total each year. Currently, the latest version of the model, whilst providing an opportunity to input bunker fuels within the calculations, does not include a value, and so essentially assumes zero bunker fuels. If *CCOptions*, or any other apportionment model, is to become a comprehensive and useful policy tool, it is important it both include the latest peer-reviewed bunker and deforestation emissions and that these be appropriately apportioned to nations responsible for them. The current growth rate of the aviation industry, particularly within Europe, demonstrates the urgency with which emissions associated with international bunker fuels need to be included with any viable apportionment model (Bows et al. 2005).

### 3.2 Recommendations

Firstly, given current rate of increase in emissions has been, in very recent years, somewhat higher than the rates captured by the IPCC's emission scenarios (SRES) (Raupach et al. 2007), any apportionment tool must be provided with the most up-to-date sources of data possible. This is also a deficiency of the FAIR model, which, despite being used widely to explore the implications of Contraction and Convergence, requires the most up-to-date input data, if the true implications of the current rates of emissions growth for future climate change targets are to be assessed. An easy function whereby the latest $CO_2$ data can be downloaded directly into the model would provide policy-makers with a broader understanding of the implications of continued high emission outputs, and the impact on future emission pathways to remain commensurate with a particular stabilisation target.

Given the complexity of most climate models, there is a clear niche for a simple apportionment tool by which policy-makers can 'experiment' with and observe the implications of a range of climate-related policy-choices on national and regional emissions budgets. Such a model should be amenable to both basic users, through clearly defined default settings, and users with the facility to understand and modify a range of major parameters. The latest *CCOptions* model, whilst partially fulfilling this role, has considerable scope for improvement in relation to a range of factors.

An essential function of a target-based policy model is its ability to lead the user through the sequence of choices necessary for the model to calculate national emission budgets. This 'correlation trail' proceeds from choosing a target *global mean surface temperature rise* (e.g. the EU council and UK government's 2°C threshold), deciding between various *climate sensitivity* values, and hence the link between temperature and the atmospheric concentration of *$CO_2$ and/or $CO_2e$*, and finally selecting the corresponding *global cumulative emissions budget* from amongst those produced by physically-based climate models (with feedbacks).[8]

All of the above parameters are subject either to scientific uncertainty (e.g. the impact of carbon-cycle feedbacks on cumulative emissions) or matter of policy choice (e.g. what temperature is deemed to represent the threshold between acceptable and dangerous climate change).[9] Consequently, if an apportionment model is to be an heuristic tool by which the user develops an understanding of the relationships between the various parameters, it is important its workings be transparent and not hidden within an opaque black-box model.

Whilst *CCOptions* certainly permits some of the parameters to be user-defined, the sequential correlations are not made explicit and would leave many policy-makers uncertain as to the relationships between the various parameters. In addition to introducing a clear progression of choices, *CCOptions* would also benefit from being somewhat less ambitious. Proceeding through the 'correlation trail' would

[8] Given that AR4 now includes cumulative emissions from a range of models *with* carbon cyclefeed-backs, it is, in the view of the authors, no longer appropriate to include non-feedback values. Whilst substantial uncertainty remains as to the actual scale of the feedbacks, the one certainty that does exist is that feedbacks do occur. On this basis, the inclusion of a non-feedback value is inappropriate and misleading.

[9] Absolute temperature (above pre-industrial) is not necessarily the ultimate target for capturing the impact of climate change; other measures may be considered more appropriate, for example, the rate of temperature change.

avoid the model having to produce its own temperature and concentration curves for particular cumulative emissions budgets, neither of which the current model is particularly good at replicating.

Finally, although *CCOptions* does allow the user to interpret global factors in terms of national emission budgets, it is arguably both too ambitious and too constraining. The FAIR and Java models, whilst apparently more user-friendly and potentially offering greater flexibility (including different apportionment regimes), do not permit disaggregation to the national level. Ultimately, with increasing demand for national government's to develop rationally-based climate strategies, it is important policy-makers have access to an appropriate national-level apportionment model. Whilst *CCOptions* could reasonably be described as a first step towards such a model, in its present form it remains unsuitable and potentially misleading for all but the well-informed user.

## 4 Conclusions

*CCOptions* is intended to provide policy-makers with a simple climate tool from which national carbon trajectories can be derived. Not only is it written for a familiar software package, Excel, its results are plainly presented allowing the user to make a relatively quick evaluation of their 'experiment' without requiring major data manipulation. Experiments are relatively easy to set up and modify, and a variety of carbon profiles can be produced for the same stabilisation level to meet a particular nation's requirements regarding the rate of convergence.

Unfortunately, whilst the aim of *CCOptions* is laudable, the application of the model is unnecessarily ambitious and as a consequence potentially misleading to all but the well-informed user. *CCOptions* would fair much better if it were to use existing scientifically-based relationships rather than attempt to derive such data itself from regression formula and required input parameters to be independent of each other. The model's credibility would be further enhanced if, based on a chosen 'correlation trail', it simply apportioned global budgets between nations (rather than provide trajectories), as well as made explicit and justified the model's underpinning assumptions.

Whatever replaces or updates *CCOptions*, in addition to its simplicity and clarity of assumptions, the model must permit and explain the range of policy choices available to the user, for example, the convergence dates and the gases to be included. Finally, interpreting a national emission trajectory from a nation's cumulative emissions budget is likely to require a good understanding of present trend data, the contemporary policy context, national emissions inventories, etc. It is only an informed synthesis of the cumulative budget and current data that permits evidence-based emission trajectories to be developed.

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