Tyndall°Centre
for Climate Change Research

Contraction & Convergence: UK carbon emissions and the implications for UK air traffic

Alice Bows, Kevin Anderson and Paul Upham

February 2006

Tyndall Centre for Climate Change Research Technical Report 40

Tyndall°Centre
for Climate Change Research

Contraction & Convergence: UK carbon emissions and the implications for UK air traffic

Tyndall Centre Technical Report No. 40

February 2006

This is the final report from Tyndall research project *T3.23* (Contraction & Convergence: UK Carbon Emissions and the Implications for UK Air Traffic). The following researchers worked on this project: Dr Alice Bows, Dr Kevin Anderson and Dr Paul Upham, Tyndall Centre (North), University of Manchester

Abstract

Stabilising atmospheric carbon dioxide concentrations at or below 550ppmv is widely believed to be necessary to avoid 'dangerous climate change'. Achieving such levels demands industrialised nations make significant emissions cuts, whilst emerging economies adopt low-carbon pathways. One proposed approach gaining support for co-ordinating the international effort essential for reducing emissions is *contraction and convergence*. This project aims to demonstrate the severe consequences for the UK in meeting its obligations to reduce carbon emissions under a contraction and convergence regime, if the UK Government continues to permit, or indeed promote, the current high levels of growth within its aviation sector.

The project reveals the enormous disparity between the UK's position on carbon reduction and the Government's inability to recognise and adequately respond to the rapidly escalating emissions from aviation. A comparison of forecasts and scenarios reflecting growing aviation emissions with contraction and convergence profiles clearly illustrates this point. Results show that at an annual growth rate of only half of that experienced by UK aviation in 2004, the UK's aviation sector accounts for 50% of permissible emissions in 2050 under the 550ppmv regime, and consumes the entire carbon budget under the 450ppmv level. Key project conclusions:

1) The UK Government must urgently update its aviation forecasts
2) Without swift action to curtail aviation growth, all the other UK sectors will have to almost completely decarbonise by 2050 to compensate
3) The proposed partial inclusion of aviation within the EU's emissions trading scheme will do little to mitigate carbon emissions
4) Aviation growth must be curbed until sufficient steps are taken to ensure fuel efficiency gains balance growth in activity, or until there is widespread use of alternative fuels that significantly reduce the industry's carbon emissions.

Keywords

Contraction & Convergence; aviation; emissions trading; passengers; carbon dioxide

Section 1 – Overview of project work and outcome

Abstract

Stabilising atmospheric carbon dioxide concentrations at or below 550ppmv is widely believed to be necessary to avoid 'dangerous climate change'. Achieving such levels demands industrialised nations make significant emissions cuts, whilst emerging economies adopt low-carbon pathways. One proposed approach gaining support for co-ordinating the international effort essential for reducing emissions is *contraction and convergence*. This project aims to demonstrate the severe consequences for the UK in meeting its obligations to reduce carbon emissions under a contraction and convergence regime, if the UK Government continues to permit, or indeed promote, the current high levels of growth within its aviation sector.

The project reveals the enormous disparity between the UK's position on carbon reduction and the Government's inability to recognise and adequately respond to the rapidly escalating emissions from aviation. A comparison of forecasts and scenarios reflecting growing aviation emissions with contraction and convergence profiles clearly illustrates this point. Results show that at an annual growth rate of only half of that experienced by UK aviation in 2004, the UK's aviation sector accounts for 50% of permissible emissions in 2050 under the 550ppmv regime, and consumes the entire carbon budget under the 450ppmv level. Key project conclusions:

1. The UK Government must urgently update its aviation forecasts
2. Without swift action to curtail aviation growth, all the other UK sectors will have to almost completely decarbonise by 2050 to compensate
3. The proposed partial inclusion of aviation within the EU's emissions trading scheme will do little to mitigate carbon emissions
4. Aviation growth must be curbed until sufficient steps are taken to ensure fuel efficiency gains balance growth in activity, or until there is widespread use of alternative fuels that significantly reduce the industry's carbon emissions.

Objectives

- To assess the suitability of the Global Common's Institute contraction and convergence model in relation to its usefulness to policy makers.
- To compare contraction and convergence profiles corresponding to the UK Government's 60% carbon reduction target with emissions generated by a growing aviation industry.
- To investigate the implications of a more stringent carbon reduction target in relation to a growing aviation industry.
- To assess the views of aviation industry stakeholders regarding the current state of the industry in terms of technology, management and its general economic health.
- To assess the views of aviation industry stakeholders regarding changes to the industry in terms of technology, management and its general economic health envisaged in the coming decades.

Work undertaken

The project began with a literature review of the available post-2012 policy options, and once it was established that Contraction and Convergence would be the policy option of choice to investigate, a technical assessment of the Global Common's Institute contraction and convergence model, *CCOptions*, was carried out. Included within this assessment were experiments to compare the output of the latest version of the *CCOptions* model with a newer version incorporating biogeochemical feedbacks. A decision was taken to use the older version of the *CCOptions* model based on the technical assessment, and using this model, experiments were generated to produce contraction and convergence profiles in line with the UK Government's 60% carbon reduction target corresponding to 550ppmv. Further experiments were then developed to produce contraction and convergence profiles in line with the lower stabilisation level of 450ppmv. These contraction and convergence profiles were then compared with the Department for Transport's (DfT's) aviation emission forecasts.

To investigate the implications for the current very high growth rates within the aviation industry in the UK for climate change, three new aviation scenarios based on historical and current growth rates and proposed fuel efficiency improvements were produced and they too compared with the 450ppmv and 550ppmv contraction and convergence profiles. Finally, an assessment of the views of aviation industry stakeholders with regard to the current and future state of the industry completed the project.

Results

The project confirmed that the contraction and convergence policy regime was suitable for looking at the possible impact of a growing UK aviation industry within the context of a nation striving to reduce its carbon emissions. The technical assessment of the contraction and convergence model – *CCOptions* – concluded that the model is a simple and useful tool for policymakers and reproduces widely accepted Hadley Centre model relationships between carbon dioxide concentrations and cumulative carbon values for all nations between today and 2200. However, it was also found that the release of the latest version of *CCOptions*, which incorporates biogeochemical feedbacks, may be somewhat premature.

Using the contraction and convergence model, the work confirmed the origin of the UK Government's 60% target as being generated by a contraction and convergence regime aiming to stabilise the UK's carbon emissions in line with a 550ppmv stabilisation target. By comparing both this stabilisation profile, and the more stringent 450ppmv profile, UK Government aviation emissions forecasts show aviation taking up between 50% and 100% of the 450ppmv UK carbon budget by 2050 and between 24% and 50% of the 550ppmv target. Moreover, results from scenarios that take into account the current very high rates of growth being seen within the industry show aviation taking up between 77% and 100% of the 450ppmv UK carbon budget by 2050 and between 38% and 50% of the 550ppmv 2050 target. The conclusion of which is an observation that the UK Government's aviation forecasts need to be updated as a matter of urgency.

The stakeholder assessment carried out produced a consensus that aviation technology is unlikely to change radically within the next 30 years, and that despite aims to improve the fuel efficiency of aircraft, these gains will likely be outstripped by industry growth.

Relevance to Tyndall Centre research strategy and overall Centre objectives

The aviation project has made an assessment of one of the most commonly debated post-2012 climate policy regimes – contraction and convergence – and used it to evaluate the implications for the UK economy of a growing aviation industry. The project therefore helps to highlight concerns over the current high levels of growth within the aviation industry, in order to instigate the formation and modification of polices that can help the UK make the transition to a more benign energy and mobility regime, in line with Tyndall's overall objectives. Furthermore, by disseminating project results via the media, the project has stimulated debate and raised awareness of the impact that individuals and their consumer behaviour have on our future climate. Stakeholder dialogue with aviation industry stakeholders has also taken a first step towards building relationships between the Tyndall Centre and the aviation industry to help encourage research towards practical and acceptable solutions.

The results from the project fed into the Theme 2 flagship project 'The Tyndall Integrated Scenarios'. Information on current, historical and predicted growth rates within the industry, alongside knowledge of possible technological and managerial advances likely to effect fuel efficiency, was used to create the end points and pathways for the aviation sector within the Tyndall scenarios.

Potential for further work

The project has opened up many possibilities for future work. The first of which could be to use the forecast data provided by the aviation industry, alongside fuel efficiency targets, fleet turnover rates, load factor data etc to produce a simple spreadsheet model to estimate more accurately the impact of current industry trends on aviation industry emissions up to 2030. This work could be carried out hand-in-hand with further interviews with aviation stakeholders to investigate more deeply the information already gleaned to find out more about specific technology issues such as flying aircraft more slowly to reduce fuel burn, turbo-prop engines, the use within the industry of Fischer-Tropsch kerosene produced from coal with carbon capture and storage or biofuels. Such additional information could be incorporated within the simple model to produce more aviation scenarios.

European aviation emissions have not been studied in any detail within this project, therefore there is scope to extend the current analysis to the EU25 nations. In particular, the impact of including aviation emissions from EU nations within the EU's emissions trading scheme should be investigated.

It is difficult to analyse the impact of air freight on the climate at present due to the fact that a considerable proportion is carried in the bellies of passenger aircraft rather than within dedicated freighters. This issue therefore requires further investigation, particularly as forecasted growth in air freight is even higher than the growth predicted in passenger numbers.

Communication highlights

Presentations

Upham, P., Anderson, K., and Bows, A., House of Lords Sub-Committee B, *Inquiry into the merits of including the aviation sector in the EU emissions trading scheme*, Oral Evidence, October 2005.

Bows, A., Anderson, K. and Upham P., *No chance for climate without tackling aviation*, Decarbonising the UK Conference, London, 2005.

Anderson, K. and Bows, A., *Growth Scenarios for EU & UK Aviation: contradictions with climate policy*, presentation to 18 MPs, Portcullis House, London, 2005.

Anderson, K., and Bows, A., EFRACOM (DEFRA Select Committee), (2004) *Climate Change: Looking Forward*, Environment, Food and Rural Affairs Committee, Oral Evidence, June, 2005.

Anderson, K. and Bows, A., *Growth Scenarios for UK Aviation: contradictions with climate policy*, presentation to Labour MPs and civil servants – event organised by SERA, Portcullis House, London, 2005.

Papers and reports

Bows, A., and Anderson K., (2005), Contraction and Convergence: An assessment of the *CCOptions* model, submitted to *Climatic Change*, 2005.

Bows, A., and Anderson, K., (2005), Contraction and Convergence: An assessment of the *CCOptions* model, *Tyndall Working Paper, 82*, 2005.

Bows, A., Anderson, K. and Upham, P. (2005) *Growth Scenarios for EU & UK Aviation: contradictions with climate policy, Report for Friends of the Earth Trust Ltd.*, Tyndall Centre for Climate Change Research (North), The University of Manchester, UK.

Bows, A., Upham, P. and Anderson, K. (2004) "Aviation and Climate Change: implications of the UK white paper on the future of aviation", *Climate Change Management*, January 2004.

Five key words/phrases

Contraction and convergence; aviation; emissions trading; uplift; carbon dioxide

Section 2 – Technical report **Page numbers**

1. Introduction and background

1.1 Introduction

There is a clear consensus amongst the scientific community that stabilising atmospheric carbon dioxide concentrations at, or below, 550ppmv is necessary to avoid 'dangerous climate change'. Achieving such levels demands very significant reductions in carbon dioxide emissions from industrialised nations, as well as the adoption of low-carbon pathways for emerging economies. One proposed approach gaining increasing support for co-ordinating the international effort necessary to reduce emissions is *contraction and convergence*. This project report demonstrates the severe consequences for the UK in meeting its obligations to reduce carbon dioxide emissions under a contraction and convergence regime, if the UK Government continues to permit, or indeed promote, the high levels of growth currently experienced within its aviation sector.

Under contraction and convergence, all nations work together to achieve a year-on-year contraction in emissions. Furthermore, nations converge over time towards equal per-capita emissions. The conflict between a contracting carbon target and the UK's expanding aviation industry is clearly illustrated within this project report. Government forecasts and Tyndall aviation scenarios of escalating aircraft emissions in the UK from today until 2050 are compared with national contraction and convergence profiles aimed at stabilising carbon dioxide concentrations at both 450 and 550ppmv. Results show that at an annual growth rate of only half of that experienced by the UK's relatively mature aviation industry in 2004 would equate to the UK's aviation sector accounting for almost 50% of permissible emissions in 2050 under the 550ppmv regime, and consuming the entire carbon budget if 450ppmv is the target. Moreover, these particular results do not include any uplift[1] that takes into account the additional aviation-induced climate change effects of contrails, cirrus clouds or additional greenhouse gases. In particular, the project reveals that the UK Government forecasts must be updated as a matter of urgency to reflect the current very high levels of growth and, in turn, kerosene consumption within the aviation industry. According to the latest copy of the Digest of UK Energy Statistics (DUKES, 2005), the consumption of aviation fuel is 10% higher in 2004 than 2003.

The project went on to assess the views of some of the aviation industry's stakeholders, and combining these insights with the experimental results. From this, conclusions were drawn relating to the implications for other sectors of the UK's economy, the inclusion of the aviation industry within the EU's emissions trading scheme and the kind of urgent action on climate change required by the UK Government, particularly whilst it is in the driving seat of the EU and the G8.

1.2 Background to climate policy

1.2.1 Current picture

The text of the Kyoto Protocol was adopted on 11 December 1997, and opened for signature between March 1998 and 1999. It finally came into force in February 2005 following Russia's signature with its objective being to stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.

Whilst awaiting ratification, many countries have been working towards the targets laid out by the Protocol. The first step on the road to reducing the impact of human activities on the climate is for industrialised nations to cut greenhouse gas emissions by an average of 5.2% from their 1990 levels

[1] It should be noted that there is substantial scientific uncertainty relating to both the size of the uplift factor that should be used, as well as to the method of simply 'uplifting' carbon values for comparison with carbon emissions profiles. Strictly speaking, such a comparison does not compare like with like

by 2008 - 2012[2]. The EU accounts for about 24% of Annex 1 greenhouse gas emissions and under the Protocol, the EU and its member states can agree to meet their commitments jointly. This 'bubble' arrangement allows the EU's target to be redistributed between member states to reflect their national circumstances. In June 1998, environment ministers agreed how the target should be shared out. The UK then pledged to reduce its greenhouse gas emissions by 12.5% by 2010, and cut its carbon dioxide emissions by 20% by 2010 and 60% by 2050.

In return for a commitment to reduce greenhouse gases, the Kyoto Protocol also set out ‘flexibility mechanisms’, intended to be least cost policy instruments. These enable joint reduction, transfer of ‘Emissions Reduction Units’ within a Party’s area of jurisdiction, trading of ‘emissions allowances’ and use of a ‘clean development mechanism’, through which emissions reductions can be earned within a non-Annex 1 Party (Missfeldt, 1998).

In 2000, the European Commission issued a consultative Green Paper on greenhouse gas emissions trading within the EU, (European Commission, 2000). This suggested that a European Community-wide emissions trading scheme should begin by 2005, as a forerunner to emissions trading under the Kyoto Protocol from 2008. It suggested beginning with carbon dioxide for ease of monitoring, and large fixed point sources, and recommended that compatibility between the Community and Kyoto schemes be ensured. The UK initiated the first national greenhouse gas emissions trading scheme in 2002.

Despite attempts to limit the growth in global atmospheric carbon dioxide concentrations through the adoption of the Kyoto protocol, anthropogenic emissions of carbon are continuing to increase, and further action is required. Atmospheric concentrations of this key greenhouse gas currently stand at around 378ppmv compared with 364ppmv in 1997 when the Protocol was adopted – a 4% increase in just seven years (CDIAC, 2005).

The world is now swiftly striding towards carbon dioxide concentration levels thought to be associated with ‘dangerous climate change’, whilst progress on post-Kyoto agreements at an international level is slow. Furthermore, recent scientific research is tending to suggest that the 550ppmv level, thought to be associated with the key 2°C global temperature increase, may be woefully off the mark (Elzen and Meinshausen, 2005). Although there is a range of emission pathways that could be followed theoretically to avoid different temperature levels, probability analysis provides a quantitative estimate of the risk that a particular temperature level would not be exceeded. For example, limiting warming to 2°C above pre-industrial levels with a relatively high certainty requires the equivalent concentration of carbon dioxide to stay below 400ppmv! Conversely, if concentrations were to rise to 550ppmv equivalent concentration, then it is unlikely that the global mean temperature increase would stay below 2°C (Hadley, 2005). In other words, the world is already extremely close to the point above which serious adaptation measures will be required.

It is clear from the current scientific understanding, such as that cited above, that there is an urgent need for extending national commitments beyond Kyoto. Globally, the first step on such a path is to agree a post-Kyoto policy regime.

[2] At Kyoto, the EU and its member states agreed to a joint reduction of -8%, the United States to –7%, Japan to –6%, Russia and the Ukraine to return to 1990 levels, and Australia +8%. Targets for individual EU member states ranged from –21% for Germany and Denmark, to –6% for the Netherlands, +13% for Ireland and +27% for Portugal (DEFRA, 2003). However, as of 2003, greenhouse gas emissions from the EU had increased for the second consecutive year, moving the EU as a whole further away from meeting its commitment to achieve a substantial emissions cut by the 2008-2012 period (EEA, 2003).

1.2.2 Post-Kyoto policy regimes

Even before Russia's signing of the Kyoto 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 United States. 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 nations as well as industrialised.

Amongst the emission reduction regimes that require 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 & Convergence mechanism (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 contraction and convergence as a practical interpretation of their philosophical principle that "every adult on the planet has an equal right to emit greenhouse gases".

In addition to the contraction and convergence policy, with an *a priori* presumption that nations should move towards per-capita equity in their carbon dioxide emissions, there are a number of related but different approaches to extending national commitments post-Kyoto. A study commissioned by the Umweltbundesamt (German Federal Environment Ministry) (Höhne et al, 2003) has assessed these approaches[3], including contraction and convergence, and makes recommendations for increasing their effectiveness and acceptability. Höhne et al's findings on ten alternative approaches to contraction and convergence are summarised here:

- *Intensity targets* can play a role in future commitments as one form of target for a particular group of countries, possibly in parallel to other types of targets for other countries. If applied to all countries, the global emission intensity (emissions per unit of GDP) has to decrease rapidly (2%-4% per year) in order to reach stringent environmental goals. Agreeing on differentiated intensity reductions may be more difficult than agreeing on the level of absolute emissions reductions, as emissions intensity involves country specific knowledge of the relationship between emissions and GDP, which also may evolve with time.
- *Contraction & Convergence*: since major reductions in emissions are necessary it is likely that per-capita emissions under any policy regime will eventually converge to a very low level. The issue is on which path. Contraction and convergence has the advantages of simplicity and stringency but does not account for the structural differences of countries, their ability to decrease their emissions (nor, directly, for historic emissions).
- *The Triptych approach*: country-specific emissions budgets are calculated that reflect the energy, industrial and household sectors. As the method takes into account existing differences between countries, it can differentiate national emission reduction targets based on need.
- *Multi-stage approaches* "will be the future of the climate regime", but there are many possibilities regarding types of stages and thresholds for moving into a next stage. The current two stages (Annex I and Non Annex I) could be extended. One criterion for moving to a further stage could be emissions per-capita.
- *The multi-sector convergence approach* describes a complete set of rules for a future climate regime, defining in essence the path on which sectoral per-capita emissions converge. A

[3] For another accessible account of post-Kyoto options, see: www.fiacc.net/app/approachlist.htm Furthermore, models based on some the different approaches can be freely downloaded from research groups.

major downside of the approach is that sectoral activities are not necessarily directly related to the population.

- *Equal mitigation costs*: setting targets so that mitigation costs are equal for all participating countries (e.g. a percentage share of the GDP) seems to be, from a theoretical point of view, a fair option. In practice, however, it may be impossible to agree on a model or calculation method for calculating the cost of countries. It is therefore not a realistic option.
- *Policies and measures* can also be a part of a mix. Especially for newly entering countries, policies that combine development and environment objectives are very attractive and could form a first stage of commitments.

Höhne et al's analysis necessarily involves subjective judgement in addition to technical analysis – it is difficult to anticipate what will and will not be acceptable in the international political arena. One could also add other policy approaches, notably the Brazilian approach in which emissions reduction responsibilities are allocated on the basis of countries' historical contribution to global temperature change.

Whilst there are clearly many post-Kyoto policy regimes, whatever approach or mix of approaches is chosen, 'dangerous climate change' can only be avoided with major carbon dioxide emissions reductions, and that such reductions need to begin within the coming decade.

1.2.3 Contraction & Convergence

Contraction and convergence is an international framework for assuming an equitable contribution to the arrest of global greenhouse gas 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, such a mechanism requires all nations to impose targets from the outset (Cameron, 2003).

The US and other industrialised nations cannot escape their responsibility that as the main greenhouse gas emitters, they will necessarily be required to make substantial cuts under any regime designed to stabilise carbon dioxide concentrations at a level that avoids global temperature increases of more than 2°C, (IPCC, 2001). Although it can be argued that the particular circumstances of different nations lead to a requirement for differing emissions profiles, the GCI fear that any allowance made for such differences will create unacceptable delays in negotiating an agreement. As stabilising the carbon dioxide concentration at or lower than 450-550ppmv 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.

Indeed, France already proposed a formula for Annex I targets in 2010 based on converging global per-capita emissions by 2100. Similarly, in 1997 the EU proposed that emission paths should eventually converge to similar per-capita or per unit of GDP levels, without specifying a timeframe or level (Höhne et al, 2003: 26). Furthermore, the Royal Commission on Environmental Pollution (RCEP) used a contraction and convergence regime to calculate that the UK would be required to cut emissions by 60% by 2050 (RCEP, 2000), a target subsequently adopted by the Department of Trade and Industry (DTI) (DTI, 2003).

Berk and den Elzen (2001) used the FAIR model (Framework to Assess International Regimes for the differentiation of commitments) (Elzen et al, 2000) to compare alternative regimes of increasing participation. The FAIR model consists of a simple integrated climate model combined with an accounting framework for calculating regional emission allowances resulting from different allocation rules. The first option assessed was a gradual increase in both the number of parties involved and their level of emissions reduction. The second option was a contraction and convergence regime with universal participation. Berk and den Elzen (2001) found that, in order to stabilise carbon dioxide concentrations at 450ppmv by 2100, the major industrialising countries must participate in emissions reduction before 2050. If stringent climate targets are set, a convergence regime seemed to provide more incentive for controlling emissions than a regime where nations are gradually incorporated.

As a threshold for a country participating in carbon emissions reductions of 4% per year, Berk and den Elzen (2001) used a per-capita income value of 50% of the 1990 average Annex 1 per-capita income, similar to that of Argentina. Upon reaching 75% of the 1990 average, countries are assumed to join Annex 1 – those countries who have agreed emissions caps – with reduction targets proportional to their per-capita contribution to carbon dioxide-induced temperature rises.[4] As a result, the global emissions ceiling required for 450ppmv is breached after 2020 due to the major developing countries such as China and India participating only after 2050. If the target were 550ppmv, an emission space for Annex 1 would exist but be extremely limited. The corollary is that a 450ppmv target requires major developing countries to participate within a few decades from now, at much lower levels of per-capita income than the 1990 Annex B average. Berk and den Elzen (2001) go on to show that 450ppmv is attainable if *per-capita* carbon dioxide emissions are used as a means of differentiating commitments. Under this scenario, Annex 1 countries would begin with emissions permits well below the global average, China would be permitted an increase from today's levels until 2025, India until 2030 and Africa until 2040.

Berk and den Elzen also tested a contraction and convergence approach for 450ppmv, with convergence years of 2030 and 2050. The emissions reductions necessary for convergence by 2030, relative to 1990, are relatively high for the time available: 75% for North America and 60% for Europe. For 2050 the reductions are a more plausible 55%, 55% and 40% respectively.

Given these findings, Berk and den Elzen (2001) consider that a contraction and convergence approach has two main advantages over an increasing participation approach (or *Continuing Kyoto* approach, in terms used by Höhne et al, [2003]). The first concerns the way in which emissions trading, an important component of contraction and convergence, is considered to offer the best opportunity for exploring the cost-reduction potential of the Kyoto Mechanisms. The second is that there would be no 'carbon leakage' (increase in developing country emissions due to business relocations from the developed countries). However, Berk and den Elzen (ibid: 478) also perceive potential problems with emissions trading: once developing countries join the system, prior beneficiaries such as Russia would find a reduced market for their surplus emissions (this could be a general problem with any strongly contractive scenario and is discussed further below). In addition, the concept of per-capita emissions equity has to date been controversial (ibid), despite economic analysis indicating welfare losses of only a few percent by 2050 compared with business as usual (Böhringer and Welsch, 2000, in Berk and den Elzen, 2001)[5].

1.2.3.1 Multi-sector convergence approach

A multi-sector convergence (MSC) approach was developed jointly by the Centre for International Climate and Environmental Research, Oslo (CICERO) and The Netherlands Energy Research Foundation (ECN) (Jansen, 2001a, b; Sijm et al, 2001). The approach is relevant to the present study for its sectoral aspect, and has the following characteristics: (i) identification of sectoral

[4] Note that as such, the targets do not take into account climate feedbacks from the carbon cycle and other effects

[5] Similarly the UK Cabinet Office estimates that only 0.02% of annual GDP growth would be foregone over each of the next 50 years if a 60% reduction in carbon dioxide emissions was pursued and achieved by the end of that period (PIU, 2002, in Houghton, 2002).

targets; (ii) eventual convergence to emissions levels of global per-capita equity; (iii) assignment of targets to non-Annex 1 countries upon reaching a per-capita greenhouse gas emission threshold; (iv) issuing of additional emissions allowances under special circumstances (Sijm et al: 483). It should be noted that the MSC approach as developed by Sijm et al (2001) uses units of carbon dioxide equivalent, as it includes CH_4 and N_2O emissions. Amongst other possible benefits, the authors argue that use of sectoral divisions may improve insight into the feasibility of global greenhouse gas reduction targets, and that use of interim budget periods allows adjustment as economic conditions and scientific knowledge change.

The MSC approach involves the following stages:
1) The distinction of seven different sectors
2) The determination of global sector emission norms
3) The determination of national emission mitigation targets
4) The inclusion of allowance factors (ibid: 486).

The seven sectors of the MSC approach are: power, households, transportation, industry, services, agriculture and waste. For each sector, per-capita emission allocations ('standards') are set; for the base year of 2010, these are set equal to the global average for each sector. An annual percentage emissions reduction is then set for each sector, by geometric interpolation, until a convergence year. The national target for a given year is determined by summing the per-capita sectoral targets for that year and multiplying by the projected population for that year. Countries take on emissions reduction commitments upon reaching per-capita emissions thresholds. Emissions allowance factors are available, to be applied nationally, to mitigate the effects of emissions control on countries with special needs arising from climate, population density, agricultural and transitional economies and a low potential for use of renewable fuels (Sijm et al:2001). They provide numerical illustrations of this approach, in part using an MSC model that can be downloaded from the ECN website[6].

1.2.3.2 Policy assessment of Contraction & Convergence

As stated above, Höhne et al (2003) have conducted a relatively detailed assessment of the main policy options for international climate negotiations during the next commitment period for the German Federal Environment Agency (UBA). The following assessment was made of contraction and convergence by Höhne et al (2003: 62-3) in terms of (italicised) criteria applied to each option.

Environmental criteria
In an illustrative case that would include all countries from 2010, levels of 450 - 550ppmv atmospheric carbon dioxide concentration could be reached by 2100. While there would be certainty over the level of emissions permitted, the approach would imply abrupt changes in the emission trend of many Parties, including major developing countries. Leakage would be avoided since all countries would participate.

Encouragement of early action
Contraction and convergence is one of the few policy approaches that encourages early action (i.e. before 2010), as all countries would know that they must reach equal per-capita emission levels.

Political criteria
With respect to *equity principles*, while the least developed countries would be permitted to increase emissions, most developing countries and all developed countries would be completely emissions-restricted from 2010. The principle of *capability* (ability to pay) is not explicitly addressed. The principle of *responsibility* (polluter pays) is partly addressed, in the sense that the higher emission countries would need to make the largest reductions. The *historic responsibility* of countries is, however, not taken into account. A newly industrialized country with currently high

[6] At www.climatepolicy.info/kyoto/burden/

per-capita emissions (e.g. South Korea) would have to reduce emissions by the same degree as an industrialized country with a similar level of per-capita emissions (e.g. France).

Regarding the *fundamental positions of the major political constituencies*, an advantage of contraction and convergence is that most developing countries have clearly indicated their preference for the convergence of per-capita emissions. The G77 and China succeeded in embedding related language in the Marrakech Accords in the context of the use of the mechanisms: “reducing emissions in a manner conducive to narrowing per-capita differences between developed and developing country Parties”. However, some developed countries are strictly opposed to the concept of per-capita emissions, and the reporting of emissions in per-capita terms in national communications was consequently excluded from UNFCCC reporting requirements.

Economic criteria

Contraction and convergence takes little direct account of the *structural differences between countries*, differentiating only to the extent that high emission countries will need to make the highest emissions reductions. The international emissions trading component of the approach should help to *minimise adverse economic effects* by narrowing the differences in marginal abatement costs in different countries by encouraging emission reductions where they can be obtained for the lowest price.

Technical criteria

*Regarding compatibility with the structure of the UNFCCC and Kyoto Protocol***,** scenarios with targets for convergent per-capita emissions could be based on the structure agreed in the Kyoto Protocol, with all countries participating. In terms of placing *moderate political and technical [demands on] the negotiation process*, Höhne et al (2003: 43-4) consider contraction and convergence as simple, transparent and easily explained. International agreement would be required on only a few factors: the convergence year and level (through a global stabilisation path), and a decision on which gases and sectors to include. “This low number of decisions would make it relatively easy to reach an agreement from a purely process point of view. The current system of reporting and reviewing greenhouse gas inventories would have to be expanded to all countries”.

Höhne et al (2003: 44) conclude that while contraction and convergence “is intriguing due to the simplicity of the approach” and is “one of the few approaches that encourage early action by countries that are not yet part of the commitment regime”, its simplicity is also a major disadvantage, in that it does not account for the structural differences between countries that affects their ability to decrease emissions. Moreover, for stabilisation levels of 450 or 550ppmv carbon dioxide, many developing countries would have to decrease emissions below their business as usual path during the coming decades. Consequently, only a few, least developed countries would be able to sell emission allowances to the developed countries, and then only for a short period of time.

Contraction and convergence is one of several options for a post-Kyoto climate regime. While it has the advantages of simplicity, an element of international equity and would include all countries, it does not in itself allow for structural differences between countries. Nevertheless, it could form a starting point for international negotiations on a post-Kyoto regime. It also enables the national, aggregate implications of the deep cuts required for carbon dioxide emissions stabilisation to be profiled and compared to emissions trends in sub-sectors.

Notwithstanding the advantages and disadvantages of the various non-contraction and convergence approaches as supported explicitly by the RCEP and implicitly by the Government’s Energy White Paper, this project focuses on the implications of a contraction and convergence approach for UK aviation.

2. The aviation industry and its impact on climate

The aviation industry is a special case when it comes to its impact on climate for three key reasons. Firstly, it has significant additional climate warming impacts, secondly, it is the fastest growing sector in the UK economy and thirdly solving the problem will likely require solid international agreements. The follow section highlights the key impacts of the aviation industry on the climate, as well as giving some information on historical and forecasted growth trends for the industry.

2.1 Historical growth

Since 1960, global air passenger traffic (expressed as revenue passenger-kms) has increased by nearly 9% per year – 2.4 times the growth rate of global average Gross Domestic Product (IPCC, 1999). Between 1993 and 2003, world air freight has also been growing at extremely high rates – 6.2% per year according to Boeing (Boeing, 2005a). Within Europe, passenger numbers in the EU15 nations increased at 5.3% per year between 1993 and 2002 (Layos, 2005) and in the ten accession nations, passenger numbers have also increased at a similar level (Stat, 2002) between 1995 and 2000. Turkey has seen the highest growth recorded in the past at 14.5% on average between 1985 and 1998, although the strongest growth recorded from the top five countries in terms of passenger numbers in the period 1985-1998 is Germany at 7.3% per year. The other top four countries in terms of passenger numbers in Europe are the UK, France, Spain and Italy (ATAG, 2000).

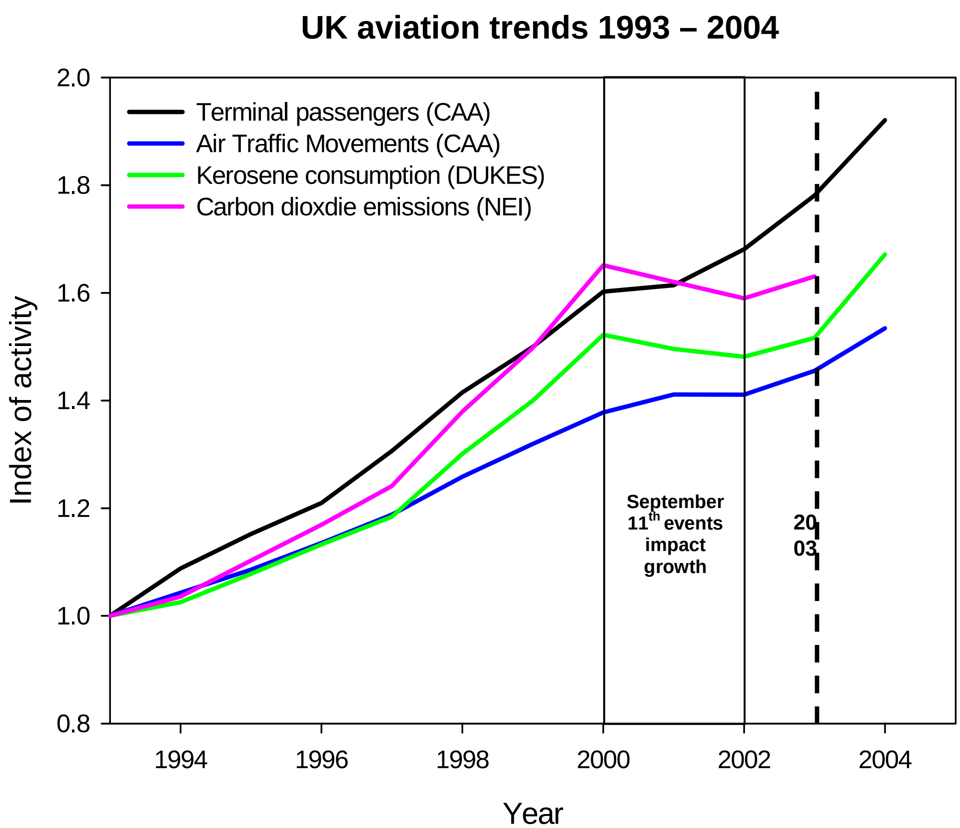

Figure 1: Recent aviation trends for the UK's aviation industry. Prior to the events of September 11, annual growth rates were as follows: Terminal passengers – 7% per year; Air Traffic Movements – 5% per year; Kerosene consumption – 6% per year; Carbon emissions – 7% per year.

The UK tops the European chart in terms of passenger numbers, in terms of the number of transfer passengers and British Airways was second only to Lufthansa in 1998 as the second largest carrier

(ATAG, 2000). Its largest airports act as key hubs for many trans-Atlantic and trans-continental flights. Despite the fact that the industry within the UK is relatively mature, growth in terms of passenger numbers has averaged at 6% per year between 1993 and 2003, including the blip due to the September 11 attacks, 7% per year excluding this period as shown in Figure 1.

Indeed between 2003 and 2004, the yearly increase in terms of passenger numbers was 8% (CAA, 2004) and the corresponding increase in fuel consumption for that period 10% (DUKES, 2005). The difference between these two figures could be due to the resurgence of long-haul flights following a reduction due to the events of September 11 (ref interview in later section). This increase in fuel consumption implies that there will be a similar increase in the carbon dioxide emissions from the aviation industry in 2004 compared with 2003. It is interesting to note from Figure1 that the rate of increase of emissions most closely follows the terminal passenger numbers trend until 2000.

2.2 Aviation industry forecasts

The aviation industry is naturally keen to produce forecasts of future passenger numbers and flights for business strategies, infrastructure planning, hardware purchase and environmental concerns. For this reason, both Boeing and Airbus, the two main aircraft manufacturers, produce forecasts for the period up to 2023/4. Some of the details of these and other forecasts are summarised below.

2.2.1 Airbus forecasts

Airbus predicts that global passenger traffic will grow on average at 5.3% per year between 2004 and 2023 and world passenger kilometres are expected to triple by 2023. This world average incorporates an average growth in passenger-kilometres of some 8.2% per year in China. This extremely high level of growth is reflected in the increased share of world air traffic for the Asia-Pacific region for 2023 from some 25% in 2003 to 31% in 2023, as shown in Figure 2 In 2003, 3.2 trillion passenger-kilometres were travelled compared with a predicted 9 trillion in 2023.

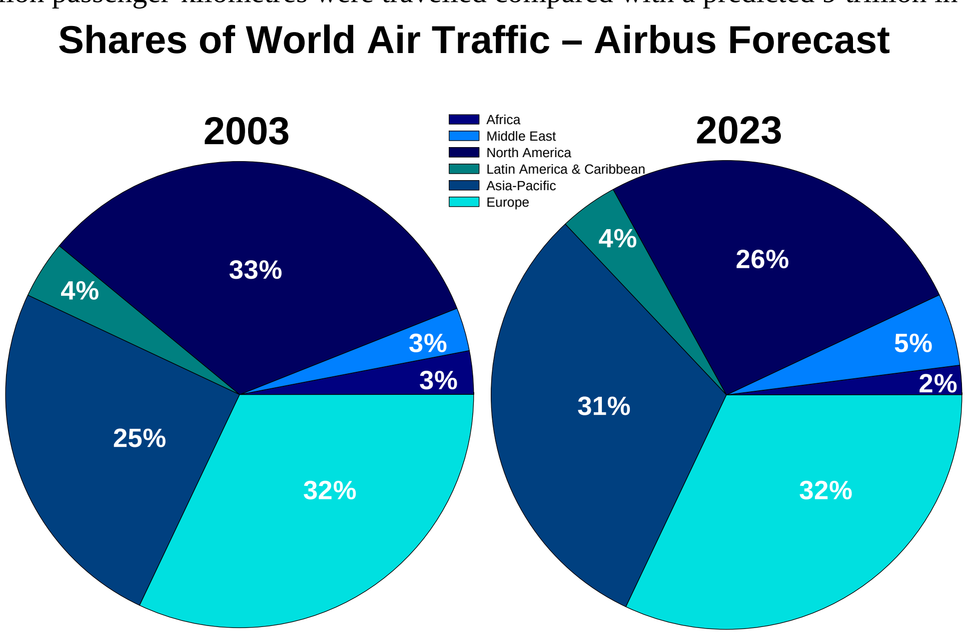

Figure 2: Latest publicly available airbus forecasts

The Airbus forecasts use projections from the Global Insight Forecasting Group and takes into account economic growth, oil prices and the export import history of countries and commodities. Regional and structural changes expected to influence the market are also included, for example the growth potential for low-cost carriers. The pace of liberalisation of markets to and from developing countries, as well as environmental and congestion constraints are said to have been considered.

In terms of growth within different regions of the world, growth for airlines domiciled in Europe is predicted to be around 5.2% per year between 2004 and 2023, with a higher rate of growth of 5.8% per year between 2004 and 2013. This prediction takes into account the mounting importance of low-cost carriers in Europe. The UK is likely to experience a rate similar to that of the rest of Europe (as evidenced by stakeholders in section 6.3.1.1).

2.2.2 Boeing forecasts

The latest forecasts from Boeing are not significantly different to those issued by Airbus in terms of their outputs. Again, they predict that world passenger growth will continue following the downturn after the September 11 attacks at a rate of 5.2% per year, cargo at 6.2% per year (Boeing, 2004) and shown in figure 3. Within the EU, air traffic for the regions carriers is also expected to be on the increase, at 4.3% per year. The rise of low-cost carriers is said to continue to generate new travel growth in Europe. European markets have completed their first decade of liberalisation, which has rapidly stimulated air travel demand. Lower fares and point-to-point services to many secondary and select hub airports are desirable to air travellers. Furthermore, inclusive tour charter operators will play a role in delivering air travel for European tourists to a wide variety of destinations, many outside of the continent (Boeing, 2005b).

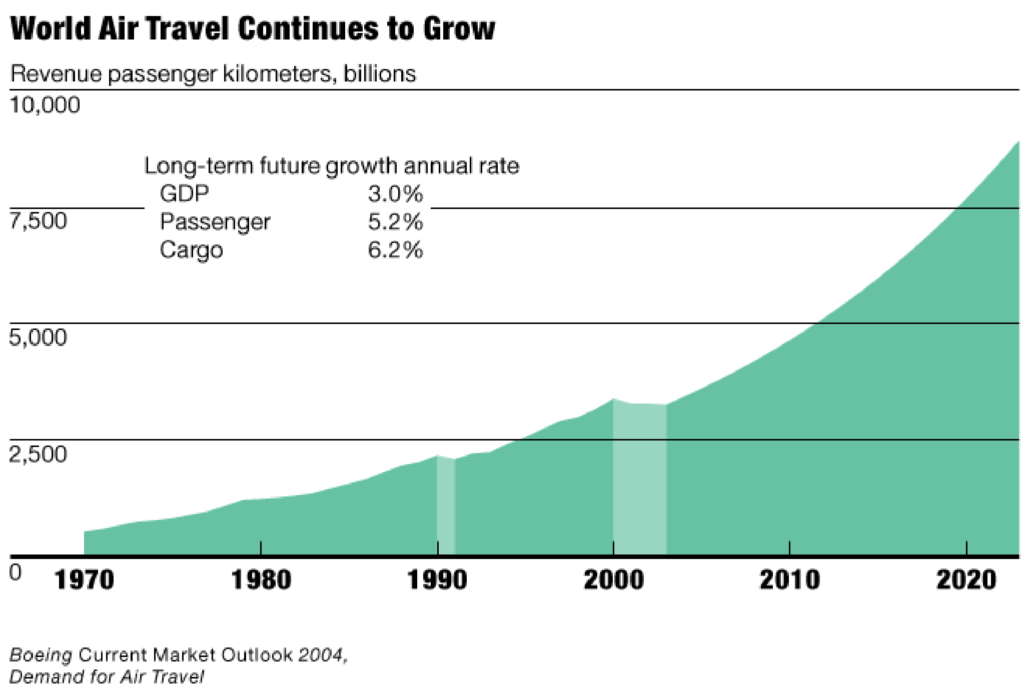

Figure 3: Latest Boeing forecasts.

2.2.3 Rolls-Royce forecasts

The engine manufacturer Rolls-Royce produces yearly forecasts for aircraft deliveries, engine markets and traffic forecasts (Rolls-Royce, 2005). In overview, they predict strong global growth in the commercial aircraft and jet engine market of the coming 20 years, driven predominantly by the rapid growth in the Asian market, as well as continued demand for new aircraft in other, more mature, markets. In its regional traffic forecasts, it predicts a 5% per year world growth between 2005 and 2024, with a corresponding 4.4% per year growth for Europe. Within the European markets, the highest growth is predicted to be in the Europe-Asia Pacific market, with a 6.1% per year growth in traffic. The lowest growth figure for Europe is the Intra-European flight market, which is forecast to grow at 3.4% per year. World air cargo within this forecast set is predicted to grow at 6.9% per year.

2.2.4 Other forecasts

For more specific data relating to Europe, Eurocontrol produce long-term forecasts of flights, summarising predicted increases in the number of flights per year within Europe and breaking the growth down into particular flows, to indicate which parts of Europe are likely to see which levels of growth. It also lists traffic growth in individual EU states and produces scenarios of possible futures. Rather than produce forecasts in terms of passenger numbers or passenger-kilometres, the data is given in terms of total flights. They use four different scenarios describing different oil prices and economic growth, and therefore generate a range of annual increases in flights from between 2.3% to 3.4% compared with an average growth of 3.8% per year between 1975 and 2001. Therefore, they conclude that the number of flights will be increasing at a lower rate in the future (Eurocontrol, 2004b).

Within forecasts for 1998-2015 produced by ATAG, they predict an average annual growth rate in terms of passenger traffic of 4.3%, with the Netherlands predicted to experience the highest growth of 5.2% per year. However, of the top five countries in terms of passenger numbers, the UK is predicted to be the fastest growing market, moving from 144 million passengers in 1998 to 313 million in 2015. The UK is also predicted to remain the most important market, followed by Germany and France. In terms of specific regional developments, the Europe to Middle East/Asia market will be the fastest growing at a rate of 5.1% until 2015, and the Europe-Americas market will be the slowest at 4.4% per year reflecting market maturity (ATAG, 2000).

In summary, the EU and the UK are predicted to have continued high growth at around 4-5% in their aviation industries until 2020, with the UK continuing to dominate the European market.

2.3 The impact of aviation on the climate

Like other modes of transport, the aviation industry burns fossil fuels, and consequently contributes to increasing global carbon dioxide concentrations. However, unlike those other sectors, the altitude at which aircraft fly contributes significant additional climate warming. In fact, the amount of carbon dioxide released by the aircraft, if measured at ground level, is only a fraction of the total emissions that contribute to climate change. There are a number of reasons for this:

1. The altitude that the emissions are released at means that water vapour, another greenhouse gas, is released directly into the stratosphere where it causes warming.
2. The nitrogen oxides released at altitude cause ozone formation in the upper troposphere which leads to warming.
3. Water vapour and soot released into the troposphere leads to the formation of contrails, which in turn cause additional warming
4. Sulphur oxides, sulphuric acid and soot lead to an increase in the cirrus cloud cover, again further increasing the climate impact of the aircraft.

The combined effect of these contributions to warming is currently being researched and continues to be uncertain. But estimates are in the region of between 2 and 4 times that of the carbon dioxide alone (IPCC, 1999), with a figure of 2.7 being commonly quoted.

The aviation industry is fully aware of these additional climate change impacts, but also recognises that addressing one kind of emission is likely to exacerbate another. For example, altering the altitude at which aircraft fly could reduce the formation of contrails and cirrus clouds, but will likely increase fuel burn, and hence carbon dioxide emissions (Williams and Noland, 2005). Similarly, noise restrictions and targets require additional engine parts, increasing the weight of the aircraft, and again the fuel burn. Although there are significant steps being taken to improve the fuel efficiency of aircraft (Aviation,2005), it is clear that to avoid carbon dioxide emissions from the aviation industry increasing significantly, the growth in the industry will need to be off-set by fuel-efficiency gains or alternative non-carbon emitting fuels.

3. Reducing aviation industry emissions

Minimising the environmental impact of the aviation industry, be it in terms of local noise pollution or climate change impacts is a concern to many within and outside of the aviation industry. Many studies, research programmes and scenarios therefore directly concern prospective aviation fuels, fuel efficiency, improving air traffic management and policy instruments that curb demand. Within this section of the report, a brief summary of the key areas where there is potential for reducing emissions are discussed.

Advances within the aviation industry aimed at having an impact on the aircraft's fuel efficiency or to reduce atmospheric pollutants come in a variety of forms. For example, modifications to the fuel source are likely to require changes to the engine design of an aircraft, the airframe design, or indeed the infrastructure for refuelling. On the other hand, improving the fuel efficiency of aircraft may be done through a more aerodynamic design, engine updates or improvements to the air traffic management system. In the following section the main technological and managerial advances envisaged in the short, medium and long-term are highlighted.

3.1 Alternative aviation fuels

3.1.1 Biodiesel

Biodiesel as an aviation fuel would be what is known as a kerosene extender. In other words, biodiesel would be mixed with mineral kerosene to produce a new, lower carbon emitting fuel. A maximum of 10-20 % of biodiesel could be used in aviation fuel, but only in such proportions as biodiesel alters the crystallisation properties of the aviation fuel at low temperatures. Current research efforts can use filtering techniques to remove such crystals in the mixture contains up to 10% biodiesel, so that the fuel continues to meet safety requirements. However, further research will be required for mixtures containing more than 10% biodiesel. Advantages of biodiesel over conventional kerosene include its lower polluting emissions, its biodegradable nature and its relatively simple production from all major biocrop feedstocks. However, mixing mineral kerosene with biodiesel compromises kerosene's ability to perform at cold temperatures, such as those experienced at altitude, even when mixed with a small proportion of biodiesel (Saynor, 2003). Further research is therefore required to improve and build confidence in cold weather performance. Moreover, adding any such material to jet fuel would not be allowed under any current fuel specifications because of compositional considerations (IPCC, 1999).

3.1.2 Fischer-Tropsch Kerosene

As an alternative to biodiesel, kerosene can be manufactured synthetically by Fischer-Tropsch or other fuel production processes from a wide variety of carboniferous feedstocks including caol with carbon capture and biomass, with the advantage of providing fuel-cycle carbon dioxide benefits compared with mineral kerosene, and eliminating oxide of sulphur. Fischer-Tropsch fuels are typically manufactured in a three-step procedure:

- Syngas generation: the feedstock is converted into synthesis gas composed of carbon monoxide and hydrogen.
- Hydrocarbon synthesis: the syngas is catalytically converted into a mixture of liquid hydrocarbons and wax, producing a "synthetic crude".
- Upgradeing: the mixture of Fischer-Tropsch hydrocarbons is upgraded through hydrocracking and isomerization and fractionated into the desired fuels.

This sort of kerosene is chemically and physically similar to mineral kerosene, and therefore broadly compatible with current fuel storage and engines (Saynor, 2003). However, its lack of aromatic molecules and the fact that it is virtually sulphur-free, give it poor lubricity. It also has a lower energy density than mineral kerosene, which would impact on long-haul flights. A few modifications could, on the other hand, improve its lubricity, making it fit for use. This type of kerosene is likely to be a medium-term development within the aviation industry. On a practical note however, the UK could only supply about 10% of the fuel required for its aviation industry (Saynor, 2003).

3.1.3 Hydrogen

Using *hydrogen* to fuel aircraft could be beneficial if derived from the gasification of biomass or electrolysis of water using renewably generated electricity with the potential for reducing the aircraft induced radiative forcing by about 20% if such aircraft were gradually introduced between 2015 and 2050 (Ponater et al., 2003). However, using hydrogen within the aviation industry would require fundamental changes to the jet design. For example, the high energy content, but low density of this gas requires much larger fuel tanks (Saynor, 2003). This would mean that although there would be a weight advantage due to aircraft carrying lighter fuel, this would then be off-set to some degree by the weight of a larger fuel tank. The volume of hydrogen carried would also be some 2.5 times that of the equivalent kerosene. The airframe would therefore need to be larger, and so would have a correspondingly larger drag. The combination of larger drag and lower weight would require flight at higher altitudes. Therefore, if and when hydrogen does come into use as an aviation fuel, it will likely be used in large long-haul, high-altitude aircraft. The requirement to carry a greater fuel volume may present an added difficulty for a hydrogen-fuelled Blended Wing Body aircraft (discussed below), a design otherwise well suited to long-haul flights (RCEP, 2002).

The effects of oxides of nitrogen would still be present when using hydrogen as an aviation fuel, depending on the burn temperature, and the enhanced production of water vapour would likely enhance the contrail effect. Aside from problems of hydrogen storage, transportation and the need for new infrastructure world-wide (IPCC, 1999), hydrogen's main by-product is water vapour – which acts as a greenhouse gas in the upper troposphere. Therefore, the sensitivity to cruising altitude is likely to be very large (Gauss et al., 2004). If, as appears likely, hydrogen fuelled aircraft were to cruise at higher levels, then the increased water emitted into the stratosphere would suggest larger radiative forcing (RCEP, 2002). Since a hydrogen fuelled aircraft produces more water than a kerosene fuelled aircraft, and since the water vapour produced by the latter cruising at 17 - 20 km gives a radiative forcing some 5 times that of a lower flying subsonic aircraft, a hydrogen fuelled supersonic aircraft flying at stratospheric levels would be expected to have a radiative forcing some 13 times larger than for a standard kerosene fuelled subsonic aircraft (RCEP, 2002).

Further research would therefore be required to ensure that any advantage gained in reducing carbon emissions, would not be exacerbated by an increase in global warming due to enhanced water vapour production. Overall, the environmental benefits of using hydrogen rather than kerosene for fuelling aircraft engines are uncertain, and therefore according to the RCEP (2002), hydrogen is likely to be discounted as an aviation fuel for many decades.

3.1.4 Other alternative fuels

Other fuels that have been investigated for the aviation industry that have subsequently been rejected include ethanol and methanol. Their very low heat content, in mass and volume terms render them useless as jet propulsion fuels. Moreover, from a safety standpoint, these alcohols have very low flash points – 12 and 18°C compared with the minimum standard allowed of 38°C (IPCC, 1999; Saynor, 2003). Nuclear powered aircraft are also not currently being considered due to safety concerns over radiation leaks and potential explosions (Saynor, 2003). Finally, bio-methane has been considered as an alternative to kerosene, but it would require similar infrastructure and aircraft design changes to hydrogen, as well as continuing to produce a certain amount of carbon emissions.

3.1.5 Summary

To summarise, although bio-diesel and bio-kerosene could be used in conventional airframe designs and engines, further research is required to make bio-diesel of practical use in cold conditions, and bio-kerosene has large land-use implications. However, bio-kerosene seems to be the most viable option in the medium term. Hydrogen on the other hand is deemed to require too many large-scale changes within the industry in terms of infrastructure and airframe design. It is unlikely that hydrogen will be used to fuel planes therefore for the foreseeable future. Thus, kerosene-type fuels are currently considered to be the only viable option for aircraft within the next 30 years, with some analysts suggesting they will still be in widespread use in 2050 (IPCC, 1999).

When the RCEP conducted a study of the different opportunities for the aviation industry in minimising its impact on climate, they concluded that many of the technically feasible options would likely be used in surface transport in preference to aviation due to cost and easy of implementation (RCEP, 2002). If however, the aviation industry were to use biofuels to reduce the climate change impact of the industry, it is likely that making such fuels unavailable to other modes of transports would have less of a climate impact than allowing the industry to continue to use kerosene. For example, there are a number of options for road transport in terms of hydrogen fuel cells and electricity; whereas it may be the case that bio-kerosene is the only alternative option for the aviation industry. In which case, it would seem unwise not to fully investigate this possibility with continued research.

One general final comment is that many of the alternative fuels mentioned are based on conventional jet engines, whereas alternative engine types, such as the turbo-prop engine, might be able to tolerate a wider range of fuels.

3.2 Airframe and engine design

The design of aircraft can have a big impact on the amount of drag produced and hence on its fuel burn. Novel and innovative aircraft designs have been investigated in the past, for example the blended wing-body (BWB) aircraft and the wing-in-ground effect vehicles (WIGS). However, the latest aircraft being designed and built by Boeing and Airbus, the two largest aircraft manufacturers, continue to use standard airframe designs. Indeed the RCEP (2002) state that aircraft designs up to 2030 are thought likely to be based around conventional airframe configurations, but integrating best practice technology.

3.2.1 Blended wing-body aircraft

In its assessment of the potential for reducing aircraft emissions, the RCEP took special account of a design concept that has considerable potential for a civil airliner, namely the blended wing-body, also known as the ‘Flying Wing’ (RCEP, 2002). This design has a long history, with precedents in the German Horten aircraft AW-52 and the Northrop YB-49 (Cranfield College of Aeronautics, 1999). The BWB has the body partly or wholly contained within the wing, so that the interior of the wing in the central part of the aircraft becomes a wide passenger cabin (see www.ccoa.aero/themes/airborne/bwb/default.asp for more detail). The Commission has declared itself convinced that the BWB could, as its proponents claim, be significantly lighter and experience very much lower drag than the conventional swept wing-fuselage airframe design. Its fuel usage would therefore be reduced, perhaps by as much as 30%, further reducing aircraft take-off weight. Because of the lower weight and drag, this type of aircraft would have a lower cruise altitude and an extended optimal range (RCEP, 2002).

The Commission regards the BWB concept as a development to be pursued in place of supersonic or near-sonic aircraft, and the concept has been positively explored in the UK by the aviation industry's Greener by Design Steering Group and developed further at Cranfield College of Aeronautics. Other NASA and industry studies suggest that a large commercial BWB aircraft could be developed to carry 800 or more passengers, although studies have also focused on vehicles in the 450-passenger class (NASA, 2002). It is thought that a BWB airliner cruising at high subsonic speeds on flights of up to 7,000 nautical miles would have a wingspan slightly wider than a Boeing 747 and could thus operate from existing airport terminals.

Nevertheless, given the long service lives of aircraft, it would be many decades before BWB aircraft were able to approach their maximum contribution to air travel (RCEP, 2002). It is also likely that the BWB concept will be applicable only to relatively large aircraft, as the embedded passenger cabin must be tall enough to enable passengers to stand up, so implying the need for large wings. The BWB is therefore unlikely to mitigate the impacts of relatively short-distance flights. Moreover, while the Greener by Design team have concluded that a BWB aircraft 50 years hence will likely have only 10% of the greenhouse effect of contemporary high altitude, long range aircraft, the RCEP consider this optimistic and observe that it assumes complete technological and commercial success, the BWB design completely replacing rather than adding to existing aircraft, and reductions in oxides of nitrogen emissions at the high end of the range foreseen by the International Coordinating Council of Aerospace Industries Associations (ICCAIA). These improvements could also only apply to long-haul flights (RCEP, 2002).

RCEP conclude that BWB aircraft could not represent a significant proportion of aircraft movements for many decades, and so would make no significant difference to the total aviation impacts for at least the first half of this century. Two thirds of all the aircraft that will be flying in 2030 are already in use (RCEP, 2002).

3.2.2 Airships

An alternative approach to the problem of reducing the climate impact of aviation is to look at entirely different methods of air transportation. One such suggested form is the airship. Modern airship designs use helium as a much safer alternative to hydrogen, which was used historically in the zeppelin. Helium is heavier and more expensive to produce than hydrogen however and additional lifting power is required on take-off, as 10% lift is lost relative to a hydrogen filled airship.

According to a recent review, (Windischbauer and Richardson, 2005), tasks such as surveillance, airborne early warning (replacing Airborne Warning and Control System aircraft (AWACS)) and long tourist trips are better suited to airships than aeroplanes and helicopters. Small airships, such as the Zeppelin NT, are currently in operation in this capacity, although do not operate economically. On the other hand, larger volume craft are likely to be profitable (Anderson and Wood, 2001).

In relation to the feasibility of airship freighters, despite causing 80-90% less radiative forcing that a conventional jet aircraft, one study concluded that their use was 'un-promising' due primarily to manoeuvrability difficulties in wind during the loading and unloading stages (Anderson and Wood, 2001). Offloading can occur in two ways:

1. The airship hovers where lateral movement (known as drift variation) is less than 1-2% of the vehicle length. Achieving this low level of drift variation is very difficult with such a large surface area against which wind and thermal forces act.
2. The airship descends and is moored to a specially built platform on land or water, although there is still the danger of capsizing in strong side winds

Recently an airship known as the German Cargolifter was designed with the intention of hauling up to 160 tonnes for distances of as far as 10 000 km, but the project failed due to bad financial and engineering management, with large losses despite building one of the world's largest hangars for the construction work, (Windischbauer and Richardson, 2005).

One of the most promising recent designs for a cargo lifter was the Skycat by Airship Technologies Group (UK) (Windischbauer and Richardson, 2005) but again this company has become insolvent as of July 2005 – another set back for the airship's future and illustrating the economic difficulties of making the technology a reality. To date, no successful large cargo lifter has been built, even though reputable firms such as Lockheed have planned projects.

3.2.3 Wing-in-ground effect vehicles (WIGs)

Aerodynamic drag on aircraft can be divided into two categories – that caused by the vortices around the wings (induced drag) and that due to the surface friction. As the distance between the ground and the wing decreases to a length less than an aircraft's wing-span, the ratio of lift to drag increases – this is known as 'ground effect'. For smaller aircraft the increase in surface friction drag due to the denser air at lower altitudes is of roughly equal magnitude to the decrease in induced drag and so any fuel benefit is lost. For large vehicles however, such as the proposed Boeing Pelican a much larger payload can be transported for a given range than for flight at conventional altitudes, or inversely, a given payload can be transported further with equivalent fuel.

The proposed Pelican aircraft would have a wing-span of 150m, will fly as low as 6m above sea level and carry a load of 750 tonnes of cargo for 18 500 km when in 'ground effect' above the sea. At more standard altitude levels, this range for the same fuel burn would be reduced to 12 000km. Whether such a large, heavy aircraft could operate from conventional runways is not certain however. Furthermore, its maximum speed would be lower at low altitude due to air density; therefore the aircraft would take longer to reach their destinations. This might be more appealing for the aviation freight industry than for its passenger industry. There could be a problem with the certification of trans-oceanic flight at low altitude as it would not fit into any current regulation. From the noise point of view, the Pelican has a significant disadvantage over conventional aircraft. Its proposed ~70 separate undercarriages would create much more noise on take-off and landing than its conventional equivalent.

3.2.4 Engine technology

Regarding technological trends, IPCC (1999) state that the most fuel-efficient engines for today's aircraft are high bypass, high-pressure ratio gas turbine engines, for which "no known alternatives are in sight". These engines have high combustion pressures and temperatures and although these features are consistent with fuel efficiency, they increase oxides of nitrogen (NO_x) formation rates – especially at high power take-off and at altitude cruise conditions.

3.3 Management developments

The aviation industry has always had a strong drive towards improving fuel efficiency as fuel costs are a high proportion of the industry's overall costs – particularly for the low-cost genre of airlines. However, as mentioned in the previous section, current aircraft use the same engines and airframe design that have been used since the 1970s. For this reason, although the technology has improved year-on-year, such designs are considered to be mature in terms of their technology, and therefore see only small incremental improvements in fuel efficiency, typically around 1-2% per year for a new aircraft. The aviation industry recognises this fact, and consequently their drive towards improving fuel efficiency in addition encompasses many managerial aspects, as will be discussed in this section.

3.3.1 Load factors

Increasing the load factor of an aircraft will reduce the amount of fuel spent per passenger, and reduce the need for as many planes to fly, if the same amount of demand is being accommodated for. Consequently, airlines are always looking at ways to push up their load-factors, although some airframe manufacturers on the other hand are less concerned with this aspect of improving fuel efficiency. However, if their customers consider it to be a priority, this might persuade them otherwise. Scheduled airlines struggle more than charter airlines to increase their load-factors, but putting more effort and research into generating sophisticated ticketing technology, differing pricing bands and demand-focussed time-tabling may all lead to load-factor improvements.

3.3.2 Air traffic management

Aircraft burn a substantial proportion of their fuel during take-off and landing, which is why an indirect flight from Manchester to London, London to Madrid, has a much larger environmental footprint than a direct flight between Manchester and Madrid. Therefore an increase in point-to-point flying rather than the commonly used hub-to-hub flights could reduce fuel consumption. Furthermore, to date aircraft have had to fly along a fixed route network when journeying from start to destination airports. This route network is an historic part of the infrastructure, resulting from the days when following a set of ground beacons was the only reliable source of navigation for aircraft. However, with the advent of global positioning satellites (GPS), and modern flight management systems on-board airliners, it is now possible to derive a set of way points which are not necessarily linked to physical locations on the ground. These new technologies enable the introduction of new concepts of operation, such as 'direct routing' whereby the aircraft determines an optimal flight path from the start to the destination airports without reference to fixed points on the ground (AD Little, 2000). Such improvements could translate directly into reductions in fuel consumption and hence a reduced global environmental impact. However, it should be borne in mind that there is also likely to be a trade-off between point-to-point flying and increasing load-factors, as it is likely that a plane that passes through a hub, will be doing so to further fill up the aircraft. This trade-off has not been explored within this work.

Air traffic operations procedures such as alternative approach and departure procedures, for example the Advanced Continuous Descent Approaches (ACDA) also offer improved fuel consumption, reduced emissions and reduced overall approach time (AD Little, 2000). Fuel savings can also be achieved through the operational optimisation of aircraft operations. These include reducing the operational weight of the aircraft, improved taxiing and optimising the aircraft speed. Whilst economic pressures on the industry have dictated that many of these factors have already been optimised by operators, the IPCC (IPCC, 1999) estimate that further optimisation of such measures can result in fuel savings of between 2-6% per trip.

3.4 Fuel efficiency and targets

The aviation industry has itself set research goals for improving fuel efficiency as laid out by the Advisory Council for Aeronautical Research in Europe (ACARE). The targets relevant to climate change are as follows:

1) To reduce fuel consumption and CO_2 emissions by 50%
2) To reduce perceived external noise by 50%
3) To reduce oxides of nitrogen by 80%

4) To make substantial progress in reducing the environmental impact of the manufacture, maintenance and disposal of aircraft and related products.

At first site, targets 2) and 3) appear to be irrelevant for climate change. However, reducing the noise impact of an aircraft will normally require some additional equipment to be added to the engine. Such additionally weight will necessarily translate into an increase in the fuel consumption. There are similar trade-offs to be made to reduce NO_x emissions, hence both targets are indirectly related to the climate change issue.

In relation to the ACARE targets laid out above, the UK's aviation industry has come together to produce a document entitled, 'A strategy towards sustainable development of UK aviation', otherwise known as Sustainable Aviation (Aviation, 2005). Within this document they review these ACARE targets and conclude that the first three ACARE goals could be interpreted as applying to aircraft entering service in 2020, using then current operating procedures, relative to new aircraft entering service using current operating procedures in 2000. Progress towards these targets would include contributions from operational improvements, including those in air traffic management. Therefore, the targets that have been adopted by the UK's aviation industry are laid out in Commitment 10 within the Sustainable Aviation document and are as follows:

1) Improve fuel efficiency by 50% per seat kilometre including up to 10% from air traffic management system efficiencies.
2) Reduce NO_x emissions by 80%
3) By 2020 based on new aircraft of 2020 relative to equivalent new aircraft in 2000

Consequently, each year, a new plane would be 2% more efficient than a new plane in the previous year. Historically there have been significant improvements in fuel efficiency – 70% in the past 40 years through improvements in airframe design, engine technology and rising load factors. More than half of this has come from advances in engine technology (IPCC, 1999). Such improvements give an annual compound fuel efficiency gain of 1.14% in terms of seat-km per kg of fuel consumed. Continued improvements are expected to continue, with airframe improvements likely to play a larger role through improvements in aerodynamic efficiency, new materials and advance in control and handling systems. New, larger aircraft with, for example, a blended-wing body or double-deck cabin offer prospects of further benefits by relaxing some of the design constraints attached to today's large conventional aircraft. But, with the very long total lifetimes of today's aircraft (up to 40 years), replacement rates are low, and the fuel efficiency of the whole fleet is likely to improve slowly; considering that there is limited fleet renewal, and that the efficiency improvements over the previous 20 years have been around 1-2% per year, which would in turn lead to around a 1-2% improvement in efficiency per year for the total fleet. Although AD Little conclude that fuel efficiency improvements to new planes of 2% per annum could in principle be obtained until 2030, the Department for Transport (DfT) are more conservative in their central case emissions forecast (DfT, 2004).

The development of new technologies for improved aerodynamics, materials, engine efficiencies and combustors can reduce global emissions, oxides of nitrogen and noise. In addition, developments in improved air traffic management and operational procedures additionally offer global and local mitigation options. In combination, such future developments could offer fuel efficiency improvements of up to 2% per year until 2030, whilst NO_x reduction technology is forecast to deliver 80% improvements from today's landing and take-off emissions by 2030 (IPCC, 1999). Despite the fact that there are significant opportunities for reducing emissions and other environmental impacts, the RCEP (RCEP, 2002) and the results of this project conclude that their effect is likely to be outstripped by the projected increases in air transport. For emissions from the aviation industry to reduce in real terms, the proposed efficiency gains would have to outstrip growth. With passenger numbers increasing for the UK's aviation industry at 8% between 2003 and 2004 (CAA, 2004), this currently seems highly unlikely.

4. UK Government energy and aviation policy

In February 2003, the UK's Department for Trade and Industry published its Energy White Paper entitled 'Our energy future – creating a low carbon economy' (DTI, 2003). In the following December, the UK's Department for Transport published 'The Future of Air Transport' referring to aviation policy across the UK. The incompatibility and conflicts of interest of the two white papers were immediately apparent. On the one hand, the UK Government wishes to push the economy towards reducing carbon dioxide emissions by 60% by 2050, and on the other, it wishes to meet the growing demand for aviation. The question therefore, is whether or not the two goals can be met simultaneously.

4.1 UK Energy White Paper

The Energy White Paper set a target of reducing total UK carbon dioxide emissions by 60% from 'current' levels by 2050 (DTI, 2003). The White paper essentially accepted the analysis of the RCEP in their 22nd report *Energy - The Changing Climate* (RCEP, 2000).

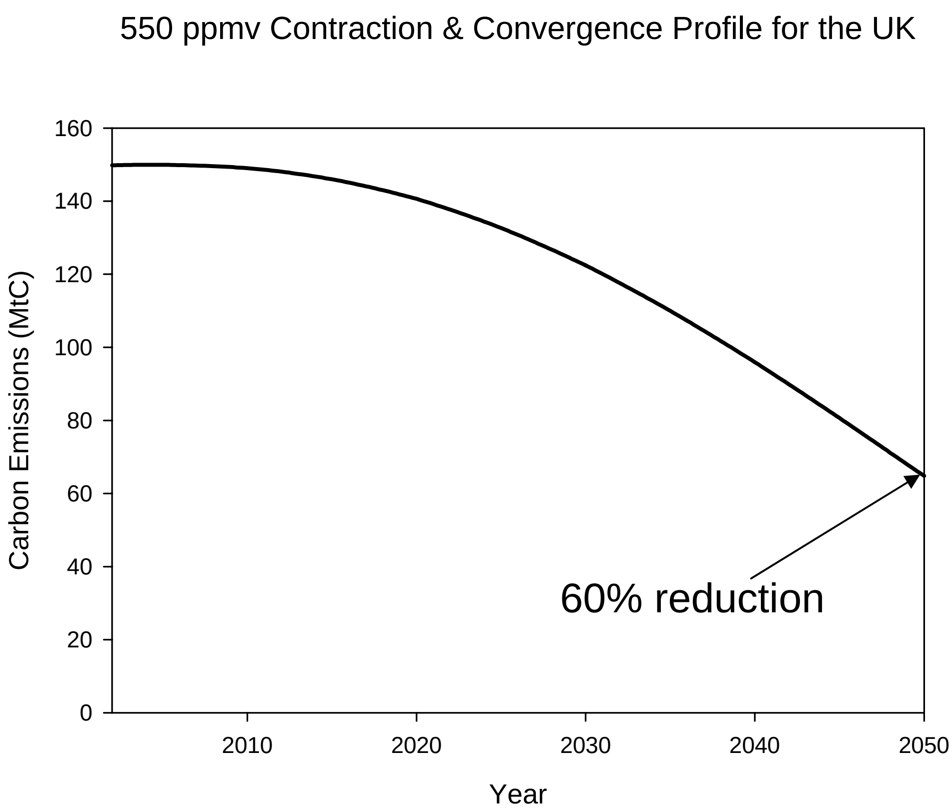

Figure 4: Contraction and convergence profile for the UK, demonstrating the origin of the 60% target.

They argued that a 'contraction and convergence' policy is required for international control of carbon dioxide emissions, a consequence of which is a requirement for a 60-90% reduction in such emissions by industrialised countries by 2050, figure 4. The principal objective of the RCEP (and by association the end point) is to avoid "dangerous climate change" by ensuring the global mean temperature increase does not exceed 2°C. Based on the best scientific evidence available at that time, this was linked with an atmospheric concentration of carbon dioxide of 550ppmv. This is understood by the UK Government and RCEP as being consistent with the goal of the Framework Convention on Climate Change (UNFCCC, 1992).

When looking further at the detail of the end point, it can be seen that this target is for domestic emissions only, and excludes international aviation and shipping emissions. However, as this target is based on a global carbon dioxide concentration target, omitting certain sectors is not an option, if the ultimate goal is to ensure that the UK plays its part in reducing the possibility of dangerous climate change.

4.2 UK Aviation White Paper

The Aviation White Paper was written to address the pressures caused by the increasing demand to travel by air, whilst at the same time meeting commitments to protect the environment (DfT, 2003b). The paper states that the UK's economy depends on air travel, with many businesses, in both manufacturing and service industries relying heavily on this mode of transport. Furthermore, visitors are said to be crucial to UK tourism, airfreight has doubled in the last 10 years and 200,000 people are employed in the aviation industry, with three times as many jobs supported by it indirectly. According to the UK Government, all of the above put pressure on airports, some of which are at, or fast approaching, capacity. Therefore, the UK Government states that the white paper sets out a measured and balanced approach that provides a strategic framework for the development of air travel over the next 30 years.

The programme of airport expansion proposed in the Aviation White Paper has stimulated considerable and ongoing debate on the appropriate scale of the aviation industry (DfT, 2003b). According to the paper, "all the evidence suggests that the growth in popularity and importance of air travel is set to continue over the next 30 years".

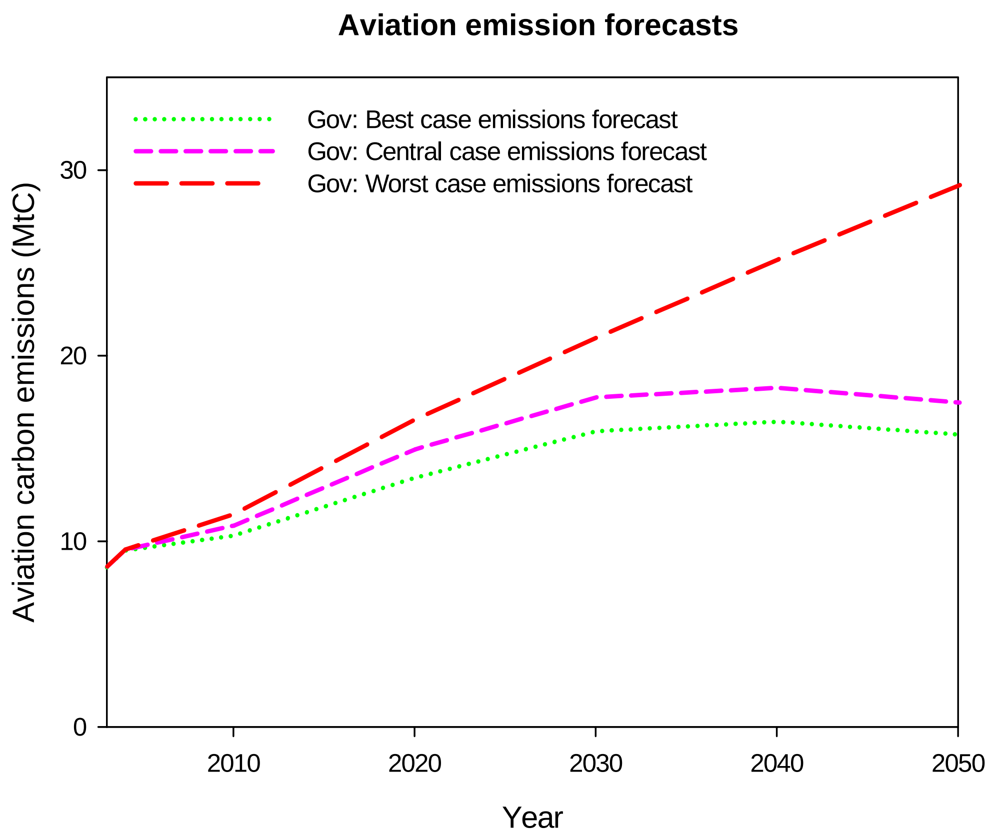

Figure 5: UK Government aviation emission forecasts from documentation supporting the Aviation White Paper (DfT, 2004).

In 2003, some 200 million passengers passed through UK airports, a figure that is predicted to rise to between 400 and 600 million by 2030 (DfT, 2003b), if sufficient capacity is provided. This implies an annual rate of increase of between 2.6% and 4.2%. Implications of such high growth for carbon dioxide emissions and climate change are far reaching. If it is assumed that the underlying structure of the aviation industry remains unchanged (i.e. routes, load factors, air-traffic management, fleet and engine efficiency) then an increase in passenger numbers would result in a proportional increase in carbon emissions. However, reductions in the amount of carbon emitted per passenger-km are likely to arise from a combination of load factor improvement, aircraft design, aircraft size, air transport management and engine efficiency. The IPCC Special Report on aviation (1999) estimates that a combination of these improvements up to 2050 will be equivalent to a 1.2% increase in seat kilometres travelled per kg fuel consumed per year. This value is a mean of the efficiency improvements estimated by the IPCC in their seven scenarios. A slightly lower rate, of 1% per year, has been suggested and used by the DfT in the Aviation White Paper. However, even a 1.2% per year fuel efficiency improvement still leaves a 1.4% to 3% increase in emissions from the aviation industry each year. Given the long lifetime of new aircraft – in the region of 30 years – the Government's current "predict and provide" approach to aviation leaves the UK wedded to a future of increasing emissions from the sector.

To illustrate the range of carbon emissions forecast by the DfT, figure 5 plots their 'worst', 'central' and 'best' emissions cases, taken from documentation produced to support the Aviation White Paper (DfT, 2004). The 'worst case' forecast assumes limited fuel efficiency improvements, limited fleet renewal, and no economic instruments and are based on the 'high capacity' case developed within the Economic Instruments paper (DfT, 2003a), but with three, rather than two, additional runways built in the South East of England, as well as, so-called, unconstrained capacity in the regions.

The 'central case' figures are again based on the 'high capacity' data, but incorporating fuel efficiency improvements envisaged by the IPCC (IPCC, 1999) and by the Advisory Council for Aeronautics Research in Europe (ACARE)[7]. Finally, the 'best case' estimates use economic instruments to produce an additional 10% fuel efficiency saving from 2020 onwards, with half of that in 2010. Figure 5 implies that apart for the 'worst' case, emissions increases due to growth within the aviation industry will be off-set by efficiency improvements from 2030 onwards. In other words, from 2030, growth has either reduced to around 1% per year, to match efficiency improvements, or efficiency gains have significantly increased to match growth. Such a picture seems unlikely as growth within the aviation industry has consistently been much higher than the UK's GDP growth, and therefore these emission forecasts require further analysis. Furthermore, the DfT's forecasts need to be considered in relation to contraction and convergence targets and profiles. Such analysis will be carried out in section 6.2.1.1.

The Aviation White Paper suggests, by way of its mid-level forecast, that growth in the UK – a country with a relatively mature aviation industry – will average 3.3% per year between today and 2030. This figure is based on a growth of around 3.8% per year in terms of passenger numbers until 2020, then a further growth of 1.8% per year from 2020 to 2030. According to the Aviation White Paper, these growth figures are based on the assumption that there will be continued growth within the short-haul market, a recovery following the events of 11 September of the long-haul market and cheaper airfares due to enhanced competition which will be enough to offset any effect of an environmental charge. It is unclear therefore, why this growth figure should reduce between 2020 and 2030. DfT's high-level forecast shows average growth of 4% per year up to 2030 – 4.5% between 2000 and 2020, and around 2.7% from 2020 to 2030. Historically, growth in passenger numbers at UK airports has been around 5.8% from 1973 to 2003, (CAA, 2004) substantially higher than DfT's future projections. Moreover, the Eurostat dataset (Layos, 2005) suggests that the current rate of growth in the UK is actually 6.4%, based on the trend between 1993 and 2001 (eliminating the short-term effects following the events of 11 September), again, significantly larger than the 3-4% assumption used in the white paper.

[7] ACARE assume 50% fuel efficiency improvement between 2000 and 2050. To incorporate this, 15% is assumed to be between 2000 and 2030, with a further 25% occurring between 2030 and 2050. The remaining 10% is already factored into the original DfT figures and arise from assumed improvement in operational measures in aviation.

5. Method

The following section discusses this project's methods and processes, covering a number of different aspects. Firstly, a policy review of the option chosen and a technical assessment of the tool to be used for experimentation. The second aspect of the method covers experimental design and execution, and the final aspect, the stakeholder interview technique employed.

5.1 Climate policy review and assessment

Contraction and Convergence was chosen as the post-Kyoto policy to be employed within this project following a decision by the UK Government to adopt the 60% target as based on the RCEP's recommendation. As mentioned previously, this target is itself based on a Contraction and Convergence policy. However, to understand this policy option in the context of the others available, a literature review was carried out prior to the commencement of the project. The results of this review essentially form section 1 of this report.

5.2 *CCOptions* model

Since 1996, the GCI has encouraged awareness of contraction and convergence as a practical interpretation of their philosophical principle that "every adult on the planet has an equal right to emit greenhouse gases". Contraction and convergence is an international framework for assuming an equitable contribution to the arrest of global greenhouse gas 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, such a mechanism requires all nations to impose targets from the outset (Cameron, 2003).

In light of the growing support for the GCI's emission reduction regime, the GCI have produced a simple spreadsheet model – *CCOptions* – to allow policymakers and researchers to investigate the impact of varying the contraction and convergence years, as well as the target carbon dioxide stabilisation levels.

5.2.1 Model description

Many climate models are complex, multi-dimensional programmes that represent the fluid dynamics, thermodynamics, chemistry and radiative effects within and between the atmosphere, oceans and biosphere. In contrast, *CCOptions* attempts neither to model the atmosphere, nor the carbon-cycle. Instead, it uses the outputs and data from the UK's Hadley Centre general circulation model (GCM) and IPCC reports as a scientific basis for determining global and national emissions trajectories. The strengths of the *CCOptions* model as a policy tool lie therefore in its internal simplicity and the direct correlation between its clear policy-relevant outputs.

The *CCOptions* model distributes the global carbon budget between nations, depending on an atmospheric carbon dioxide concentration target and individual nations' populations, to reveal national carbon emission reduction targets for each year up until 2200. By keeping the model simple, policymakers can readily interpret its results, using them to set yearly targets for their own nation's carbon emissions.

5.2.1.1 Input data

The *CCOptions* model comprises a set of Excel worksheets and accompanying documentation. The main worksheet contains details of a proposed contraction and convergence scenario, as well as graphs and data representing the key results. Supplementary worksheets contain input data and the results for individual nations. The input data for the model come in two forms; the raw historical carbon dioxide and population data for each nation, and the experimental parameters.

Fundamental to the model is a comprehensive list of all nations' respective population and carbon dioxide emissions data. Gathering such data is a non-trivial exercise due, for example, to national boundary changes, poor carbon dioxide accounting etc. The nations that are used in the latest version (Version 8.6) of *CCOptions* are those included in the Carbon Dioxide Information Analysis Centre's (CDIAC) 2003 listing. The carbon dioxide data for all nations is therefore taken from the CDIAC database (CDIAC, 2004)[8] giving values in million tonnes of carbon for each year between 1800 and 2000. 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.

The population data used in *CCOptions* is taken from the UN median population figures and forecasts (UN, 2002) and lists annual values for each nation between 1950 and 2050. The list of nations includes one labelled 'other' intended to account for a number of small islands. In relation to both the 'other emissions' and the 'other population', the GCI claim that because both values are very small, they do not significantly effect the calculations for carbon emissions within the model.

An important characterisation of the model is the stabilisation of the population figures at a chosen date 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.

5.2.1.2 Model calculations

The *CCOptions* model calculates both the global and national carbon budget for each year between 2000 and 2200 using carbon dioxide and population data alongside a series of experimental input parameters. The calculation is divided into two stages, *contraction* and *convergence*.

5.2.1.2.1 Contraction

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 the global carbon budget is itself divided into two stages.

The first calculates the budget between the start date and the contraction year – the year in which this target is attained – by solving a quartic equation of the form:

$$z_y = k + ly + my^2 + ny^3 + py^4 \ldots [1]$$

where z_y represents the carbon emissions in a particular year y (Figure 1), k, l, m, n and p are coefficients. The quartic equation is chosen as it produces a profile that adequately represents what

[8] The only nation's carbon emission which are not listed are those for Taiwan, where the data comes from the US bureau of census

the GCI consider to be a viable distribution of emissions over time[9], with global emissions initially rising, before continuously declining (contraction).

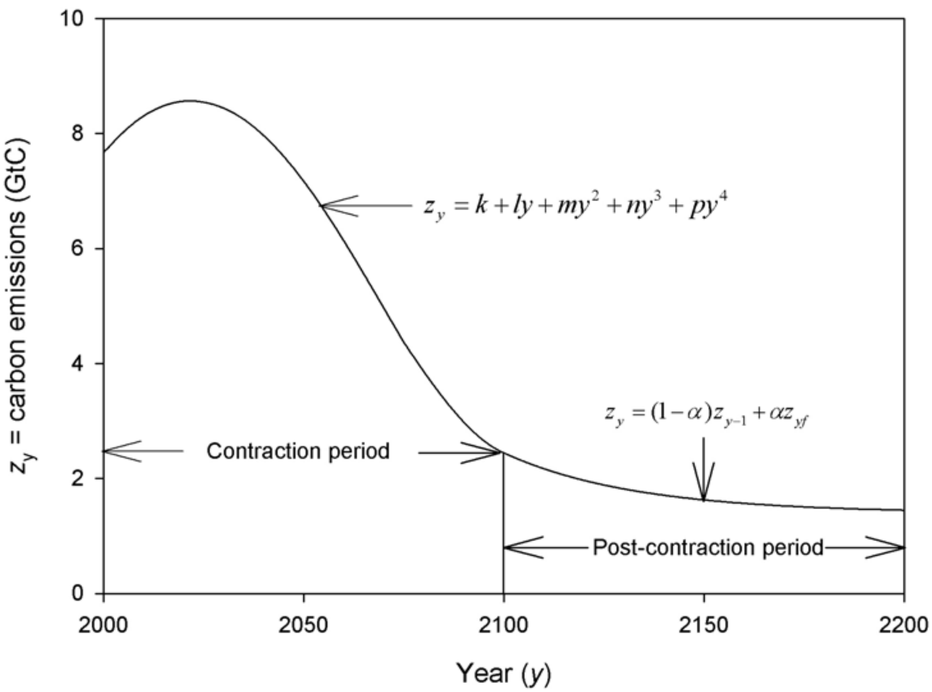

Figure 6: An example contraction profile, with a contraction year of 2100, a contraction target of 2.5Giga tonnes of carbon (GtC) and a 2200 carbon value of 1.8GtC.

The user defines a series of experimental *input parameters* within the model. These parameters are subsequently used to solve sets of simultaneous equations that provide the variables *k, l, m, n* and *p*.

The input parameters are:

- The start year (y_s)
- The value of carbon emissions in the start year (z_0)
- The emissions growth rate in the start year (r_0)
- The contraction year (y)
- The carbon emissions value in the contraction year (z_1) – contraction target.
- The emissions decline rate in the contraction year (r_1)
- The cumulative emissions between the years 1990 and 2100 (T)

The second stage of the contraction process (figure 6) continues from the contraction target, and slowly and smoothly decreases the emissions profile year on year according to the equation

$$z_{y+1} = (1-\alpha)z_y + \alpha z_{yf} \quad \ldots[2]$$

where α is a smoothing factor and z_{yf} is a second carbon target – the global carbon budget value in 2200. z_{yf} is calculated from the user-defined carbon dioxide concentration target in parts per million by volume (ppmv) and the emission-concentration relationship based on Hadley Centre and IPCC results (IPCC,1995, Hadley, 2002). Within the *CCOptions* model, the desired carbon dioxide concentration level is reached after the contraction period.

[9] A smooth and continuous profile, which only rises once, and then falls once this maximum is reached.

The model also has the facility to include an additional contraction stage – similar to that described above. This would be necessary if, for example, an initial target of 550ppmv was later revised to 450ppmv.

5.2.1.2.2 Convergence

Having calculated the annual global carbon emissions budget, the model proceeds with the convergence process. Nations converge towards equal per-capita emissions in a particular user-defined year – the convergence year *(y_c)*. From this year onwards, equal per-capita emissions are assumed to continue indefinitely with the actual value continuing a gradual decline. 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:

$$S_y = \frac{S_0(y_c - y) + P_c(y - y_0)}{y_c - y_0} \ldots [3]$$

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.

Consequently a nation's share of the world's emissions from the convergence year onwards is equal to their share of the world's population.

5.2.1.3 Output data

Key results calculated by the model are displayed in graphical format on the front page of the Excel spreadsheet including the global and per-capita emissions for a number of world regions (based on evaluating equations [1], [2] and [3] during the contraction and convergence process). The carbon dioxide concentration and global temperature profiles between the start year and 2200 are also displayed (based on equations [1], [2] and [3] and dependent on the total global emissions released during contraction and, to a lesser extent, on how they are distributed between the year 2000 and 2200).

To ensure that the carbon dioxide concentration displayed by the model matches the IPCC and Hadley Centre predictions for cumulative emissions and their respective stabilisation concentrations, *CCOptions* reproduces the relationships between cumulative emissions and carbon dioxide concentration using regression formulae. All the pre-2000 concentration data in the model are taken from the IPCC (IPCC, 1995).

5.2.1.3.1 Biogeochemical feedbacks

In 2002, The Hadley Centre produced model runs of the climatic response to increasing carbon dioxide in an atmosphere in which the principal biogeochemical feedbacks were included (Hadley, 2002). The newest version of the *CCOptions* model produces 3 carbon dioxide concentration profiles all based on the 2002 Hadley results, but each with a different level of feedbacks included:

The first profile calculates the atmospheric carbon dioxide concentration in which no carbon sinks or feedbacks are considered[10]. For this calculation, values are obtained by simply adding each year's emissions divided by 2.12GtC (equivalent to 1ppmv) to the previous carbon dioxide concentration value.

The second *CCOptions* profile is based on the Hadley Centre with sinks, but without carbon-cycle feedbacks. A regression formula of the following form is used:

$$C_y = C_{y-1} + 0.04\left[A_0\left(y - A_1\right) + A_2 z_y + A_3 C_{y-1}{}^2\right] \ldots [4]$$

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 Hadley projections.

This formula was produced using a *least squares minimisation* so as to match, as closely as possible, the concentration-emissions relationship shown in existing documentation (IPCC, 1995, Hadley, 2002).

The third *CCOptions* profile reproduces the relationship between emissions and carbon dioxide concentrations for Hadley Centre results that incorporates carbon-cycle feedbacks. This concentration profile is calculated using a similar regression formula to equation [4] and for years where the year y is 2130 or earlier, takes the following form:

$$C_y = C_{y-1} + 0.04\left[B_0 + B_1\sqrt{(y - y_0)} + B_2\left(z_{y-25} + z_y\right) + B_3\left(C_{y-1} - 270\right) + B_4(C_{y-25} - 270)^2\right] \ldots [5a]$$

beyond 2130, the equation takes the form:

$$C_y = C_{y-1} + 0.04\left[B_0 + B_1\sqrt{130} + B_2\left(z_{y-25} + z_y\right) + B_3\left(C_{y-1} - 270\right) + B_4(C_{y-25} - 270)^2\right] \ldots [5b]$$

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

The terms in the above two equations relate to the year of emissions and the quantity of emissions, as well as previous carbon dioxide concentration values and the concentration of carbon dioxide twenty-five years previous.

In addition to the emissions and atmospheric carbon dioxide concentration curves replicated by *CCOptions*, a temperature curve for both the non-feedback and feedback Hadley Centre model concentrations is also produced. This uses a regression formula designed to reproduce the carbon dioxide concentration and temperature relationships contained within the IPCC's 'best guess' 2.5 °C sensitivity data.[11] The first stage in estimating the temperature profile is to apply a time lag to the carbon dioxide concentration data. This accounts for the time it takes for carbon dioxide to be absorbed by the oceans due to their high thermal capacity. The following formula is used:

$$C_{smoothed} = \beta C_y \left(1 - \beta\right) C_{smoothed-25y} \ldots [6]$$

where:

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

The temperature is subsequently calculated for a given year and carbon dioxide concentration from the equation:

[10] In other words, an estimate of the carbon dioxide concentration if all of that gas were to remain in the atmosphere.
[11] 2.5°C climate sensitivity means that the mean global temperature will increase by 2.5°C if CO_2 concentrations double.

$$T_y = D_0 + D_1 y + D_2 C_y + D_3\sqrt{C_y} + D_4 C_{ysmoothed} + D_5\sqrt{C_{ysmoothed}} \ldots[7]$$

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

5.2.2 Assessment of *CCOptions* model

To assess the suitability of the *CCOptions* model, two versions of the model were downloaded. The first being the original version of the model as used to produce the UK Government's 60% carbon reduction target. The second being the newest version of the model which incorporated new biogeochemical results from the Hadley Centre (Hadley, 2001, Bows and Anderson, 2005). The initial stage of the analysis involved a rigorous assessment of the *CCOptions* model to identify its general strengths and weaknesses. Secondly, identical experiments for both model versions that attempted to reproduce the UK Government's 60% target using a number of different contraction dates and cumulative emissions values. In each case, the convergence year of 2050 was chosen in line with the guidance given by the RCEP, (RCEP, 2000). Within the new version of the model, experiments can be carried out that either incorporate biogeochemical feedback results from the Hadley Centre, or omit such results. The third part of the analysis therefore looked in more detail at the latest model version to see how well it reproduced standard experiments for stabilising carbon dioxide concentrations at 450, 550 and 750ppmv. It also compared these results with those from the earlier version of the model.

Based on the assessment of the *CCOptions* model further described in section 6.2 the decision was taken to use the older version of the model for the project experiments. This decision was essentially based on two key drivers. Firstly, although *CCOptions* adequately reproduces widely accepted Hadley Centre model relationships between carbon dioxide concentrations and cumulative carbon values for all nations between today and 2200, releasing the latest version was perhaps premature as it attempts to reproduce Hadley Centre results that incorporate biogeochemical feedbacks from the carbon-cycle whilst the magnitude of such feedbacks remains uncertain. Arguably, the latest *CCOptions* model, in attempting to capture elements of the climate change science still characterised by considerable uncertainty, jeopardises its credibility as a relatively objective policy tool. Secondly, updates to the model render it different from that used to calculate the UK Government's 60% carbon reduction target.

5.3 C&C vs aviation experiments

To assess the impact of a growing aviation industry within a nation attempting to significantly reduce its carbon emissions, a number of experiments comparing scenarios and forecasts of the carbon emissions generated by the aviation industry are carried out using the *CCOptions* model. As an initial stage, different contraction years and cumulative emission values were inputted into the model to generate a profile that most clearly stabilises at the desired carbon dioxide concentration level. When this initiation process was complete, the experimentation could begin. In all cases the convergence year of 2050[12] and contraction year of 2100 are chosen, but two different carbon dioxide stabilisation levels, 550ppmv and 450ppmv were considered.

5.3.1 C&C vs DfT aviation forecasts

The UK Government forecasts shown in figure 5 for the coming 45 years are compared with stabilising atmospheric carbon dioxide concentrations at 550ppmv – in line with the UK Government's 60% carbon reduction target, and with the lower level of 450ppmv as described in section 6. No attempt has been made to 'uplift' the carbon emissions from aviation to account for

[12] This is in line with the RCEP's recommendation as mentioned in a previous section

contrails and other gases, as there is much controversy over the scientific basis for applying such a multiplier. The forecasts were developed following an assessment of a high and low capacity case for the UK (DfT, 2003a). The high capacity case assumes new runways at Heathrow, Gatwick, Stansted, Manchester, Birmingham and Edinburgh. The low capacity case assumes no new runways. According to the DfT (DfT, 2004), in both cases the fuel efficiency improvements assumed may be underestimates. The DfT produced revised forecasts based on these estimates, which, as described previously, represent:

> '*worst case*' – assumes limited fuel efficiency improvements, limited fleet renewal, and no economic instruments and are based on the 'high capacity' case but with three, rather than two, additional runways built in the South East of England, as well as, so-called, unconstrained capacity in the regions.
> '*central case'* – based on the 'high capacity' figures, but incorporating fuel efficiency improvements envisaged by the IPCC (IPCC, 1999) and by the Advisory Council for Aeronautics Research in Europe (ACARE)[13].
> *'best case'* – based on the 'high capacity' figures but estimates use economic instruments to produce an additional 10% fuel efficiency saving from 2020 onwards, with half of that in 2010.

To examine the impact within the UK economy of the predicted growth in aviation-induced carbon dioxide, a comparison is made between contracted profiles of emissions designed to stabilise carbon dioxide concentrations at 550ppmv and 450ppmv and the DfT's latest forecasts for carbon emissions from aviation over the next 50 years. Results are described in section 6.2.1.1.

5.3.2 C&C vs UK aviation scenarios

The availability of detailed public domain data relating to the growth in carbon emissions from the aviation industry is limited, particularly for nations other than the UK. Moreover, detailed aviation emissions modelling requires access to not only a range of data, but also to aero-engine and route models. The aviation scenarios developed here therefore use a methodology that is simple, transparent and based on publicly available information. The objective is to highlight the likely scale of the problems to be faced if demand is not explicitly constrained through either a moratorium on additional airport infrastructure or further demand management measures (for example, through a fuel or emissions charge).

Given the requirement of this project to construct carbon emissions scenarios from relatively simple public domain information, three options exist. The first option is to base emission scenarios on forecasts of future air traffic movement numbers, or to extrapolate on the basis of current flight growth figures. EUROCONTROL's *Air Traffic Statistics (EUROCONTROL Air Traffic Statistics and Forecasts Service (STATFOR), Forecast of Annual Number of IFR Flights (2003-2010)* provides air traffic growth estimates up to 2010 for International Flight Rules (IFR) flights (EUROCONTROL, 2004a). [14] Although this dataset has figures for all the EU nations, it was not used for this project for the following reasons: 1) the scenarios are only up until 2010, 40 years short of this project's timeframe, and 2) the dataset makes assumptions that are not explicit regarding, for example, engine efficiency, airframe design, load factors, flight distances and different fleet mixes.

---

[13] ACARE assume 50% fuel efficiency improvement between 2000 and 2050. To incorporate this, 15% is assumed to be between 2000 and 2030, with a further 25% occurring between 2030 and 2050. The remaining 10% is already factored into the original DfT figures and arise from assumed improvement in operational measures in aviation.
[14] In December 2004, mid-way through the present research, STATFOR also produced air traffic growth estimates for 2004-25 (EUROCONTROL, 2004b).

In terms of the second option, carbon emissions data from the aviation industry for each EU nation is available from the United Nations Framework Convention on Climate Change (UNFCCC)[15]. For each nation, the data are split into civil aviation and international bunker fuels for international travel. Bunker fuel data are an approximation to each nation's international aviation emissions split 50:50 between arrival and departure. If a projected or historical growth figure for aviation fuel use in each EU nation for aircraft carbon emissions were available, then this could be applied to the UNFCCC data to project emissions up to 2050. However, the only figure widely available in terms of fuel burn growth is the 1.7% world average growth figure which appears in the IPCC (1999). Growing EU emissions and specifically the UK's emissions at this rate – which naturally includes many nations where growth is much lower than the current European average – would likely underestimate the true impact of the industry in Europe.

The third option of using passenger growth rates is used in this project as it is transparent and relates most clearly to demand and hence to policy options. Although it is aircraft that directly emit greenhouse gases, not passengers, passengers are obviously the key driver for aircraft traffic (we have not considered freight at all here, but plan to do so in future work). Furthermore, according to the DfT (DfT, 2005), both 'passengers uplifted[16]' and 'terminal passengers[17]' grew on average at 7% per year between 1993 and 2000. During which time, fuel consumption grew on average at 6% per year (DUKES, 2005). This illustrates the close relationship between passenger growth rates and fuel consumption growth rates, bearing in mind a fuel efficiency improvement of around 1% per year accounts for the difference between 7% growth for passengers and 6% for fuel. Therefore, if demand management proves necessary, then it is passengers who must be directly influenced. Having an indication of future passenger numbers and growth rates is useful in this regard, and passenger numbers are also likely to be more readily comprehensible to the wider public when considering aviation policy options. Moreover, initial use of historical passenger growth rates as a basis for constructing these emissions scenarios reveals the consequences of permitting on-going growth in demand.

Three scenarios were developed for this project based on the knowledge of passenger growth rates and fuel efficiency estimates as described in previous sections. It is important to note that use of passenger growth rates as a basis for carbon emissions growth requires the assumption that the mean length of flights remains unchanged. The characteristics of the three scenarios are summarised below:

Scenario 1 – Government in the know!
Growth:
2004-2015 – continuation of pre-2001 trend of 6.4%[18] per year
2015-2050 – reduction to 3.3% in line with DfT projections
Fuel efficiency improvements
2004-2050 - 1.2% per year in line with historical trends and future predictions

[15] unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/2761.php Tables 1.A(a) sheet 3 and Table 1.C), apart from values for Cyprus and Malta. Some data on Maltese aviation emissions can be found at unfccc.int/parties_and_observers/parties/items/2142.php
[16] Passengers flying on UK airlines
[17] Passengers passing through UK airports
[18] This figure is slightly different from the CAA value of 7% shown in figure as it includes the figure for 2001 rather than averaging over 1993 – 2000.

Scenario 2 – Market soon matures
Growth:
2004-2010 – continuation of pre-2001 trend of 6.4% per year
2010-2050 – reduction to 3% representing market maturity
Fuel efficiency improvements
2004-2050 – 1.2% per year in line with historical trends and future predictions

Scenario 3 – **Europe rules**
Growth:
2004-2010 – continuation of the current trend of 7% per year
2010-2030 – reduction to 4% per year in line with European forecasts
2030-2050 – reduction to 3% per year representing market maturity
Fuel efficiency improvements
2004-2010 - 1.7% per year in line with BA target
2010-2050 – 1.2% per year in line with historical trends and future predictions

The first scenario is essentially in line with Government forecasts, but with an update to take account of the recent growth seen both prior to 11 September, and the resurgence seen in the last couple of years. The second scenario is more conservative, suggesting a significant drop in the growth rate by 2010, indicating a major downturn in the industry.

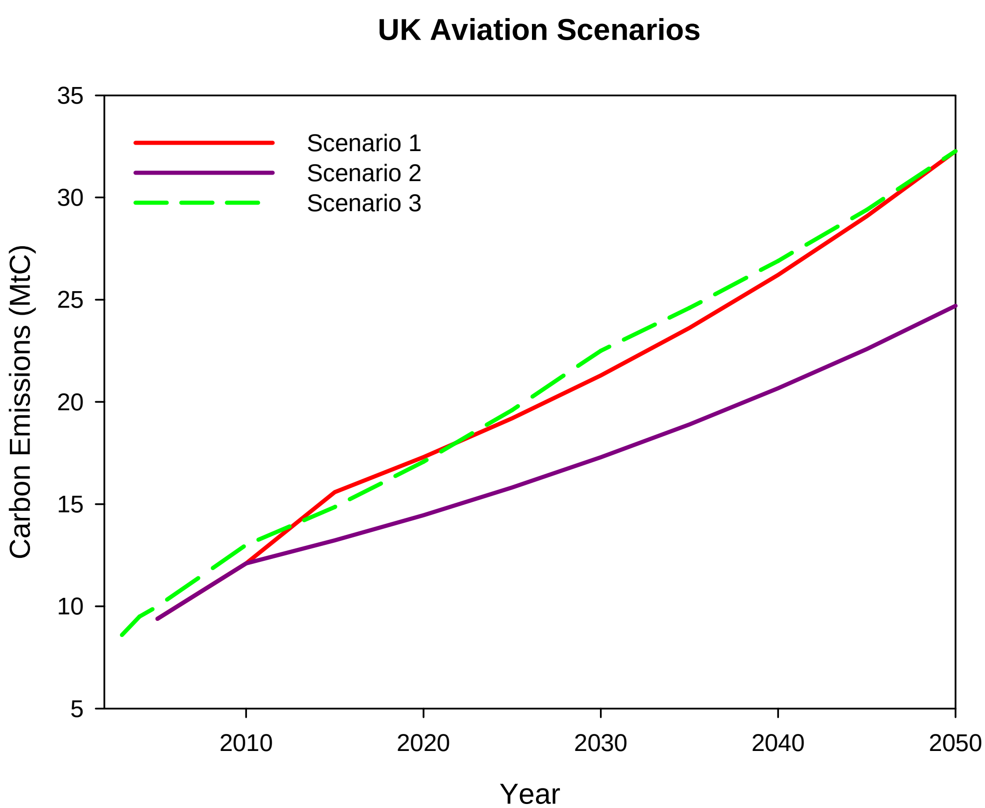

Figure 7: Three aviation scenarios for the UK's aviation industry in terms of carbon emissions between today and 2050.

The final scenario uses highly optimistic fuel efficiency improvements until 2010, suggesting that the whole fleet operating in and out of the UK has improved fuel efficiency at BA's target rates. In terms of growth, a continuation of current levels is again curtailed to European projected growth rates until 2030. Following this period, the industry is assumed to be mature. The justification for assuming the scenarios to have *conservative* growth rates in the absence of additional airport capacity constraints is that:

a) the UK has a relatively mature aviation industry, yet contemporary passenger number increases per year are still substantially higher than 3.3%: an on-going annual increase of 3.3% per year is well within the bounds of possibility;
b) 3.3% is only 0.5% above current levels of GDP annual growth in the UK, and the aviation industry has historically grown at levels well above GDP. A similar study also recently projects UK passenger numbers increasing at 3, 4 and 5% per year up until 2050 (Lim, 2004), with no explicit additional airport capacity constraint.

The impact of these growth scenarios on carbon emission from the UK's aviation industry are illustrated in figure 7.The difference between the early years of scenario 3 and the other 2 scenarios is due to this scenario being produced after the release of the latest energy consumption data for 2004 from the Digest of UK Energy Statistics (DUKES, 2005) indicating that fuel consumption has risen by 10% between 2003 and 2004. The range of emissions exhibited by the scenarios in 2030 is 17.3MtC to 22.5MtC, and at 2050 is between 24.7MtC to 32.3MtC. Scenarios 1 and 3 are therefore close to the DfT's 'worst' case scenario presented in figure 5, with scenario 2 bridging a gap between the 'worst' case and the 'central' case. In none of these scenarios do the emissions level-off. Without deliberate policy decisions for curbing the rate of air traffic and passenger growth, there appears to be no reason to assume that the industry will stop growing within the timeframe of this analysis (i.e. to 2050).

The three aviation scenarios described and illustrated above were then compared with 450ppmv and 550ppmv contraction and convergence profiles using the older version of the *CCOptions* model. Results are described in section 6.2.1.

5.4 Assessing stakeholder opinions

Following the understanding of the aviation and climate issue gleaned from the research method described in the previous sections, and the results illustrated in the following section, an investigation into aviation stakeholder opinions of the situation as it stands was carried out. The methodology of this assessment is described in the following section.

5.4.1 Stakeholder selection

A number of categories of aviation stakeholders were drawn up initially to ensure that a broad spread of relevant stakeholders could be devised. The categories were:

- Academics
- Aircraft and part manufacturers – referred to collectively as manufacturers
- Airport operators
- Airlines
- Consultants
- Government
- NGO

A list of names underneath each category was then drawn up based on the most relevant job responsibility. Where possible, individuals with responsibility for climate change issues, as opposed to other environmental specialisms were sought. Due to time pressures however, only a limited number of interviews were possible. Therefore, all efforts were made to interview at least one candidate from each category. To date, twelve interviews have been carried out.

5.4.2 Interview technique and questions

The assessment took the form of a recorded telephone interview with a set of standard open questions. No information was given to the interviewees with regard to the knowledge of the answer to a particular question by the interviewer to ensure an absence of question leading, bias or influential comments. All interviewees gave their consent to contribute.

The questions were as follows:

1. Could you describe your role within the company, and what your company's business is?
2. The UK, along with many other nations, is experiencing renewed levels of high growth within the aviation industry following a slowdown after 11th September attacks. What sort of levels of growth in annual percentage terms are you seeing *currently* for both domestic and international aviation? If you want to split this between long haul and short haul, this would be helpful. [Please state whether this is in flights, passenger numbers, passenger kms etc]
3. Do you have any idea of what an overall figure for European international aviation growth might be?
4. Do you or your company have or use forecasts for growth within the aviation industry? If so, what data do you use – is it your own, government's, provided by an outside body etc?
5. If you are aware of such figures, what are your forecasts for growth in the aviation industry, for both international and domestic traffic for the UK over the next 10, 30 and/or 50 years?
6. Do you have any similar figures for European air traffic – i.e. within and between European nations, as well as international traffic departing from or arriving in European countries?
7. What are the assumptions underlying the forecasts you use?
8. What are the current annual fuel efficiency improvements that are being seen across the entire fleet in the UK and Europe? What are you seeing in your planes/fleet (if relevant).
9. What is the current fleet turnover on average within the UK and in Europe? Your fleet, rest of fleet, long haul fleet, short haul fleet. How do you measure this?
10. How do you see the fuel efficiency of aircraft changing over the next 10, 30 and 50 years?
11. What technological or managerial advances do you see progressing through the aviation industry over the next 10, 30 and 50 years?
12. Do you think that these advances will be driven by any one particular factor – e.g. environmental noise, climate change, fuel prices, etc?
13. Are you aware of the UK Government's long term target to reduce carbon dioxide emissions? If so, what is it?
14. Are you aware that this target currently excludes international shipping and air travel? What is your view on this?
15. This target is based on trying to help the world stabilise carbon dioxide concentrations at 550ppmv to avoid dangerous climate change. If the aviation industry were also included within this target, what measures or methods do you envisage will enable the UK

Government to reach this 60% reduction (this can be for other sectors as well as the aviation sector)?

16. Currently this 60% target leaves the UK aiming to emit no more than 65MtC by 2050, but there is also talk about the target needing to be closer to 32MtC. With the high rates of growth currently being seen in the industry, this is likely to mean that the UK's aviation industry will be accounting for a greater and greater portion of this emission target. Is this likely to influence the aviation industry in any way, and if so, how?
17. Obviously carbon dioxide is not the only issue when dealing with aviation and climate change. The IPCC approximate that the true climate impact could be around 2.7 times that of the carbon dioxide alone. What is your view on this figure and how it is used?
18. How do you envisage this additional problem could be addressed by the aviation industry?

Interviewees were told that any quotes taken from the interview and used in this and other reports would be passed by them in advance of publication, and that their comments would remain anonymous.

6. Results

The results section of this report essentially mirrors the methodology section, presenting results firstly about the *CCOptions* model, followed by experimental results generated using the *CCOptions* model, and finally an assessment of the stakeholder opinions.

6.1 *CCOptions* model

The *CCOptions* model was developed as a simple policy tool and it is in relation to that function that this part of the results section discusses its particular strengths and weaknesses.

With regard to the basic set-up of the model, the use of Excel spreadsheets makes it accessible to many users. All workings and calculations are visible and modifications can be made easily thereby offering a substantial degree of user flexibility. The model exists in two forms, one calculating the carbon budget for all nations, the other grouping nations together in regions; both models take only a matter of seconds to perform their respective runs. Whilst neither version gives the user the facility to choose to output the results in a graphical format for a particular nation, national outputs can be easily extracted by those users with moderate Excel experience.

6.1.1 Input data

Despite the carbon data used in the model originating from the Carbon Dioxide Information Analysis Centre (CDIAC), a comparison of CDIAC data with that used in the *CCOptions* model shows that whilst the majority of figures between 1979 and 1995 match, values prior to 1979 are slightly different, with values for 2000 extrapolated from the 1995-1999 trend. According to the GCI, they obtained the most comprehensive data available at the time of compilation. However, manipulation of CDIAC data by the model writers was still necessary to produce the dataset used in *CCOptions* (GCI, 2004). For example, when nations split and merge, such has recently occurred in the Baltic States, CDIAC data had to be adjusted accordingly. Nevertheless, the current *CCOptions* model would benefit from being updated with the most recent set of CDIAC data.

The population data used in the model is that readily available from the UN (UN, 2002) for the years 2000 to 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 GCI approach provides as reasonable approximation to the UN’s figures. The current model forecasts population between 2000 and 2003 despite recorded data existing up to 2003. It would therefore again be appropriate to update the model to include the latest data available. Furthermore, it may be beneficial if the range of low, medium and high variant population figures were incorporated within the model to provide uncertainty estimates for the emission profiles. This would enable model users to set a target range for future years.

6.1.2 Model calculations

6.1.2.1 Contraction

The *CCOptions* model produces emissions pathways to contraction targets that are dependent on both the carbon dioxide concentration target and the cumulative carbon emissions over the contraction period. The process of generating emission pathways does, however, have some drawbacks

- If the contraction target chosen by the user is too low for a particular experiment, (e.g. an 80% contraction target in conjunction with a 450ppmv stabilisation and a cumulative emissions value of 650GtC), the emissions profile will fall towards the *contraction target*, before rising to meet the *carbon dioxide concentration target* and then falling again under the post-contraction regime (Equation [2]). The cause of this undulating profile is the separate treatment of the pre- and post-contraction year emissions; the contraction target emission level is set by the user, whereas the value immediately following this is based on the target carbon dioxide concentration level (Equation [3]). The model cannot allow such an undulating profile, as once the contraction target is reached, the model is designed to produce continually reducing global carbon emissions, in accordance with the Hadley Centre profiles (Hadley, 2002).
- There is an upper limit for the contraction target for each individual experiment. If the target chosen is considered to be unrealistically high, then the emissions profile will dip prior to the contraction date to ensure that value of cumulative carbon emissions (equivalent to the area under the curve) is not exceeded. In this case, the profile is then forced to rise to meet the contraction target. The model indicates when such a discontinuity occurs.
- The contraction year must lie between 2002 and 2100.
- The user requires some knowledge of the cumulative emissions over the next century.

During the post-contraction period, the contraction equation and therefore the emissions profile are kept as simple as possible to reduce the need for any long-term and hence inevitably highly suspect assumptions about the profile of the post-contraction emissions. The choice of a relatively simple equation (Equation [2]) ensures that the target carbon dioxide concentration level is reached through a slow, continuous emissions decline. A consequence of this simplicity is that the smoothing parameter used must take values between, but not including, 0 and 1. The actual value of the parameter, provided between 0 and 1, has very little impact on the actual form of the concentration profile.

6.1.2.2 Convergence

In earlier versions of the model, there was an option for the user to choose between either the linear formula (Equation [3]) or an exponential curve for calculating the convergence profile. However, the GCI decided that providing a choice of equations, and hence convergence profiles, created unnecessary argument over the rate of convergence that nations could achieve. In reality, convergence is likely to take a variety of different paths, and it is doubtful that the path towards convergence will be steady for each nation. However, given the appeal of the *CCOptions* model is its simplicity, the GCI considered providing a linear convergence profile sufficient for those policymakers likely to use it. Moreover, the flexibility of the model provides the competent Excel user with an opportunity to modify the convergence equation, if they so wish, to devise alternative convergence trajectories.

Whilst, the model literature recommends that the convergence year should lie between 2001 and 2100, the model itself gives a choice of convergence year up to 2200. The population cut-off year, the year after which the population forecast remains constant, can be set at any year between 2000 and 2050. However, the population cut-off year should 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.

Clearly, it is impossible to specify emissions per capita accurately up until 2050 as population numbers over the next 45 years may vary in ways not predicted in current forecasts. Therefore, it is essential that population data is periodically updated so that new and improved targets can be set.

Furthermore, any carbon reduction target set today will need to be re-examined as new and improved data is published.

6.1.3 Output data

Experiments carried out with the *CCOptions* model are limited to carbon dioxide stabilisation levels of between 350ppmv and 750ppmv. Such levels are widely discussed in relation to avoiding 'dangerous climate change'. Until recently, the scientific consensus has regarded 'dangerous climate change' to correspond to a global mean surface temperature increase of 2°C and a carbon dioxide stabilisation level of 550ppmv. However, scientific studies are increasingly suggesting that 450ppmv is a closer correlation with a 2°C rise (Cox, 2005), requiring nations to make even larger cuts in their carbon emissions than was previously thought necessary

The most important variable used in experiments conducted with the *CCOptions* model is the cumulative emissions value, which is the sum of the carbon released in the 1990s, the cumulative carbon emissions released during the contraction period and the cumulative emissions between the contraction date and 2100. As the carbon dioxide stabilisation level is highly dependent on the cumulative amount of carbon emitted up to stabilisation, and only remotely related to the actual emissions path followed en route (IPCC, 1995), the choice of the contraction emissions target within *CCOptions* is not particularly important.

Given the importance, within *CCOptions*, of choosing an appropriate cumulative emissions value to achieve a chosen stabilisation concentration level, the model's accompanying literature provides substantial guidance. In the original version of the model, a range of cumulative emissions values for 350, 450, 550, 650 and 750ppmv, taken directly from data published by the IPCC (1995), were provided. For example, the cumulative emission value for 550ppmv was between 870GtC and 990GtC. The range, as opposed to a single value, arising from the different emissions scenarios used within the GCMs. This range is subject to a further 15% increase or decrease depending on the specific carbon-cycle model used in conjunction with the GCM (see below).

6.1.3.1 Including carbon-cycle feedbacks

The atmospheric concentration of carbon dioxide depends not only on the quantity of carbon dioxide emitted into the atmosphere (natural and anthropogenic), but also on changes in land use and the strength of carbon sinks within the ocean and biosphere. As the atmospheric concentration of carbon dioxide increases (at least within reasonable bounds), so there is a net increase in the take-up of carbon dioxide from the atmosphere by vegetation (carbon fertilisation). Changes in temperature and rainfall induced by increased carbon dioxide affect the absorptive capacity of natural sinks and climate change alters the geographical distribution of vegetation and hence its ability to store carbon dioxide (Hadley, 2002). 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 (Cox, 2005; Cramer et al., 2001). For example, dynamic global vegetation models used to predict the carbon storage potential of soil and vegetation produce results that differ considerably from model to model, (Cox, 2005, Freidlingstein, 2005). However, all models agree that a global mean temperature increase will reduce the biosphere's ability to store human-induced carbon emissions.

In an attempt to incorporate carbon-cycle feedbacks, the Hadley Centre used a simple climate carbon-cycle model that included feedbacks from vegetation, soils and the ocean. This model reproduced the results of the Hadley Centre coupled climate-carbon cycle model and was used to make new estimates of the emissions required to stabilise carbon dioxide concentrations at particular levels. Their results show that the amount of cumulative carbon dioxide emitted into the atmosphere that is likely to lead to stabilisation at 550ppmv could be nearer to 680GtC, (Jones et al. 2005b; Hadley, 2002) than the range of 870GtC to 990GtC discussed above. They also show that more carbon than was previously calculated can be released into the atmosphere to meet certain stabilisation levels if no feedbacks are included. However, research comparing different models carrying out fully coupled carbon-climate simulations indicates that a similar version of this Hadley Centre model generates larger carbon-cycle feedbacks than the others with which it is compared (Zeng et al., 2004, Friedlingstein et al, 2005).

Despite the absence of a clear consensus in relation to the scale of the carbon-cycle feedbacks, the *CCOptions* model has been updated to include two calculations of the carbon dioxide concentration profiles (based on some of the Hadley carbon-cycle work), one with and one without carbon-cycle feedbacks, (Equations [4] and [5]). In addition, within the new *CCOptions* model, emphasis has been taken away from recommending a particular cumulative carbon value, and redirected towards the two concentration curves. This allows the user to determine suitable cumulative carbon values based on their stabilisation level and whether or not they wish to include feedbacks. The resulting difference between the 110-year cumulative emissions value required for the feedback and non-feedback concentration profiles is significant. For example, a target stabilisation concentration of 550ppmv requires the cumulative emission value to be 640GtC when allowing for carbon-cycle feedbacks, but nearer to 1000GtC for the non-feedback concentration curve. Evidently, this has a dramatic effect on any calculations carried out using *CCOptions* regarding the percentage cuts that individual nations have to make to reach chosen stabilisation levels.

A suggested improvement to *CCOptions* with regard to the cumulative emissions value is to enable it to provide a cumulative carbon emissions value for the user based on the stabilisation level required. This may ease the iteration process in finding the desired cumulative carbon emissions value for a particular contraction and convergence date. However, this may be limited by the fact that cumulative emissions values generated by climate models are not available for the full range of contraction and convergence dates that the model can produce.

One obvious limitation to the *CCOptions* model is the inclusion of a particular Hadley Centre model output, thereby ignoring other climate model outputs. Although a substantial body of research does predict that future climate change will cause the land carbon sink to cease at some point in the future and become a source (Cox et al., 2000; Friedlingstein, 2001; Jones, 2003; Zeng et al., 2004; White et al, 1999; Lenton, 2000, Cox 2005) there exists at least one study that suggests a persistent carbon sink (Cramer et al, 2001). However, all models show a weakening of the carbon sink compared with the 'no climate change' case. However, the issue of whether or not the sink becomes a source remains uncertain (Berthelot et al, 2005).

If dynamic global vegetation models are embedded within global climate models, uncertainties associated with the effect of carbon dioxide fertilization on photosynthesis, the temperature sensitivities of photosynthesis and plant and soil respiration feedback mechanisms become added complications, (Lenton and Huntingford, 2003). Nevertheless, there is a clear consensus emerging that calculations for carbon dioxide stabilisation levels should be revised to include the dynamic evolution of vegetation and its influence on global carbon and water cycles (Cramer et al, 2001).

Prior to the contraction date, the *CCOptions* equations relate a parabolic emissions profile with the atmospheric concentration curve. Post-contraction, the emissions curve is much simpler (almost linear) and so *CCOptions* uses a simpler equation to relate emissions to concentration. Within the latest *CCOptions* model, carbon-cycle feedback results are also taken into account during this post-contraction period. Equation [2] is used to calculate the carbon emissions from the contraction date onwards, and to do so, the target carbon dioxide concentration value is converted into an equivalent emission value for each year – each value being a fraction of this 2200 figure. Until the latest version of the *CCOptions* model was released (i.e. excluding the carbon-cycle feedback data), these figures were taken directly from the IPCC (IPCC, 1995). According to the IPCC, the concentration value of 550ppmv is likely to have resulted from a total global carbon emissions value of 2.8GtC in 2200 – a value replicated in the old *CCOptions* model. However, this data does not correspond to the new carbon-cycle feedback model results reproduced by the latest version of *CCOptions*. Consequently, the GCI suggest new values for each stabilisation level. Once stabilisation is reached, the emissions must exactly balance the natural climate system sinks. The revised estimates of total global carbon emissions are therefore derived from carbon-cycle experiments. Table 1 illustrates selected old and new figures:

Target carbon dioxide concentration level	Old model version	New model version
350ppmv	0.2GtC	0.2GtC
450ppmv	1.5GtC	0.8GtC
550ppmv	2.8GtC	1.4GtC

6.1.3.2 Regression formulae

The process of developing equations for the *CCOptions* model that match with the Hadley and IPCC results was very much a trial and error approach and, as the relationship between carbon dioxide emission and concentration data for the different profiles differs in each case (350ppmv to 750ppmv), the use of one regression formula for all emission scenarios is not ideal.

In equation [4], the terms do not specifically relate to all the physical processes involved, but instead attempt to give the best fit possible to existing data. For example, increases in the carbon dioxide concentration, C_y depend on the carbon emissions z and the previous year's carbon dioxide concentration, which is an appropriate dependence. However, the relationship between the carbon dioxide concentration and the year y seems strange. It may be representing some sort of evolution of temperature, but as the carbon dioxide level stabilises, this relationship is likely to weaken (Jones, 2005 personal communication). It might be more appropriate therefore to incorporate the temperature into this equation. The factor of 0.04 in the equation, in addition to the other constants, helps to account for the carbon sinks.

Unlike equation [4], equations [5a] and [5b] do not appear to have any scientific basis, yet their complicated nature implies so. It would therefore preserve the model's aim to be a simple and transparent policy tool, and treat this important relationship more scientifically, if a basic carbon-cycle model equation were included, rather than rely on this rather unnecessarily complicated and contrived formula. A similar conclusion can be drawn when looking at the temperature equation [6].

To find out how well the *CCOptions* model reproduces the latest Hadley Centre output, equations [4] and [5] were applied to non-feedback and feedback results for 450ppmv, 550ppmv and 750ppmv provided by the Met Office (Chris Jones, private communication). Compared with figures 8(b) and (c), figure 8(a) demonstrates that the *CCOptions* equations most adequately reproduce the Hadley Centre data for the 450ppmv scenario. For this scenario the largest discrepancy between the *CCOptions* feedback carbon dioxide concentration and the Hadley Centre carbon dioxide concentration occurs in the years prior to 2050 (though for policy purposes the discrepancy is insignificant).

***CCOptions* model results for the 2 different model versions**

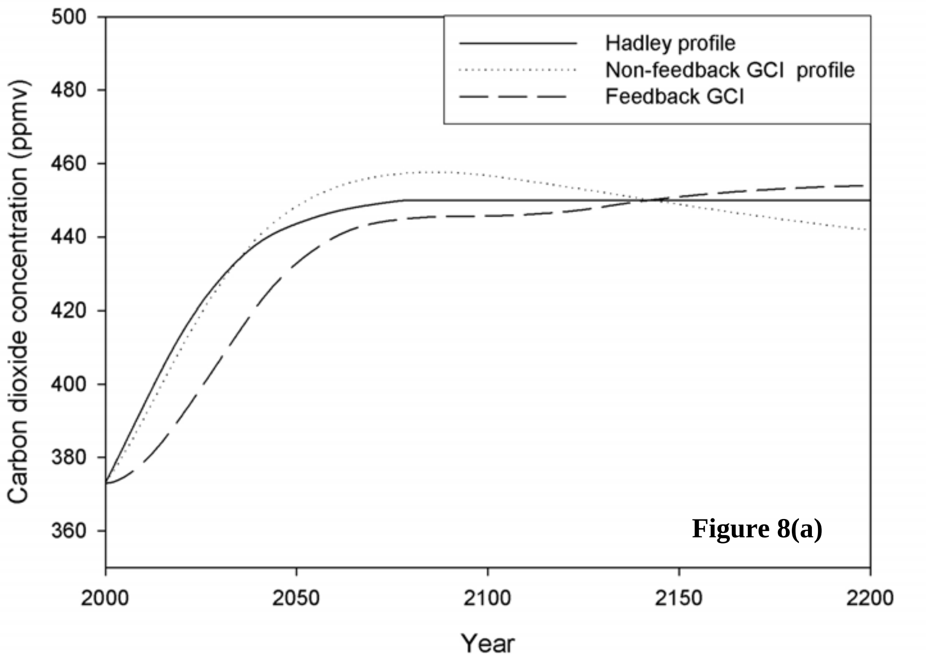

Figure 8(a)

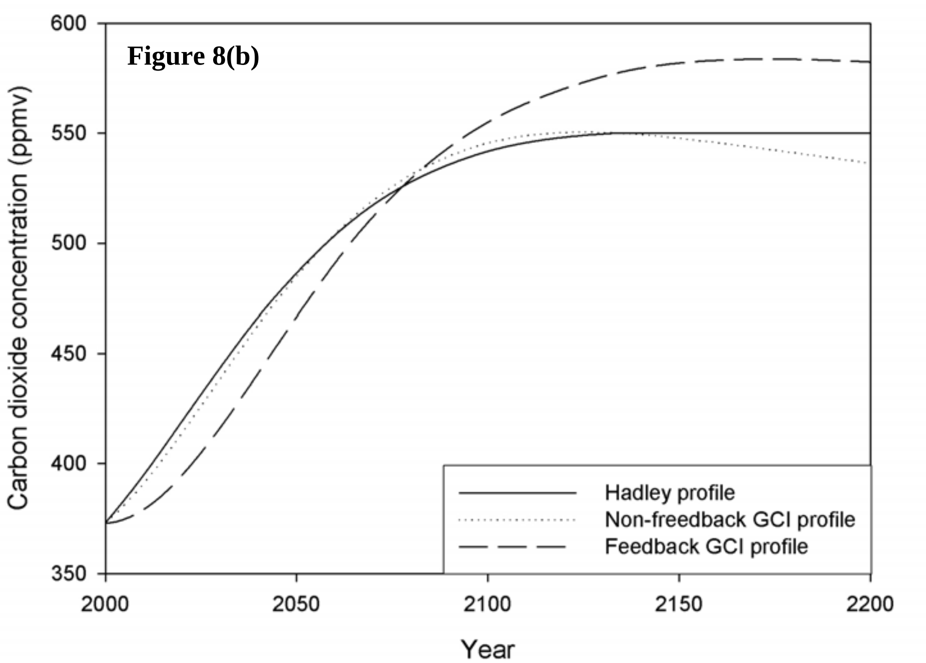

Figure 8(b)

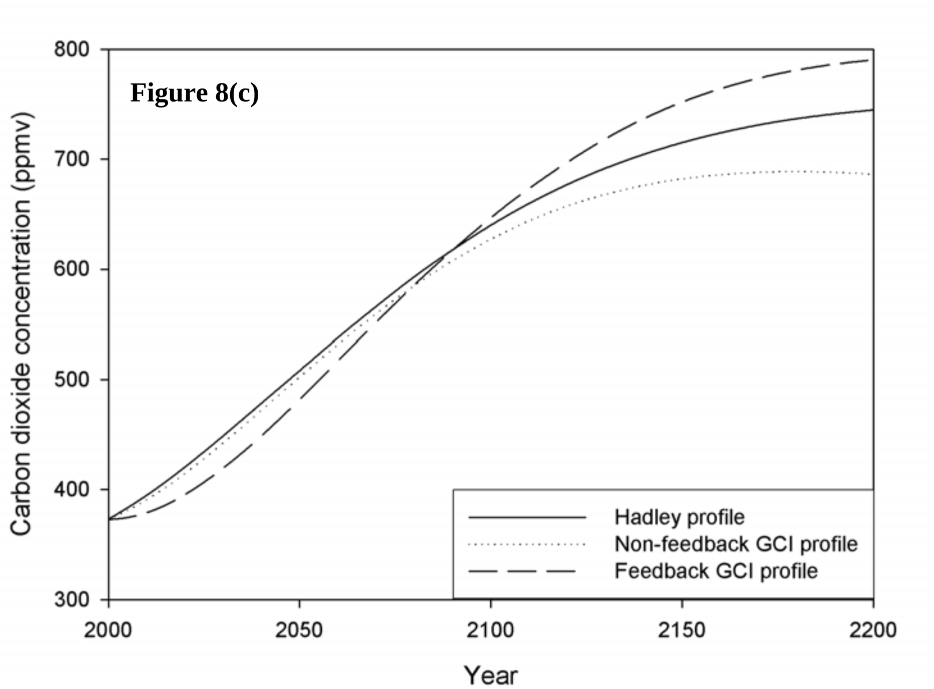

Figure 8: Carbon dioxide concentration profiles for (a) 450ppmv, (b) 550ppmv and (c) 750ppmv. The Hadley profile represents the latest carbon dioxide concentration profile aiming to stabilise at 450ppmv, 550ppmv and 750ppmv respectively. The non-feedback GCI profile is the result of applying the GCI's equation [4] to the Hadley Centre's non-feedback cumulative carbon emission data. The feedback GCI profile is the result of applying the GCI's equation [5] to the Hadley Centre's cumulative carbon emission data where carbon-cycle feedbacks are incorporated.

For the 550ppmv results, shown in figure 8(b), the non-feedback curve more closely resembles the Hadley Centre results than the feedback curve, with the feedback curve indicating that less carbon can be emitted to achieve 550ppmv within *CCOptions* than suggested by the Hadley Centre data (again the discrepancies are small in policy terms). Both the non-feedback and feedback curves for 750ppmv do not stabilise at the desired level (Figure 8(c)). Experiments with the *CCOptions* model also show that the 110-year cumulative carbon emission values required to reach those stabilisation levels are similar to the latest Hadley results. Therefore, the *CCOptions* model equations better reproduce non-feedback results than the feedback results.

6.1.4 General issues

As a general criticism, the current version of the model only includes one greenhouse gas – carbon dioxide. It could be argued that as the dominant greenhouse gas, and as *CCOptions* has been built as a simple policy tool, it is unnecessary to include other gases from Kyoto's basket of six. However, if the model is to be useful globally, and greenhouse gas emission levels are to be correctly converted into temperature increases, then including the other greenhouse gases will be beneficial for countries to set targets for all emissions, rather than just for carbon dioxide. Moreover, it may be wiser to include known contributions to climate change, such as the effects of the other gases, prior to the inclusion of the uncertain carbon-cycle feedback effects.

Other simplifications within the model include the treatment of deforestation and bunker fuels, both of which are assumed to be world overheads. In other words, rather than ascribing emissions to individual nations, an additional amount of carbon is added to the global total each year. Predicted carbon emission values for deforestation over the 1990 and 2100 period are 50GtC and are expected to decline to negligible levels from 2075 onwards. As there is a current paucity of data on deforestation, this seems a reasonable approximation.

No figures for bunker fuels, which are intended to account for international aviation, have been included in the current version of the model due to a lack of relevant data. It is hoped that in future, international transport emissions will be apportioned between nations, and then added into the model within each nation's carbon emission budget. The current growth rate of the aviation industry, particularly within Europe, points to an urgent need to update and improve this aspect of the model (Bows and Anderson, 2005).

6.2 C&C results

In the following section, results comparing contraction and convergence profiles with aviation emissions forecasts and scenarios are described. The purpose being to highlight the impact a growing aviation industry will have on a UK economy attempting to reduce its carbon emissions year-on-year to contribute towards stabilising global carbon dioxide concentrations at a level that aims to avoid dangerous climate change.

6.2.1 C&C vs aviation forecasts and scenarios

The climate change implications of the projected on-going growth in global aviation emissions over the next 50 years are becoming increasingly controversial. This is particularly so in the UK, an island state with both a major international aviation hub in the form of Heathrow airport, and the Government's 60% carbon reduction target. Add to this ministerial prioritisation of climate change for both the EU and G8 presidencies in 2005[19], an air transport white paper with the stated aim of including intra-EU flight emissions in the second phase of the European Emissions Trading System (i.e. from 2008), and entry into force of the Kyoto Protocol in February 2005, and it is not perhaps surprising that the climate impact of aviation emissions is an increasing focus of attention.

Through 2003-4, the UK House of Commons Environmental Audit Committee vigorously debated projected aviation growth and its impacts with the DfT. The Committee's concern about the impact of aviation emissions on the UK's long term carbon dioxide reduction target was echoed by the House of Lords EU sub-committee on environment and agriculture in November 2004 (House of Lords, 2004), who recommended incorporating the full climatic forcing effects of intra-EU aviation emissions into the European Emission trading Scheme at the earliest possible opportunity.

The UK House of Commons Environmental Audit Committee (2004) has questioned whether an EU or international emissions trading system can accommodate global projected aviation growth while "delivering carbon reductions of the order needed" and questioned DfT as to whether and what modelling had been undertaken on this matter. DfT replied that they had not modelled this for the EU emissions trading scheme but would need to.[20] More significant, perhaps, was DfT's response to Q.343 on what modelling had been undertaken: DfT makes it clear that in its view the 60% target relates to 'domestic' emissions only and that if the UK was to be held responsible for its international aviation emissions on the basis, for example, of a 50:50 split between origin and destination countries, then the 60% target would need to be re-examined.

Clearly, aviation emissions are increasingly a high-stakes issue, raising serious technical and policy concerns. For example, the question of properly dealing with high altitude effects alongside ground level greenhouse gas emissions in an emissions trading system (Lee and Sausen, 2000; Cames et al,

[19] See: www.number10.gov.uk/output/page6260.asp
[20] Mr. G. Pendlebury's response to Q.349, uncorrected transcript of oral evidence to be published as HC 233-iv.

2004), leading to debates centring on scientific uncertainties, location- and region-specific effects and the need to avoid perverse signals to manufacturers and airlines[21]. More than any other industry sector, aviation emissions threaten the integrity of the UK long-term climate change target. The UK Government response to this challenge will likely influence the reaction of other European states. As Europe's position is in turn important in terms of international progress on a post-Kyoto agreement, examining the implications of aviation growth under conditions of an international 550ppmv, 450ppmv or other stabilisation commitment is becoming an increasingly pressing issue.

6.2.1.1 C&C vs DfT aviation forecasts

As a first step to assessing the implications of projected growth within the aviation industry, the DfT's aviation forecasts are compared with output from *CCOptions*. Figure 9 illustrates the results for a profile that stabilises carbon dioxide concentrations at 550ppmv using the version of the *CCOptions* model that is consistent with the UK Government's 60% target. Similarly, the figure illustrates a profile that stabilises carbon dioxide concentrations at 450ppmv. Both the profiles set a convergence date of 2050, as assumed in the UK's 60% target. The DfT's 'worst', 'central' and 'best' case forecasts for carbon emissions generated by the UK's domestic and international aviation industry are also plotted.

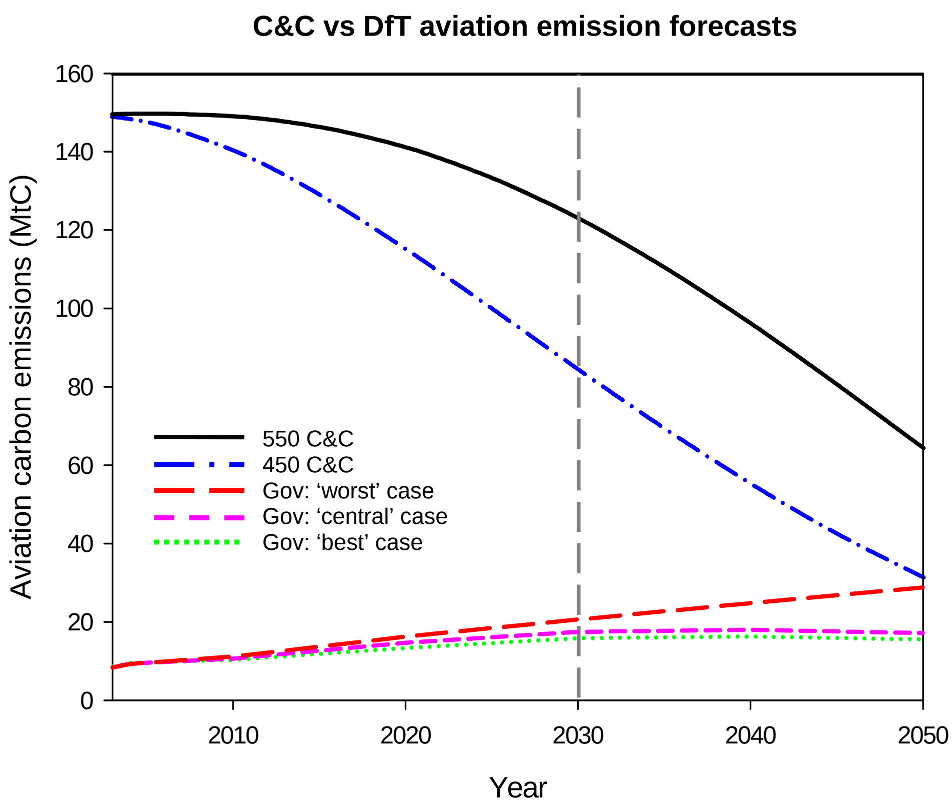

Figure 9: DfT aviation forecasts in terms of carbon emissions for the UK in relation to contraction and convergence profiles for 450ppmv and 550ppmv, each with a convergence date of 2050. The contraction and convergence profiles were generated using a version of *CCOptions* consistent with the UK Government's 60% carbon reduction target.

---

21 For example, applying a multiplier to carbon dioxide to represent radiative forcing, without a flanking instrument such as a tighter NO_x standard for aero-engines, could lead manufacturers to raise engine efficiency at the expense of higher NO_x emissions, so increasing the formation of ozone, a greenhouse gas. On location specificity: contrails form in a vertically narrow zone of the atmosphere and under particular conditions; regionally, ozone formation varies by latitude in response to temperature and ambient pollution.

The contraction profiles for 550ppmv in figure 9 again show where the UK's 60% target is derived from: between 2000 and 2050, carbon emissions reduce from around 150MtC to around 65MtC – around 60% lower than current levels. To stabilise carbon dioxide concentrations at 450ppmv, emissions would need to further reduce to around 80% lower than current figures by 2050.

Turning to the aviation forecasts illustrated within figure 5 in section 4 and again here in figure 9, the results show that under the DfT's 'worst' case forecast, carbon emissions from the aviation industry are close to 100% of the total carbon budget for the 450ppmv profiles by 2050. This is particularly worrying as recent scientific research (Elzen and Meinshausen, 2005) indicates that stabilising carbon dioxide concentrations at levels closer to 450ppmv rather than 550ppmv will be necessary to avoid so-called dangerous climate change. Furthermore, even under the DfT's best case forecast, 50% of the UK's contracting carbon budget under the 450ppmv regime will be taken up by the aviation industry by 2050. Allocating such a huge proportion to one sector will inevitably have significant consequences for all other carbon-emitting sectors of the economy. It should also be stated that the data within the *CCOptions* model does not include international aviation. If such data was included, then the cuts necessary to achieve the desired stabilisation level would in fact be larger, therefore the results here are likely to be an underestimate of the true scale of the problem.

Looking at the 550ppmv profiles, even the DfT 'best' case forecast is taking up 24% of the contracting carbon budget by 2050. The aviation industry currently accounts for around 5% of the UK's carbon budget. The shift to this much higher proportion would indicate that other sectors need to substantially decarbonise to compensate for air travel, either through reductions in demand or a move towards a low-carbon energy supply.

6.2.1.2 C&C vs UK aviation scenarios

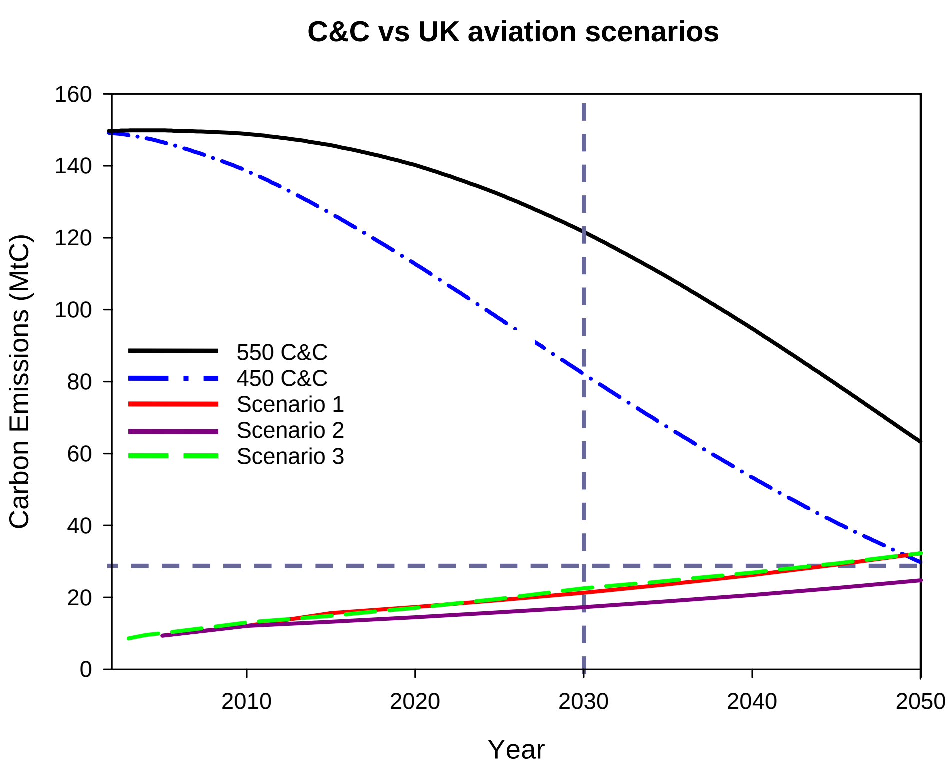

Figure 10: Tyndall aviation scenarios in terms of carbon emissions for the UK in relation to contraction and convergence profiles for 450ppmv and 550ppmv, each with a convergence date of 2050. The contraction and convergence profiles were generated using a version of *CCOptions* consistent with the UK Government's 60% carbon reduction target.

In a similar analysis, the Tyndall aviation scenarios as described in section 5.3.2 are compared with the same contraction and convergence profiles as those used to investigate the impact of aviation growing at rates predicted by the DfT previously.

Clearly, despite starting from a relatively low base in 2003, a fact often stressed by the aviation industry (see section 6.3.4), the rate of growth of the industry combined with the fuel efficiency improvements used in these scenarios lead to a rapid increase in the proportion of the UK's total carbon budget being emitted by this one industry. By 2020, the range of carbon emissions being generated by the aviation industry is between 14.5MtC and 17.3MtC. This compares with the range of 13.4MtC and 16.5MtC predicted by the DfT's forecasts as shown in figure 9.

Under the 550ppmv contraction and convergence profile, the scenario range is therefore contributing between 10 and 12% of the total carbon budget in 2020. Whereas, if the 450ppmv profile is to be aimed for, already by 2020, the aviation industry is taking up between 13 and 15%. Similarly for 2030, the figures range between 14% and 18% for the 550ppmv profile and 21% and 30%. What is also particularly interesting to note is that the quantities of emissions being generated by 2030 are already close to the 2050 target. This will mean that the aviation industry will have to work extremely hard to stabilise emissions at least from this date onwards, to avoid exceeding the target altogether, leaving little or no leeway for other sectors of the economy. Furthermore, by 2050, only *Scenario 2* does not exceed the 450ppmv target, but even this scenario is contributing to 77% of the total carbon budget. Under the 550ppmv profile, the range taken up by the aviation scenarios is between 38% and 50% of the total.

The results presented here present a stark picture. If, as is now commonly thought (Hadley, 2005), the UK needs to put itself on a path towards reducing emissions by 80% by 2050, rather than 60%, corresponding with the 450ppmv profile, then the aviation industry can not continue to grow at current rates, or those rates forecasted over the coming 20 years, without significant step changes in aviation technology or management to reduce fuel burn.

6.3 Stakeholder opinions

As described in the methodology section of this report, a number of stakeholders were interviewed to investigate the opinions of aviation industry stakeholders in relation to aviation growth and climate change. The questions are listed in section 5.4.2 and the responses are summarised under the headings below.

6.3.1 Aviation growth

When asking questions relating to current aviation growth, the majority of the respondents immediately quoted future growth figures rather than those being seen today within the UK. Whether or not this was a deliberate attempt to ignore the current very high levels of growth being seen, or simply because the culture is always towards looking to the future is unclear. Specific responses to the question of current growth are highlighted in this section.

6.3.1.1 Current aviation growth

There was a huge variation in the readily available knowledge of interviewees on current levels of growth for either the UK or Europe ranging from no declared knowledge at all from airline, airport operators and government interviewees, to specific regional and national figures up to a maximum quoted figure of 12% per year, in terms of passenger numbers for the UK, according to a consultant. Those interviewees whose companies produced their own forecasts had the best knowledge of current growth rates. The most commonly referred to figure for growth in the UK was between 4-5% per year in terms of passenger numbers, similar to the average growth rate for the rest of Europe. Specific figures of interest quoted by interviewees were a 7% per year global growth figure in terms of passenger-kms and a comment from one of the airline manufacturers that the aviation industry is currently seeing remarkable growth, particularly in terms of freight.

When the stakeholders were asked about the published current rate of growth of 8% per year in terms of passenger numbers for the UK's aviation industry (CAA, 2004; DfT, 2005), most were unaware of this figure, or felt that it may unfairly take into account transit passengers. One airline manufacturer who said that UK growth was currently about 4.5% in terms of passenger-kilometres, suggested that the difference between these figures could be accounted for by; a) higher growth in low-cost carriers than traditional airlines b) their correspondingly higher load factors and c) the fact that these carriers do not fly as far. However, the latest figures released in October 2005 from the DfT show a 7% increase in passenger-kilometres between 2003 and 2004 (DfT, 2005). There was also some feeling that growth rates had bounced back from the blip between 2001 and 2002, and may therefore be higher than usual between 2003 and 2004 as the industry recovers.

6.3.1.2 Future aviation growth

The interviewees were generally much more confident in their knowledge of forecasts and projections of growth than of the current levels of growth being seen within the UK and Europe. This may be because those interviewed tended either to produce detailed forecasts themselves or use detailed forecasts produced by others, and appeared to pay less attention to the current figures available from the Civil Aviation Authority (CAA, 2004), the DfT (DfT, 2005), the UNFCCC (NEI) and DTI (DUKES, 2005). On the other hand, none of the interviewees were prepared to give growth figures for longer than 20 year periods. The advantage of more detailed knowledge of forecasts meant that interviewees were also able to provide some information on the kind of variation in growth rates that are likely to be seen within the industry. For example, more than one respondent indicated that higher levels of growth are expected in intra-European short-haul flights rather than long-haul traffic, despite the recent recovery in transatlantic flights. This growth is likely to be particularly attributable to robust growth in terms of low-cost European carriers, which are currently exhibiting the highest levels of growth.

According to the airline manufacturers interviewed, the aviation industry is likely to see sustained, high growth over the coming 20 years, with the highest growth likely to be seen in China – around 8% per year in terms of passenger numbers, and the lowest in the US where the growth rate is likely to be around 4% per year. One airline manufacturer stressed however, that this level of growth will still have a significant impact on the numbers of aircraft that will be required as the base level within the US is already extremely high. They also commented that the impression the US aviation industry likes to portray is that of a struggling industry, but business is in fact buoyant and growing apart from within a small number of airlines. An interviewee from government said that globally, most of the forecasts that project traffic growth tend to give a figure of the order of 5% per year, with significant regional variations. As the aviation industry is international, they said that it was difficult to give a forecast figure specifically for the UK, and prefer therefore to look at Europe as a whole. Here they predict an annual passenger traffic growth figure of around 4%. However, one aircraft manufacturer did point out that there are many constraints to growth in the aviation industry, particularly the difficulty in getting permission to build new airport infrastructure.

There was a general consensus amongst the stakeholders that the growth rate in terms of passenger numbers in Europe is likely to be between 4 and 5% per year, with eastern Europe expected to see somewhat higher rates of growth. Despite the aviation industry being mature within many European nations, the 5% per year growth of the European aviation industry predicted by airline manufacturers to continue until 2020 is higher than the US's growth projection because of the current relatively low propensity to travel of central and eastern Europeans. For example, growth within the aviation industry in Poland is currently 20% per year according to Boeing forecasts (Boeing, 2004). The reason that stakeholders believed this situation to be maintainable is due to the prospective influence of the low-cost airlines, particularly within these relatively new markets.

The airline and airport operator interviewees were unable to give any specific figures for predicted growth rates for the UK or Europe, although they did say that they expected the UK to grow at a similar rate to the rest of Europe.

Only one interviewee referred to predicted growth in cargo, and quoted a figure of 7% per year in terms of freight-tonne-kilometres.

6.3.1.3 Forecasts used and assumptions made

Those stakeholders whose companies or organisations produced their own forecasts said that they were based on economics, although two of the airline manufacturers differed considerably in what they said were the drivers of growth. One said that GDP growth was not nearly as important as may be expected, with exchange rates and international trade also key drivers. Whereas, another stated that Europe is likely to follow the same economic model as the US, where the aviation industry is now mature. They said that historically, the growth rate in the US has been a couple of percent more than annual GDP growth, with a gradual slow down to a figure that is eventually equal to that of GDP. However, one could argue that the aviation industry is indeed mature within the US, and yet growth there is still considerably higher than the GDP growth rate.

With regard to the UK Government forecasts as shown in the Aviation White Paper, some government interviewees said that the figures are likely to be revisited towards the end of 2006. It should be noted however that there is a discrepancy between the figures used (DfT, 2004) to produce the emissions forecasts in the Aviation White Paper and its diagrammatic representation within the White Paper.[22]. This discrepancy is at worst a 20% difference in the emissions forecast in 2010.

The DTI also produces its own forecasts for aviation growth which are, according to an interviewee, based on unconstrained demand forecasts. However, it was stressed that this is often misinterpreted to mean that there are therefore no constraints whatsoever on the forecasts, and that this is not the case. There are already many constraints on airports in terms of noise and local pollution regulations, capacity constraints etc which are all taken into account in these so-called unconstrained demand forecasts. Unfortunately however, there have not been any updated publicly available forecasts produced by the DTI since 1996.

[22] The orange plot on page 25 of the Aviation White Paper should be shifted five years to the right to be correct.

6.3.2 Fuel efficiency and fleet turnover

As described in section 3.4, fuel efficiency improvements have an impact on the emissions produced by the aviation industry, and fleet turnover in turn affects these efficiency gains. The quicker the fleet is renewed, the higher the fuel efficiency improvements. In the following section, the aviation industry stakeholders were asked for their knowledge on both fuel efficiency and fleet turnover.

6.3.2.1 Fuel efficiency

There was a general consensus that historically, fuel efficiency has been improving at about 1-1.5% per year across the entire fleet, and that this figure is broadly what is being seen today. The ACARE targets, as described in section 3.4, were mentioned by the interviewees from aircraft manufactures, airlines and airport operators as being key drivers and attainable in terms of fuel efficiency. Specific caveats relating to the ACARE targets were pointed out during the interviews however. For example, an interviewee from an airport operator noted that there is a target of reducing carbon dioxide emissions by 50% per passenger by 2020 for those aircraft manufactured within the EU. However, they suggested that any targets being aimed for by European manufacturers are also likely to influence the design and production of aircraft by competitors outside of the EU. The operator also noted that although the efficiency targets are important and attainable, the challenge still remains to ensure that any efficiency gains in terms of absolute emissions are not outstripped by growth.

It was argued by an NGO interviewee that the current efficiency gains of 1% per year over the entire fleet could in fact be pushed to 2% per year, if the right kinds of incentives in the form of taxes, charges and trading were implemented. They stated that until this was the case, new and innovative ways of further improving fuel efficiency would not come to the fore. There was also concern expressed about British Airways' 1.7% per year efficiency gain target over their entire fleet. It was felt that this was very high considering they already have a relatively young fleet, and questions were raised over what this figure was being compared with in the past – for example, was Concorde in the previous calculations? Comparing the current fleet with one that included supersonic aircraft will naturally have an impact on the efficiency gains seen. This point merits further investigation. A consultant interviewed highlighted the fact that a step-change in terms of fuel efficiency is really what the industry is looking for, but as long as it sticks with predominantly aluminium airframes and a swept wing design, this is unlikely to happen.

According to one of the aircraft manufacturers, a detailed study has been recently carried out looking at the historical and projected fuel efficiency improvements for the UK's aviation industry. The study investigated the seven biggest UK airlines, and compared the aircraft they had in 1990 with those of 2000. Using typical load factors and standard aircraft efficiencies, analysts then worked out the efficiency gains in terms of fuel per revenue passenger-kilometres. Between 1990 and 2000 these airlines saw a 21% improvement. To project future efficiency gains, forecasts were used of how the fleets would grow and change. The study predicts that by 2012, there will be a 34% improvement compared with 1990 levels. This averages at about 1.5% per year in terms of compound annual change. Although this is higher than the 1% per year figure often quoted by the UK Government (DfT, 2003b), the UK airlines discussed within this study have some of the newest planes in Europe, and would therefore be expected to have made better gains than others between 1990 and 2000. In terms of what proportion of this gain is from the different elements effecting efficiency, around 1% per year is from improvements to the engine design. This translates as an engine in a new aircraft in 2020 being 20% more efficient than the best one produced in 2000.

An airline interviewee also had detailed figures on energy efficiency improvement targets. Their aim to improve fuel efficiency across their entire fleet by 30% between 1990 and 2010 has already seen improvements of 27%. This gain is apparently reflected by regularly updating the fleet, buying more efficient, new aircraft, and a focus on cost minimisation. The price of fuel was highlighted as a key driver towards improving fuel efficiency[23], therefore the airline looks to ways of reducing aircraft weight, improvements in air traffic management using new technology onboard its aircraft to produce more direct routings and increasing its load-factor. However, it was stated that any action taken to reduce fuel consumption must also take into account of the impact of aircraft in terms of noise, local pollution and other emissions. Therefore, there is often a trade-off that needs to take place. An airline interviewee stated that fuel price has always been a key driver, and therefore they have continually been improving their fuel efficiency. However, if the price of fuel was to continue to increase, they stated that this would not necessarily lead to extra fuel efficiency improvements on top of those already planned.

The historic improvement trend in terms of fuel efficiency as measured in seat kilometres per kg fuel consumed has been about 1% improvement per year according to a government stakeholder. This does not necessarily relate to the number of passengers carried and hence the load factor of the aircraft. They didn't think that this figure would be likely to change significantly over the short, medium or long term, although fortunately it is affected by many different drivers including aircraft size, engine design, airframes, passenger handling, air traffic management etc. They also stated that this is a conservative industry, and therefore unlikely to see improvements beyond its current performance.

One interesting point of view expressed by one of the aircraft manufacturers however, was that they notice a limited amount of interest and research into how to change the aviation industry. They felt that most of the research money was still going into squeezing 1% per year efficiency improvements out of a jet engine. They therefore felt that incentives need to come quickly to help the industry to make radical changes.

To summarise, it appears then that the aircraft manufacturers and airlines are generally confident in the efficiency gains they are likely to see in the future, and in meeting their ACARE targets. On the other hand, interviewees from government, NGOs, airport operators and the consultants felt that not much more could be done to improve the rate of efficiency gains, and NGO and consultant interviewees suggested that some of the targets appeared ambitious without new incentives. Furthermore, the issue is confused by the difference between metrics used to measure fuel efficiency. For example, the IPCC (IPCC, 1999) and UK Government tend to use a change in seat-kilometres per kg fuel consumed as the measure, whereas an airline stakeholder and one of the manufacturers used fuel consumed per revenue passenger km. This second metric is therefore affected by the aircraft's load factor. However, it should be noted that if the load factor is increased, but everything else remains the same, then the efficiency per passenger of the aircraft has improved, but the fuel efficiency of the aircraft itself has not. In other words, the same amount of carbon dioxide will be being emitted by the aircraft. This could lead to an emissions reduction if the passengers used to fill up this aircraft would have flown on a separate flight. If, however, they are new passengers, then the absolute emissions will be increasing.

6.3.2.2 Fleet turnover

Those interviewees with some knowledge of fleet turnover in Europe were in broad agreement that the average age of an aircraft is between 6-9 years, with freighters being somewhat older. The UK is at the top end of this average age. One of the manufacturers stated that improvements in terms of

[23] 10% of the overall cost according to an airline stakeholder interviewed

fuel efficiency of new aircraft give a greater incentive to ditching old aircraft and purchasing new ones. This should lead to a shortening of aircraft age rather than a lengthening. There was some disagreement however on whether or not aircraft would be built to last shorter lengths of time in the future. One manufacturer felt it was certain to be the case with a drive towards cheaper materials with which to build the aircraft, others were unsure.

6.3.3 Advances envisaged

There was a great deal of variety in terms of the technological and managerial advances envisaged by the different interviewees, as demonstrated below.

6.3.3.1 Technology

In terms of alternative fuels, there was a general consensus that hydrogen would not be used as an aircraft fuel for at least 30 years, if at all. The key constraints cited were the implications for a redesign of the aircraft, the need for a world-wide hydrogen fuel supply and concerns over water vapour emissions. Furthermore, one manufacturer suggested that only when there has been a world-wide supply of hydrogen for land-transport for at least 10 years, will the aviation industry consider hydrogen. Some of the interviewees also indicated that the aviation industry sees itself as consuming the last drop of oil on the planet whilst everyone else has re-engineered themselves to reduce their fossil-fuel consumption. Therefore technologies perceived as difficult by the industry are unlikely to receive much attention over the coming decades.

The possibility of using biofuels in aircraft received a slightly more positive response in terms of technological feasibility and acceptability. The manufacturers stated that there was no reason why it could not be used in current aircraft, but that the key barrier was making it economically viable. As long as it costs more to produce, natural kerosene will be used. An airline interviewee couldn’t see biofuels breaking through into the aviation industry for at least 30 years, and felt that the likelihood is that any such alternative fuel would be used in land transport as a cheaper option in the first instance – a view reiterated by a government interviewee.

Changes in airframe design again appear to be limited, with only radical changes likely to be seen after at least 30 years according to the respondents. In the short term, manufacturers envisage changes to the materials used to build the aircraft, such as carbon composites, which will make the aircraft lighter and cheaper to produce. It is also expected that all aspects of current aircraft design will be optimised before new designs come onto the market. Such design improvements are already in the process of coming to fruition. For example, the new aircraft from Boeing – the Dreamliner – will be 50% carbon composite. Further improvements in engine design and weight are also expected.

The blended-wing body design or ‘flying wing’ as described in section 3.2.1 was mentioned by a number of respondents as something they expected to see in the longer term. One government interviewee said that they would be surprised if there wasn’t a move towards blended wing body eventually, as it offers a small step-change in terms of fuel efficiency. One of the manufacturers also added that ‘flying wings’ will permit putting the engine on top of the aircraft, thereby reducing the noise impacts, and hence giving further fuel efficiency improvements.

Other specific technological advances mentioned by the interviewees included the issue of supersonic aircraft – one aircraft manufacturer stated that they were not looking to produce any such aircraft in the foreseeable future, whereas a government interviewee thought that the US was keenly investigating the possibility of small supersonic jets. For short-haul travel within Europe, one government interviewee suggested that advanced turbo-props might be brought into the mix due to their fuel-burn benefits. However, the technology with regard to acoustic damage would need to be addressed prior to their introduction. Air-to-air refuelling was also mentioned as another measure to improve the energy efficiency of a flight.

6.3.3.2 Management

Although respondents listed a number of technological advances that they could envisage over the coming decades, the majority expected more to be done in terms of reducing fuel burn through better air traffic management prior to the technological advances listed above. One of the manufacturers also indicated that their business was keen to reduce emissions not only within the aircraft themselves, but also in the production of the aircraft and encouraging their business partners, suppliers and subcontractors to do the same. An NGO interviewee felt that in the short-term, most efficiency gains would be operational and focus on eliminating the inefficiencies that exist such as flying more direct routes, avoiding keeping aircraft in holding patterns and pushing for higher load factors. They also felt that a closer examination of plane rotations was needed. For example, at present it sometimes appears to be economical for an airline to fly an empty plane back to its origin just so it is in the right place at the right time. One airline interviewed felt that all airlines would be further developing their fuel management systems, and working hard to measure their own carbon dioxide emissions.

One issue that was mentioned by all respondents and was re-iterated on a number of occasions was the problem of the trade-off between noise and fuel-burn. In the past, noise has been one of the biggest issues for manufacturers and airlines. However, noise abatement technology is often heavy and therefore leads to greater fuel burn. An airline interviewee said that the new Airbus A380 has been specifically designed to meet certain noise requirements, and it is therefore up to 2% less fuel efficient than it could have been. Furthermore, one of the aircraft manufacturers stressed the importance of the noise issue within this debate. They said that noise is still a huge and costly issue, and any decision on whether or not to build a new airport will be fought on noise terms rather than climate change terms. They pointed out the apparently ridiculous situation where a small island nation such as the UK chooses not to build its airports near to the sea and away from built-up areas where noise is less of a problem.

6.3.3.3 Drivers

When questioning the stakeholders about technological and managerial advances, the conversation often developed into a discussion of policy drivers. An airport operator interviewee felt that although there would be impressive improvements in terms of fuel efficiency, they would not be enough to deal with the climate change issue, hence the importance of emissions trading. They felt that there was a need to debate emissions trading, since a market mechanism to internalise the costs, and influence the aviation industry's impact on climate change, was desirable. They said, "Given society's growing demand for air transport, and given the absence of short-term technological solutions which will allow a breakthrough in reducing carbon dioxide emissions, participation in an emission trading scheme would allow aviation to purchase the necessary additional allowances from other sectors to enable the industry to continue to grow and to meet its emissions obligations. If the price of carbon rises in the future, then this would impose an additional operating cost which would work its way through to air fares and affect demand. Or alternatively, it would incentivise airlines to make technological and operational changes. The challenge would then be to find those technological or operational changes which allow airlines to grow their businesses without growing their costs". The operator also recognised that it was unlikely that there would be any technological breakthroughs within the next 20 years.

An NGO stakeholder on the other hand felt that emissions trading would be inadequate as discussions over trading are only ever about regional or partial industry coverage. They felt rather that any radical technology change is more likely to be driven by a huge rise in the price of fuel, or by energy security issues.

One of the aircraft manufacturers went on to discuss the issue of having a public license to operate. They felt that if the aviation industry wasn't being seen to be acting responsibly to help avoid climate change, as other industries are likely to be seen to be doing, then the public would turn against the industry. They felt that those airlines and manufacturers demonstrating a climate conscience would gain a larger portion of the market from those seen to be acting irresponsibly. This particular stakeholder also felt that the manufacturing industry was unclear as to where to focus its efforts in terms of research and technology development, and would therefore like to see some guidance from governments.

One final and interesting point raised in terms of drivers towards action to improve fuel efficiency, was the likelihood of low-cost airlines operating on the long-haul market. One of the government interviewees said that they didn't see why this shouldn't happen, and if it did, that this would be another reason to revisit the existing forecasts for traffic demand.

6.3.4 Awareness of climate targets

There was a general awareness amongst the stakeholders of the UK Government's 60% carbon reduction target, and that it excluded international aviation and shipping emissions. However, one aircraft manufacturer did refer to the target as one that seemed to have been plucked from the air. They also stressed that the aviation industry currently accounts for just 2% of world emissions, and the issue should not be blown out of proportion. When asked about the possible exclusion of these international emissions from the UK's 60% target, one interviewee from government said that it could be argued as regrettable that emissions from international aviation were not currently part of existing control measures – not least because such inequity offers confusing signals to the industry. However, this situation might be inevitable given the complexities in gaining international consensus on the means to control greenhouse gas emissions from aviation beyond national borders and the constraints of binding bilateral agreements that exist to facilitate air travel between consenting states. The general consensus view amongst the industry stakeholders on the issue was that as international aviation was not covered under the 60% target at present, the ACARE targets were those to be aimed for and concentrated on instead. Having a focus on the ACARE targets does appear logical in the absence of any governmental pressure to do otherwise.

6.3.4.1 Reaching the UK's target

Discussion as to how the UK can meet its 60% target, post-Kyoto regimes and how the aviation industry might do its part towards mitigating climate change tended to focus on the EU emissions trading scheme. Those who broadly supported the scheme included an airline, airport operators and aircraft manufacturing interviewees. When asked when aviation could be included in any emissions trading scheme and under what terms, a variety of answers were given. An airline stakeholder said that aviation could be included as soon as 2008 in terms of intra-EU flights as a first step, although ultimately a global solution guided by the International Civil Aviation Organisation (ICAO) is necessary if all international flights are to join emissions trading. The choice of limiting it to intra-EU flights was based on having something "workable and politically deliverable within a reasonable timescale, that isn't going to cause international disputes or distortion". Problems envisaged by one airline in terms of including all international emissions are centred around allocation problems, non-industrialised nations' own climate targets and an absence of a framework to address these international emissions through ICAO. An airline stakeholder also felt that if the emissions trading framework was done properly, it would be an important instrument in accounting for the external costs, and growth would in turn be moderated to some extent. Furthermore, they added that incorporating aviation into a comprehensive global framework to address climate change is an important goal in ensuring aviation plays its part in managing future emissions growth.

One of the aircraft manufacturers, despite being a supporter of bringing international aviation emission into the EU's emissions trading scheme, considered the starting date of 2008 was premature and more likely to be 2010 for the intra-EU bubble. They said that this would then cover 15% of all global flights, which is not a large enough proportion to drive innovation within the industry. The EU are, however, apparently discussing including all aircraft departing from EU airports, which would account for 40%. However, according to this stakeholder, expanding the remit in this way is likely to cause many more problems in terms of implementation. If, as expected, only intra-EU flights are incorporated, they suggested that this would have an insignificant effect in terms of emissions reduction, but a large symbolic impact.

An airport operator interviewee was also supportive of the EU emissions trading scheme and expected it to be successful as long as a suitable cap is chosen. They added, “The aviation industry should be mainstreamed as part of the global policy process to achieve the reductions necessary to avoid dangerous climate change through an international emissions trading scheme”. The operator also noted that the EU is talking about a 70% reduction in emissions by 2050 which they felt should include international aviation. This target would then be used to set a reducing cap, which is likely to increase the price of flights and in turn translate into incentivising supply-side effects within the industry. They felt that the challenge for the industry was to look at the long-term trajectory and to do what it can to find supply solutions and bring them on track as quickly as possible. This stakeholder was also keen to stress that the ultimate goal is an international emissions trading scheme that includes all flights. However, they also felt that the best starting point would be to use intra-EU flights in the first instance, with a risk in delaying starting any scheme if the plan is more ambitious. They expected the start date to be 2008 or soon thereafter, and suggested that discussions should then focus on allocating international aviation emissions to work towards a global solution from 2013.

A much more cynical point of view was expressed by an NGO interviewee who claimed that the aviation industry was keen to engage on the issue of emissions trading because they are aware that it will not drive passenger numbers down. In their opinion, the aviation industry clearly sees themselves as different from all the other sectors of the economy. Although their sustainable aviation strategy (Aviation, 2005) commits the industry to efficiency targets, when it comes to more overarching climate change targets, they see themselves as part of the system. They feel that the rest of the system has a lot more opportunities to reduce their climate impact than they do. Therefore, until there is a successor to Kyoto that includes international shipping and aviation emissions, the aviation industry will continue to rely on other sectors and will not feel the pressure felt by other sectors to mitigate their emissions.

6.3.5 Additional climate impacts of aviation

The final part of the stakeholder interview covered the area of the uplift factor often used to account for the additional climate change impacts of the aviation industry as described in section 2.2. In terms of the value of this ‘uplift factor’, all the interviewees accepted that there was considerable uncertainty over the figure itself, will values ranging from just under 2 to 4.

In terms of the existence of an uplift factor, there was a general consensus that although it is crucial that the additional impacts of aviation are accounted for, simply ‘uplifting’ the carbon dioxide emissions by a radiative forcing factor can be misleading and inadequate. On the other hand, there was some feeling that the use of this ‘uplift factor’ has helped to raise awareness of the additional climate change impacts, and is helping the industry to focus new research in these areas. However, one aircraft manufacturer felt that it is not a good guide to policy measures as it is a “backwards looking metric” and another two stakeholders expressed concern that the metric risks misleading the policy focus. The manufacturers, airline and government stakeholders were in agreement that simply ‘uplifting’ emissions to try and account for additional climate change impacts within an emissions trading scheme is inappropriate. However, all also agree that these other impacts must be addressed, but probably by using separate measures, and certainly require further research. An airport operator interviewee suggested that there could even be air traffic management solutions to avoid the formation of contrails and cirrus clouds, but that the science would have to be more certain before aircraft are re-routed.

7. Discussion and conclusions

The final section of this report discusses the key results and draws together conclusions relating to the *CCOptions* model, the UK Government's aviation forecasts, implications of high aviation growth for other sectors of the economy and finally some recommendations of practical measures to reduce the climate impact of the aviation industry.

7.1 *CCOptions* model – a simple and useful tool for policymakers

The *CCOptions* model is a simple and useful tool for policymakers. Not only is it written for a familiar software package, Excel, its results are plainly presented allowing the user to make a quick evaluation of their experiment without involved data manipulation. Experiments are also very 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 speed of convergence.

CCOptions adequately reproduces widely accepted Hadley Centre model relationships between carbon dioxide concentrations and cumulative carbon values for all nations between today and 2200. However, releasing the latest version of *CCOptions* is arguably premature as it attempts to reproduce Hadley Centre results that incorporate biogeochemical feedbacks from the carbon-cycle whilst the magnitude of such feedbacks remains uncertain. This drawback is exacerbated by the 'with biogeochemical feedback' regression equation being, relative to the 'without feedbacks' equation, both complex and less successful in reproducing the Hadley centre relationship. Arguably, the latest *CCOptions* model, in attempting to capture elements of the climate change science still characterised by considerable uncertainty, jeopardises its credibility as a relatively objective policy tool. On the other hand, the inclusion of biogeochemical feedbacks could be said to provide a more realistic carbon-reduction target for given carbon dioxide stabilisation levels, and consequently may lead to more appropriate mitigation polices. (Hadley, 2002; Cramer et al., 2001).

To conclude, the *CCOptions* model is a useful policy tool, in which complicated assumptions about population trends, paths towards convergence and the historical positions of particular nations are foregone in favour of transparent and inclusive analysis. However, if *CCOptions* is to remain relevant to the dynamic climate change debate, it is important it continually updates its underlying data sets and include all carbon emission sources, particularly international aviation and bunker fuels. Moreover, in developing *CCOptions*, the GCI must guard against too rapid inclusion of scientific advances that have not undergone substantial peer review. Finally, if *CCOptions* is to more fully correlate emissions with temperature, the GCI must consider the inclusion of other non-carbon greenhouse gases.

On balance, permitting analysis of the relationship between stabilisation levels and reduction targets, with and without biogeochemical feedbacks, is a good compromise, offering both simplicity and more informed policy involvement. However, for the purposes of this project, it was felt better to make use of the version of *CCOptions* that had been used by others and that was in line with the UK Government's 60% target.

7.2 Government forecasts require updating as a matter of urgency

Aviation emissions forecasts produced by the UK Government and Tyndall aviation scenarios were compared with contraction and convergence profiles for 450ppmv and 550ppmv in section 6. Although the Tyndall aviation scenarios were produced prior to the stakeholder engagement conducted, subsequent input from the stakeholders supported the idea that the industry within the UK and Europe is currently growing at very high rates and that despite concerted efforts to improve fuel efficiency, any relative reduction in emissions will be hidden by a continuation of this high growth.

Given that knowledge of current and near-future aviation growth rates is essential to assess the climate impact of the aviation industry, one of the key concerns with the UK Government forecasts highlighted within this work is their continued use of the relatively low growth forecasts laid out in 'Aviation and Global Warming' (DfT, 2004 and figure 5) and used in the Aviation White Paper (DfT, 2003b). According to information provided about the Government's Aviation White Paper[24], these forecasts were generated prior to the events of September 11th, which could not have been envisaged. However, traffic to date has actually been broadly in line with those forecast figures despite the unusual events that significantly affected the industry. The forecasts are therefore considered to be close to the mark. If the logic of this argument is followed through however, without the events of September 11th, their forecasts would have fallen well short of their predictions in terms of passenger numbers and the consequent emissions generated by the aviation industry. This is illustrated in figure 11; actual carbon emissions values from the UK's aviation industry taken from the National Emissions Inventory are plotted for the period from 1993 to 2004[25] (shown in the grey box). It can be seen in the figure that until the unusual events of 2001, emissions from the aviation industry were increasing rapidly, on average at 7% per year between 1993 and 2000. Whereas, even the 'worst' of the UK Government's aviation forecasts suggests an annual average increase in emissions from the industry of just 3% per year between 2004 and 2010, despite there being a 10% increase between 2003 and 2004.

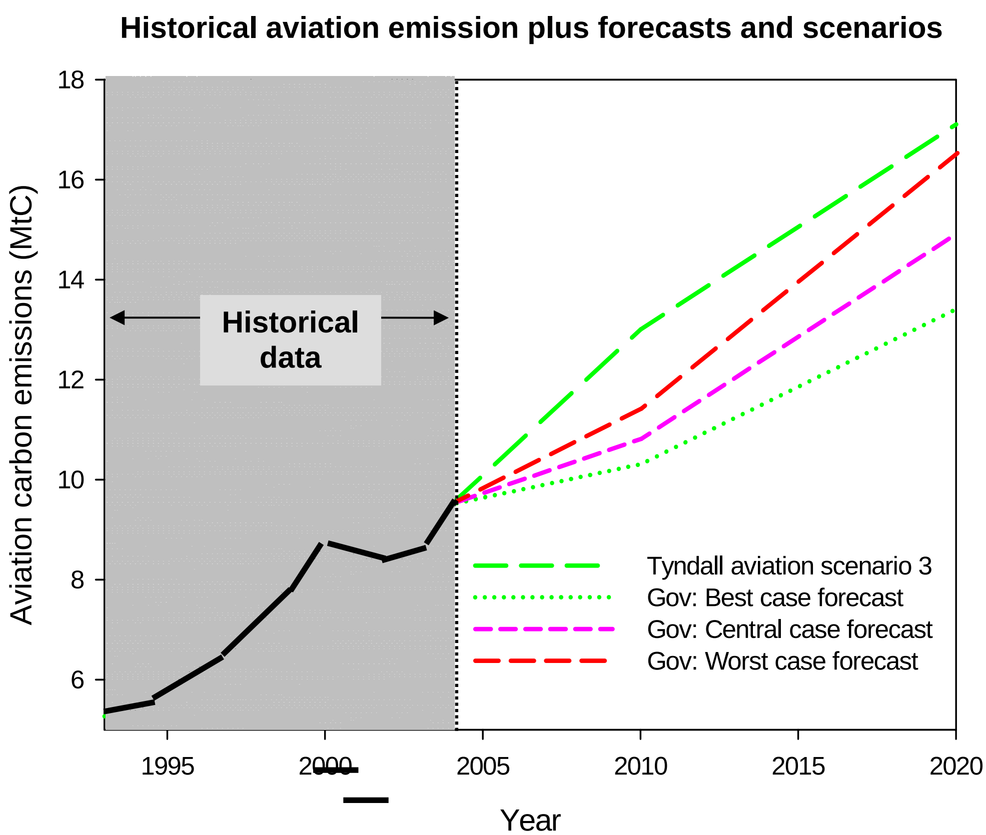

Figure 11: Historical emissions from the aviation industry in the UK compared with UK Government forecasts and the Tyndall aviation scenario number 3.

---

[24] Private communication

[25] Values from the National Emissions Inventory (NEI) currently exist up to 2003, but are directly related to the energy consumption figures produced in the Digest of UK Energy Statistics (DUKES, 2005) via the kerosene emission factor. The latest version of DUKES shows a 10% rise in the kerosene consumed by UK aviation. When the kerosene emission factor is applied to this value, the 2004 aviation carbon emission value is calculated to be 9.5MtC for 2004.

Meeting the Government's 'worst' case forecast for emissions would therefore require a decrease in annual compound emissions growth of 7% between 2004 and 2005. It is difficult to imagine how this could possibly occur. Such would require a reduction of growth within the industry of 6% in one year – down to a figure below the annual increase in the UK's GDP, plus fuel efficiency improvements of at least 1%.

This project therefore recommends that the UK Government forecasts must be updated as a matter of urgency.

7.3 C&C vs forecasts and scenarios – stark implications for other sectors

By comparing aviation emission scenarios with contraction and convergence profiles for 450ppmv and 550ppmv, this project concludes that without measures to curtail growth within the aviation industry, its carbon emissions alone will be contributing to an ever increasing proportion of the UK's carbon budget. Moreover, even if the industry were allowed to continue to grow at half of its current rate of growth, and without any radical step-change in technology, the resulting emissions will take up more than the UK's total carbon budget under a 450ppmv regime. As such, the current state of the aviation industry, with its dependence on kerosene, long-term lock-in to conventional airframe designs and higher rates of growth than any other sector, has huge implications for all of the other sectors of the economy.

Bringing these results to the attention of policy and decision makers is of tremendous importance whilst solutions to addressing the growing climate problem are still being debated. Furthermore, the UK Government is currently in the driving seat, (or should that be cockpit?), by holding the presidencies of both the G8 and the EU. However, whether or not these results can lead to any modification to the development of the UK's aviation industry is heavily reliant on the following key policy issues:

- The choice by the UK Government to include international emission within its carbon reduction target.
- The choice by the UK Government to maintain, reduce or strengthen its 60% target for 2050 carbon dioxide emissions.
- The level of constraints: economic (national, regional and international), fiscal policy (taxes, charges) and airport infrastructure supply.
- The effect of strong carbon reduction targets on the development of other sectors both in the UK and the wider EU.
- The choice by the EU of its carbon reduction target.
- The state of involving the aviation industry within the EU's emissions trading scheme.
- Whether or not international emissions are allocated to nations in a post-Kyoto regime.
- The possibility of trading international aviation emissions within a global emissions trading scheme.

Many industry stakeholders, as highlighted in section 6.3, believe that incorporating aviation within the EU's emissions trading scheme could be the silver bullet for aviation and climate change. However, given that the most likely option for including such emissions will be an incorporation of only intra-EU emissions by, at the earliest, 2008 this option will still omit 70% of the emissions from the EU's aviation industry. In other words, adding aviation into the EU's emissions trading scheme will do little to solve the problem.

The manufacturing, airline and airport operator interviewees were convinced that with all of the other economic sectors having much more room to manoeuvre in terms of energy efficiency and low-carbon supply, the aviation industry could continue with current practice by buying carbon permits from these sectors within such an EU trading scheme. This view ignores the fact that the aviation industry is also expanding rapidly throughout Europe, in some countries at much higher rates than the UK (Bows et al., 2005; ATAG, 2000). Combining this with a contraction limit on the emissions space available for all the sectors of the economy will result in a requirement for substantial trade-offs with other sectors within Europe. Furthermore, if the carbon reduction target for Europe was based on the latest science available, and hence aimed to stabilise carbon dioxide concentrations at 450ppmv, all of the other sectors of the economy would have to virtually completely decarbonise by 2050 to allow the aviation industry to grow (Bows et al., 2005).

Using the UK as a closed example[26], under the 450ppmv profile, there will be approximately 32MtC left for the whole economy by 2050. If the aviation industry is emitting 32MtC, as it does in the Tyndall aviation scenarios 1 and 3, and the UK Government's 'worst' case scenario, then this leaves 0MtC for all of the other sectors. This would mean that the household sector for example, would need to reduce emissions from 40MtC today, to zero, and road transport from 32MtC today, to zero. Furthermore, household energy consumption is currently growing at just under 1% per year, similarly energy consumption in private road transport is growing at 2% per year (DUKES, 2005). Given the Tyndall Centre's 40% house project views reducing emissions from the household sector by just 60% by 2050, a "considerable challenge" (Boardman et al., 2005), slashing carbon emissions to zero appears to be far too great a challenge to overcome. Consequently, the aviation industry must urgently accept that it can not rely on the other sectors of the economy for it to continue to grow. Only with the swift implementation of a global emissions trading scheme with an appropriately contracting cap, could aviation growth be accommodated within a world attempting to avoid dangerous climate change. However, whilst such analysis is beyond the scope of this study, the potential for reconciling the predicted 5% per year growth in the aviation industry until 2020 (section 2.2), a global economic growth of over 4% per year and climate change targets at 550ppmv or below, must be in doubt. Clearly this is a matter that even within a global emissions trading system would require urgent investigation.

To further compound the problem, the results presented within this project report do not attempt to include the additional impacts of aviation on the climate in the form of warming caused by contrails, cirrus clouds and other greenhouse gas emissions. These additional effects are thought to increase the impact of aviation on the climate by between 2 and 4 times. It can easily be concluded therefore that growth within the aviation industry needs to be curbed as a matter of urgency to ensure fuel efficiency gains do not outstrip growth, and to allow the UK Government's targets to be reached, and more importantly, to have the desired effect.

7.4 What can be done to reduce emissions?

The discussion above leads to the conclusion that aviation growth must be curbed if no step-change in technology is to affect the aviation industry in the short to medium term. Although emissions trading is thought by industry stakeholders to be one way of increasing ticket prices, and hence reducing the level of growth (section 6.3.3), they also accept that it is unlikely that aviation will be incorporated into the scheme before 2010, and even then, as discussed, the scheme is unlikely to include all international flights to and from the EU. In the meantime, governments across Europe will be looking to increase airport capacity in the same way as the UK Government plans to do

[26] Emissions per capita in the UK are in the top 8 of the EU25 according to data taken from the CCOptions model (GCI, 2004), therefore the UK will need to make substantial cuts to its carbon emissions under a comprehensive emissions trading scheme.

(DfT, 2003b). Therefore, one way to curb growth in the interim, and avoid an irresolvable situation in the future, would be to put a freeze on the expansion and construction of new airports and runways. It is difficult to see how, once a new airport is built, it will be in the government's or private developer's best interests to leave the airport dormant – a foreseeable problem in light of the urgency to address the climate issue.

An alternative way of preventing the construction of new airport infrastructure and capacity, is to pay significant attention to increasing load factors on planes. The current average load factor in Europe is 60%, but it could possibly be pushed closer to 90% by investing in more sophisticated and integrated ticketing arrangements, encouraging greater flexibility on the side of the passenger and facilitating a radical shift in the relationships between the companies who bring about these changes.

The consideration of a slower form of flight offers large fuel efficiency gains due to the relationship between drag and speed, and could therefore be employed to reduce emissions per passenger. This is also something that could be implemented without any change to the aircraft's airframe or technology. Airships may also offer low-carbon forms of flight, but a great deal of research and funding will be required to boost the industry enough to encourage the new infrastructure it would require, and also possibly engender cultural change.

The one fuel that offers a low-carbon alternative future to the aviation industry is Fischer-Tropsch kerosene produced from biomass or synfuel from coal. However, industry stakeholders generally rejected its use within the industry as it is assumed that it will be used primarily in road transport. However, it should be borne in mind that road transport also has the option of using electrically-powered or hydrogen powered vehicles. One could ask therefore, if such kerosene proved viable for aviation, would it not be better to use this alternative fuel in the one industry that has no other alternative low-carbon supply, so that, along with all of the other industries, the aviation industry begins to play its, arguably obligatory, role towards alleviating climate change?

7.5 Final conclusion

The aviation industry is a successful, well-established and technically-mature sector, contributing significantly to both the development and culture of the UK specifically and the EU more generally. However, whilst this relatively competitive industry continually pursues technical and operational improvements, there is little evidence to suggest that such improvements will offer more than relatively small incremental reductions in fuel burn. Hydrogen is often mooted as an alterative to kerosene, but foreseeable problems include enhanced water vapour emissions and the practicalities of both low-carbon production and storage. Biofuel and biofuel-kerosene blends are possibly more plausible in the medium term; however the land-take implications, though still characterised by uncertainty, are likely to be very substantial. Consequently, the aviation industry is in the unenviable position of seeing the demand for its services grow at unprecedented rates, whilst at the same time being unable to achieve substantial levels of decarbonisation in the short to medium term. Indeed the new airbus A-380 continues to use high-pressure, high-bypass jet turbine engines that contain only incremental improvements over their predecessors.[i] Moreover, a combination of both long design runs (already 35 years for the Boeing 747) and design lives (typically 30 years), locks the industry into a kerosene-fuelled future. If the A380 were to follow a similar path to the 747 it will, in gradually modified form, be gracing our skies in 2070. Consequently, decisions we make now in relation to purchasing new aircraft and providing the infrastructure to facilitate their operation have highly significant implications for the UK's and EU's carbon emissions profile from now through until 2070.

The Tyndall analysis reveals the enormous disparity between the UK's position on carbon reduction and the UK Government's singular inability to seriously recognise and adequately respond to the rapidly escalating emissions from aviation. Indeed, the UK typifies the EU in actively planning and thereby encouraging continued high levels of growth in aviation, whilst simultaneously asserting that they are committed to a policy of substantially reducing carbon emissions. The research conducted within this project not only quantifies the contradictory nature of these twin goals, but also illustrates how constrained are the responses. Ultimately, the UK and the EU face a stark choice: to permit high levels of aviation growth whilst continuing with their climate change rhetoric; or to convert the rhetoric into reality and substantially curtail aviation growth.

8. References

AD Little (2000) *Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK*, Final Report to Department of the Environment, Transport and Regions (DETR), November 2000, DETR Contract No. PPAD 9/91/14, Cambridge, www.aviation.dft.gov.uk/techchange/pdf/techchange.pdf

Anderson, K. and Wood, L., (2001), Airships as a means of freight transport, a feasibility study, CATE, REF: GR/R 32499

Anderson, K., Shackley S., Mander S. and Bows, A (2005), *Decarbonising the UK – energy for a climate conscious future,* Tyndall Centre for Climate Change.

ATAG, (2000), *European Air Traffic Forecasts 1985-2015*, produced by IATA consultancy services.

Aviation (2005), *A strategy towards sustainable development of UK aviation*, Sustainable Aviation Publication, First Published June 2005.

Berk, M.M. & den Elzen, M.G.J. (2001) *Options for differentiation of future commitments in climate policy: how to realize timely participation to meet stringent climate goals*, Climate Policy, 1:465-480.

Berthelot, M., Friedlingstein,P., Ciais,P., Dufresne,J., Monfray,P. 2005. How uncertainties in future climate change predictions translate into future terrestrial carbon fluxes. *Global Change Biology*. Vol 11, Issue 6, Page 959

Boardman, B., Killip, G., Darby, S., Sinden, G., Newborough, M., Wright, A. (2005), 40% House Report, Tyndall Centre, 2005.

Boeing (2004) *2004 current market trend output*, http://www.boeing.com/commercial/cmo/2-1.html

Boeing (2005a) 2005 World Transport Forecast, http://www.boeing.com/commercial/cargo/01_06.html

Boeing (2005b) *Current market outlook 2005*, http://www.boeing.com/commercial/cmo/2-1.html

Böhringer, C. and Welsch, H. (2000) *Contraction & Convergence: the economic implications of permit trading*, ZEW Discussion Paper No. 99-13, Mannheim, www.zew.de/en/publikationen/

Bows, A. and Anderson, K. (2004) *Planned growth in aviation contradicts government carbon targets*, Climate Change Management, Jan 2004.

Bows, A. and Anderson, K. (2005) *Evaluation and assessment of the Global Common's Institute Contraction & Convergence model*, *CCOptions*, Tyndall Centre Working Paper 82, 2005.

Bows, A., Anderson, K.A. and Upham, P., (2005) 'Growth Scenarios for EU & UK Aviation: contradictions with climate policy', Tyndall Centre for Climate Change/Friends of the Earth, Manchester, (2005).

CAA (2002) Table 02.2, *Summary of activity at UK airports*, www.caa.co.uk/docs/80/airport_data/2002Annual/Table_02_2_Summary_of_Activity_At_UK_Airports_2002.pdf

CAA (2003), *Air passenger growth and airport capacity, advice to the Department for Transport on the future nature of the distribution of demand for air travel*, www.dft.gov.uk/stellent/groups/dft_aviation/documents/page/dft_aviation_031847.pdf

CAA (2004) Table 02_1 http://www.caa.co.uk/docs/80/airport_data/2004Annual/Table_02_1_Main_Outputs_of_UK_Airports_2004.pdf

CDIAC (2005) cdiac.esd.ornl.gov/

CDIAC (2004) cdiac.esd.ornl.gov/

Cameron J, A. Evans, *What happens after Kyoto? More of the same – or 'Contraction & Convergence'?*, New Economy, 3, 10, 128-131, 2003.

Cames, M., Deuber, O. and Rath, U. (2004) *Emissions trading in international civil aviation*, Oko-Instiute e.V., Berlin.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A. and Totterdell, I.J. (2000) *Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model*, Nature, 408 (6809), pp.184-7.

DEFRA (2004) *Scientific and technical aspects of climate change, including impacts and adaptation and associated costs*, Department for Food and Rural Affairs, London, www.defra.gov.uk/environment/climatechange/pdf/cc-science-0904.pdf

Cox, P.M., (2005) 'Conditions for positive feedbacks from the land carbon cycle'. Paper presented at the International Symposium on Stabilisation of Greenhouse Gases, Met Office, Exeter, February 2005.

Cranmer, W., Bondeau, A., Woodward, F.I., Prentice, I.C., Betts, R.A., Brovkin, V., Cox, P.M., Fisher, V., Foley, J.A., Friend, A.D., Kucharik, C., Lomas, M.R., Ramankutty, N., Sitch, S., Smith, B., White, A. and Young-Molling, C., (2001) 'Global response of terrestrial ecosystem structure and function to CO2 and climate change: results from six dynamic global vegetation models', *Global Change Biology*, 7, 357-373

DEFRA (2003a) *The Scientific Case For Setting A Long-Term Emission*

Reduction Target, Department for Environment, Food and Rural Affairs, London, www.defra.gov.uk/environment/climatechange/ewpscience/ewp_targetscience.pdf

DEFRA (2003b) *Climate Change: Action to tackle Global Warming*, *DEFRA web pages*, Department for Environment, Food and Rural Affairs,

www.defra.gov.uk/environment/climatechange/02.htm

DfT (2002a) *Regional Air Services Co-ordination Study. RAScarbon dioxide Final Report*, July, Department for Transport,

www.aviation.dft.gov.uk/consult/airconsult/rasco/index.htm

DfT (2002b) *The Future Development of Air Transport in the United Kingdom: Scotland*, Summary Consultation Document, Department for Transport, London.

DfT (2003a) *Aviation and the Environment: Using Economic Instruments*, Department for Transport, London,

www.hmtreasury.gov.uk/documents/taxation_work_and_welfare/tax_and_the_environment/aviation/tax_avi_index.cfm

DfT, (2003b) Department for Transport, Aviation White Paper, 'The Future Development of Air Transport', The Stationery Office, London, 2003.

DfT (2004) *Aviation and Global Warming*, Department for Transport, London.

DfT (2005) *Transport statistics Great Britain*, The Stationery Office, London, 2005.

DTI (2002) *UK CO_2 Emission Projections (MtC)*, Energy Paper 68: Energy Projections for the UK (London, Department for Trade and Industry), www.dti.gov.uk/energy/inform/energy projections/ep68final.pdf

DTI (2003) *Our Energy Future - creating a low carbon economy*, Cm 5761,

www.dti.gov.uk/energy/whitepaper/ourenergyfuture.pdf

EEA (2003) *Annual European Community greenhouse gas inventory 1990-2001 and inventory report 2003 (Final draft).* Technical report No 95, European Environment Agency, reports.eea.eu.int/technical_report_2003_95/en

EUROCONTROL (2004a) *STATFOR Forecast of Annual Number of IFR Flights (2004-2010)*, volumes 1 and 2, Brussels,

www.eurocontrol.int/statfor/public/standard_page/forecast_methodology.html

EUROCONTROL (2004b) *EUROCONTROL long-term forecasts of flights*, DIA.STATFOR.DOC.103.v0.1

Elzen, M.G.J. den, Berk, M., Both, S., Faber, A. and Oostenrijk, R. (2000) *FAIR 1.0: An interactive model to explore options for differentiation of future commitments in international climate policy making*, report nr. 728001013, RIVM National Institute of Public Health and the Environment, Bilthoven, the Netherlands, arch.rivm.nl/fair/index.html

Elzen, M.G.J. den and Meinshausen, M. (2005) *Emission implications of long-term climate targets*, Conference Proceedings, Avoiding Dangerous Climate Change, International Symposium on Stabilisation of Greenhouse Gases, Exeter.

European Commission (2000) *Green Paper on greenhouse gas emissions trading within the European Union*, COM(2000) 87 final, 8.3.2000, Brussels,

europa.eu.int/eur-lex/en/com/gpr/2000/com2000_0087en01.pdf

Friedlinstein, P., Bopp, L., Ciais, P., Dufresne, J., Fairhead, L., LeTreut, H., Monfray, P., and Orr, J., 2001. In: 'Positive feedback between figure climate change and the carbon cycle,' *Geophysical Research Letters*, 28, 1543-1546.

Friedlingstein, P., P. Cox, R. Betts, W. von Bloh, V. Brovkin, S. Doney, M. Eby, I. Fung, B. Govindasamy, J. John, C. Jones, F. Joos, M. Kawamiya, W. Knorr, K. Lindsay, H. D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R. Schnur, K. Strassmann, S. Thompson, A. J.Weaver, and N. Zeng, Climate –carbon cycle feedback analysis, results from the C^4MIP model intercomparison, draft paper, 2005.

Gauss, M. (2004), Isaksen, I.S.A., Wong, S., Want, W.-C., *Impact of H2O emissions from cryoplanes and kerosene aircraft on the atmosphere*, Journal of Geophysical Research, Vol. 108, No. D10, 4304.

GCI, (2004), http://www.gci.org.uk

Hadley, (2002). *Stabilisation and commitment to future climate change*, Scientific results from the Hadley Centre.

Hadley (2005) *Report of the International Scientific Steering Committee*, International Symposium on Stabilisation of Greenhouse Gases, Avoiding Dangerous Climate Change, Met Office, Exeter, 1-3 Feb 2005

Höhne, N., Galleguillos, C., Blok, K., Harnisch, J. and Phylipsen, D. (2003) *Evolution of commitments under the UNFCCC: Involving newly industrialized economies and developing countries*, report by Ecofys Gmbh for the Federal Environmental Agency, Umweltbundesamt Research Report 201 41 255 UBA-FB 000412, Berlin,

www.umweltdaten.de/klimaschutz/Climate_Change_01-03_UBA.pdf

House of Commons Environmental Audit Committee (2004) *Third Report. Pre-Budget Report 2003: Aviation Follow-up*, HC 233I/II, The Stationary Office, London, 16 March 2004.

House of Lords (2004) *The EU and Climate Change*, Lords Select Committee on the European Union (sub-committee (E) on environment and agriculture), 30th Report, Session 2003-04, HL Paper 179, London, Stationery Office,

www.publications.parliament.uk/pa/ld/ldeucom.htm

Houghton, J. (2002) *The challenges of energy—response to Moody-Stuart*, Ethics in Science and Environmental Politics, 26 September 2002, pp. 47–51.

ICAO (2000) The Economic Benefits of Air Transport 2000 edition, prepared for the ATAG by IATA, www.icao.int.ATworkshop/EconomicBenefitsAirTransport.pdf

IPCC (1994) Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harries, N. and Maskell, K.,. *Climate Change: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, Cambridge, Cambridge University Press (Science Publishers), 339.

IPCC (1995), Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harries, N., Kattenberg, A. and Maskell, K., *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the IPCC*, Cambridge, Cambridge University Press (Science Publishers), 572.

IPCC (1999) *Aviation and the Global Atmosphere. Summary for Policymakers*. A Special Report of IPCC Working Groups I and III in collaboration with the Scientific Assessment panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, Penner, JE,

Lister, DH, Griggs, DJ, Dokken, DJ and McFarland, M (eds). Intergovernmental Panel on Climate Change, Geneva, www.grida.no/climate/ipcc/aviation/index.htm

IPCC (2001) *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,

www.grida.no/climate/ipcc_tar/wg1/pdf/WG1_TAR-FRONT.PDF

Jansen, J.C., Battjes, J.J., Ormel, F.T, Sijm, J.P.M., Volkers, C., Ybema, J.R., Torvangar, A., Ringius, L., Underdal, A. (2001b) *Sharing the burden of greenhouse gas mitigation*, Final Report of the joint CICERO-ECN project on the Global Differentiation of Emission Mitigation Targets Among Countries. *ECN Report ECN-C-01-009*, Petten, The Netherlands, and CICERO Working Paper No. 5, CICERO, Oslo, Norway.

Jones, C., McConnell, C., Coleman, K., Cox, P., Falloon, P., Jenkinson, D., Powlson, D., 2005a. In: 'Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil', *Global Change Biology*, 11, 154-166.

Jones, C., Cox, P., Huntingford, C., 2005b. 'Impact of climate-carbon cycle feedbacks on emission scenarios to achieve stabilisation,' *Proceedings of the International Symposium on Stabilisation of Greenhouse Gases*, Exeter, DEFRA.

Jones, C.D., Cox, P.M. and Huntingford, C., 2003. In: 'Uncertainty in climate-carbon cycle projections associated with the sensitivity of soil respiration to temperature,' *Tellus*, 55B, 642-648.

Layos, L.de la F., 2005, *Statistics in Focus, Passenger Air Transport, 2002-2003,* Eurostat ISSN 1562-1324.

Lee, D.S. and Sausen, R., (2000). *New Directions: Assessing the real impact of CO2 emissions trading by the aviation industry*, Atmospheric Environment, 34, 5337-5338.

Lenton, T.M. and Huntingford, C., (2003). In: 'Global terrestrial carbon storage and uncertainties in its temperature sensitivity examined with a simple model', *Global Change Biology*, 9, 1333-1352.

Lenton, T.M., (2000). In: 'Land and ocean carbon cycle feedback effects on global warming in a simple Earth system model', *Tellus*, 52B, 1159-1188.

Liebeck, R.H., Page, M. A. and Rawdon, B.K., 'Blended Wing Body Subsonic Commercial Transport', AIAA-98-0438, American Institute of Aeronautics and Astronautics, 36th Aerospace Sciences Meeting, Nevada, USA, 1998.

Lim, L.L, D. Lee and S.C.B. Raper (2004), *The role of aviation emissions in climate stabilisation scenarios*, poster presentation at the Avoiding Dangerous Climate Change conference, Exeter.

Meyer, A. (2000) *Contraction & Convergence - The Global Solution to Climate Change*, Schumacher Briefing No.5, Green Books, Devon, England.

Missfeldt, F. (1998) *Flexibility Mechanisms: which path to take after Kyoto?,* Review of European Community and International Environmental Law, 7 (2): 128-139.

NASA (2002) The *Blended Wing Body: A Revolutionary Concept in Aircraft Design*, NASA Facts On-Line, FS-2001-04-24-LaRC, NASA Langley Research Centre, Virginia, oea.larc.nasa.gov/PAIS/BWB.html

Ponater, M. (2003), S. Marquart, L. Ström, K. Gierens, R. Sausen, G. Hüttig, On the potential of the cryoplane technology to reduce aircraft climate impact, Proceedings of the AAC-Conference, June 30 to July 3, 2003, Friedrichshafen, Germany.

RCEP (2000) *Energy - The Changing Climate*, Twenty Second Report of the Royal Commission on Environmental Pollution, Cm4749. www.rcep.org.uk/pdf/chp4.pdf

RCEP (2002) *The Environmental Effects of Civil Aircraft in Flight*, Special Report of the Royal Commission on Environmental Pollution, www.rcep.org.uk/

Rolls-Royce (2005) *The outlook 2005*, http://www.rolls-royce.com/civil_aerospace/overview/market/outlook/downloads/outlook2005.pdf

Saynor, B.,(2003), Bauen, A. and Leach, M., 'The potential for renewable energy sources in aviation', report commissioned for the DTI, Imperial College Centre for Energy Policy and Technology.

Sijm, J., Jansen, J. and Torvanger, A. (2001) *Differentiation of mitigation commitments: the multi-sector convergence approach*, Climate Policy (1): 481-497.

Stat, (2002), *Statistics in focus, Air transport in the candidate countries 1995-2000,* Theme 7, Eurostat, ISSN: 1562-1324

UN, 2002: World population prospects, revision 2002, http://www.un.org/popin/data.html, Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat

UNFCCC (1992) *United Nations Framework Convention On Climate Change*, United Nations, Bonn, unfccc.int/resource/docs/convkp/conveng.pdf

UNFCCC (1992) *Kyoto Protocol To The United Nations Framework Convention On Climate Change*, Bonn, unfccc.int/resource/docs/convkp/kpeng.pdf

White, A., Cannell, M.G.R. and Friend, A.D., (1999). In: 'Climate change impacts of ecosystems and the terrestrial carbon sink: a new assessment', *Global Environmental Change*, 9, S21-S30.

Williams, V. and R.B.Noland (2005) Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation, *Transportation Research Part D*, Vol 10, 4, pp 269-280.

Windischbauer, F. and J. Richardson (2005) *Restrostrategy: Is there another chance for lighter-than-air vehicles*, Foresight, Vol 7, No. 2, pp. 54-65.

World, 2003. *World population data sheet, population reference bureau: demographic data and estimates for the countries and regions of the world*, http://www.prb.org/pdf/WorldPopulationDS03_Eng.pdf

Zeng, N., Qian, H., Munoz, E. and Iacono, R., (2004) 'How strong is carbon cycle-climate feedback under global warming?', *Geophysical Research Letters*, 31 L20203

Appendix

Conference papers:

Bows, A., Anderson, K. and Upham P., *No chance for climate without tackling aviation*, Decarbonising the UK, London, 2005.

Presentations:

Anderson, K. and Bows, A., *Growth Scenarios for EU & UK Aviation: contradictions with climate policy*, presentation to 18 MPs, Portcullis House, London, 2005.

Upham, P. and Viner, D. (2005) *Can you afford your holiday in the sun?*, Climate Outreach and Information Network, July 7th, Oxford Town Hall.

Anderson, K. and Bows, A., *Growth Scenarios for UK Aviation: contradictions with climate policy*, presentation to Labour MPs and civil servants – event organised by SERA, Portcullis House, London, 2005.

Anderson, K. *Growth Scenarios for EU & UK Aviation: contradictions with climate policy*, Presentation to UK Aviation Minister, Aviation Ministers from 10 EU nations and associated civil servants. Dinner in London organised by SERA, London, 2005.

Anderson, K. *Growth Scenarios for EU & UK Aviation: contradictions with climate policy*. Summing up Conference of National Parliaments of the EU and the European Parliament including presentation of Tyndall aviation work. Event organised by EFRACOM, Forthcoming –London, November 2005.

Anderson, K. *Growth Scenarios for EU & UK Aviation: contradictions with climate policy*. Presentation to Green Group – Green MEPs conference in London, organised by Caroline Lucas MEP. Forthcoming –London, November 2005.

Consultancy:

Bows, A., Anderson, K. and Upham, P. (2004) *Contraction and Convergence Greenhouse Gas Emissions Policy: indicative implications for UK aviation within a European Emissions Trading System. Extended Interim Report for Friends of the Earth Trust Ltd.*, Tyndall Centre for Climate Change Research (North), The University of Manchester, UK.

Bows, A., Anderson, K. and Upham, P. (2005) *Growth Scenarios for EU & UK Aviation: contradictions with climate policy, Report for Friends of the Earth Trust Ltd.*, Tyndall Centre for Climate Change Research (North), The University of Manchester, UK.

Policy responses:

Upham, P., Anderson, K., and Bows, A., House of Lords Sub-Committee B, *Inquiry into the merits of including the aviation sector in the EU emissions trading scheme*, Oral Evidence, October 2005.

Köhler, J., Upham, P., Bows, A. and Anderson, K. (2004) "Proposals for development of the Department for Transport's Evidence and Research Strategy 2004 from the Tyndall Centre for Climate Change Research", submission to Department for Transport, Tyndall Centre, UK.

Upham, P, Anderson, K., and Bows, A., (2004), Department for Transport research strategy consultation.

Anderson, K., and Bows, A., EFRACOM (DEFRA Select Committee), (2004) *Climate Change: Looking Forward*, Environment, Food and Rural Affairs Committee, Oral Evidence, June, 2005.

Environmental Audit Committee (2004) *The international challenge of Climate Change: UK leadership in the G8 and EU.*

Media interviews:

Anderson, K., BBC Radio 4 – the issue of growth in the aviation industry vs climate change, September 2005

Anderson, K., BBC Breakfast - the issue of growth in the aviation industry vs climate change, September 2005

Anderson, K., Five Live - the issue of growth in the aviation industry vs climate change, September 2005

Anderson, K., Radio Scotland - the issue of growth in the aviation industry vs climate change, September 2005

Anderson, K., Radio Wales - the issue of growth in the aviation industry vs climate change, September 2005

Anderson, K., The Independent - the issue of growth in the aviation industry vs climate change, September 2005

Anderson, K., Sky News - the issue of growth in the aviation industry vs climate change, September 2005

Anderson, K., BBC 3 News - the issue of growth in the aviation industry vs climate change, September 2005

Bows, A., BBC Radio One – the issue of growth in the aviation industry vs climate change, November 2004.

Bows, A., BBC TV News 24 – the issue of growth in the aviation industry vs climate change, September 2005

Bows, A., BBC TV World – the issue of growth in the aviation industry vs climate change, September 2005

Bows, A., Radio Stockport – the issue of growth in the aviation industry vs climate change, September 2005

Bows, A., Radio 3 Counties – the issue of growth in the aviation industry vs climate change, September 2005

Bows, A., Climate Change Management – the issue of growth in the aviation industry vs climate change, September 2005

Journal papers:

Upham, P.J. and Mills, J.N. (2005) Airport Environmental Sustainability Indicators: Data Availability and Stakeholders, *Benchmarking - An International Journal*, vol. 12, no. 2, pp.1463-5771.

Upham, P., Butlin, S., Davis, M., Nilsson, U., Smith, T. (2005) Allocating aircraft carbon dioxide emissions to airports on the basis of passenger share: scenarios for Manchester Airport, *World*

Transport Policy and Practice, vol.11, no. 1, pp.5-12, http://www.eco-logica.co.uk/WTPPhome.html

Upham, P.J. (2003) "Climate Change and Planning and Consultation for The UK Aviation White Paper", *Journal of Environmental Planning and Management*, 46 (6): 911-918.

Bows, A., Upham, P. and Anderson, K. (2004) Aviation and Climate Change: implications of the UK white paper on the future of aviation", *Climate Change Management*, January 2004.

Bows, A. and Anderson K., (2005), Contraction and Convergence: An assessment of the *CCOptions* model, submitted to *Climatic Change*, 2005.

Bows, A. and Anderson, K. (2005) *Evaluation and assessment of the Global Common's Institute Contraction & Convergence model, CCOptions*, Tyndall Centre Working Paper 82, 2005.

Bows, A., Anderson, K. and Upham, P., (2005), White paper clash: Can projected aviation growth be reconciled with the UK Government's 60% carbon reduction target?, submitted to *Transport Policy*, 2005.

Other articles:

Upham, P., 2004, Greenhouse gas emissions and the Aviation White Paper: at the expense of other sectors, Science and Public Affairs.

Bows, A., Pie in the sky, Planet Earth, Nerc Magazine, October 2004.

Bows, A. and Anderson, K., Flying Into Dangerous Climate Change, Manchester Evening News, September 2005.

---

[i] Given the storage requirements of hydrogen, it is highly unlikely that the A380 could be converted to operate with hydrogen-fuelled jet engines – should a low-carbon hydrogen source become readily available. The use of hydrogen for fuelling aviation will require a new generation of aircraft designed to store a fuel with very different characteristics and properties from that of kerosene. Given the very long design and regulatory environment associated with new aircraft, it is difficult to envisage a substantial penetration of hydrogen-fuelled aircraft before 2030 to2040.

Tyndall°Centre
for Climate Change Research

The inter-disciplinary Tyndall Centre for Climate Change Research undertakes integrated research into the long-term consequences of climate change for society and into the development of sustainable responses that governments, business-leaders and decision-makers can evaluate and implement. Achieving these objectives brings together UK climate scientists, social scientists, engineers and economists in a unique collaborative research effort.

Research at the Tyndall Centre is organised into four research themes that collectively contribute to all aspects of the climate change issue: Integrating Frameworks; Decarbonising Modern Societies; Adapting to Climate Change; and Sustaining the Coastal Zone. All thematic fields address a clear problem posed to society by climate change, and will generate results to guide the strategic development of climate change mitigation and adaptation policies at local, national and global scales.

The Tyndall Centre is named after the 19th century UK scientist John Tyndall, who was the first to prove the Earth's natural greenhouse effect and suggested that slight changes in atmospheric composition could bring about climate variations. In addition, he was committed to improving the quality of science education and knowledge.

The Tyndall Centre is a partnership of the following institutions:

University of East Anglia
University of Manchester
Southampton Oceanography Centre
University of Southampton
University of Cambridge
Centre for Ecology and Hydrology
SPRU – Science and Technology Policy Research (University of Sussex)
Institute for Transport Studies (University of Leeds)
Complex Systems Management Centre (Cranfield University)
Energy Research Unit (CLRC Rutherford Appleton Laboratory)

The Centre is core funded by the following organisations:

Natural Environmental Research Council (NERC)
Economic and Social Research Council (ESRC)
Engineering and Physical Sciences Research Council (EPSRC)
UK Government Department of Trade and Industry (DTI)

For more information, visit the Tyndall Centre Web site (www.tyndall.ac.uk) or contact:

Communications Manager
Tyndall Centre for Climate Change Research
University of East Anglia, Norwich NR4 7TJ, UK
Phone: +44 (0) 1603 59 3906; Fax: +44 (0) 1603 59 3901
Email: tyndall@uea.ac.uk

Recent Tyndall Centre Technical Reports

Tyndall Centre Technical Reports are available online at
http://www.tyndall.ac.uk/publications/tech_reports/tech_reports.shtml

- Bows, A., Anderson, K. and Upham, P. (2006) **Contraction & Convergence: UK carbon emissions and the implications for UK air traffic**, Tyndall Centre Technical Report 40
- Starkey R., Anderson K., (2005) **Domestic Tradeable Quotas: A policy instrument for reducing greenhouse gas emissions from energy use**:, Tyndall Centre Technical Report 39
- Pearson, S., Rees, J., Poulton, C., Dickson, M., Walkden, M., Hall, J., Nicholls, R., Mokrech, M., Koukoulas, S. and Spencer, T. (2005) **Towards an integrated coastal sediment dynamics and shoreline response simulator**, Tyndall Centre Technical Report 38
- Sorrell, S. (2005) **The contribution of energy service contracting to a low carbon economy**, Tyndall Centre Technical Report 37
- Tratalos, J. A., Gill, J. A., Jones, A., Showler, D., Bateman, A., Watkinson, A., Sugden, R., and Sutherland, W. (2005) **Interactions between tourism, breeding birds and climate change across a regional scale**, Tyndall Centre Technical Report 36
- Thomas, D., Osbahr, H., Twyman, C., Adger, W. N. and Hewitson, B., (2005) **ADAPTIVE: Adaptations to climate change amongst natural resource-dependant societies in the developing world: across the Southern African climate gradient**, Tyndall Centre Technical Report 35
- Arnell, N. W., Tompkins, E. L., Adger, W. N. and Delany, K. (2005) **Vulnerability to abrupt climate change in Europe**, Tyndall Centre Technical Report 34
- Shackley, S. and Anderson, K. et al. (2005) **Decarbonising the UK: Energy for a climate conscious future**, Tyndall Technical Report 33
- Halliday, J., Ruddell, A., Powell, J. and Peters, M. (2005) **Fuel cells: Providing heat and power in the urban environment**, Tyndall Centre Technical Report 32
- Haxeltine, A., Turnpenny, J., O'Riordan, T., and Warren, R (2005) **The creation of a pilot phase Interactive Integrated Assessment Process for managing climate futures**, Tyndall Centre Technical Report 31
- Nedic, D. P., Shakoor, A. A., Strbac, G., Black, M., Watson, J., and Mitchell, C. (2005) **Security assessment of futures electricity scenarios**, Tyndall Centre Technical Report 30
- Shepherd, J., Challenor, P., Marsh, B., Williamson, M., Yool, W., Lenton, T., Huntingford, C., Ridgwell, A and Raper, S. (2005) **Planning and Prototyping a Climate Module for the Tyndall Integrated Assessment Model**, Tyndall Centre Technical Report 29
- Lorenzoni, I., Lowe, T. and Pidgeon, N. (2005) **A strategic assessment of scientific and behavioural perspectives on 'dangerous' climate change**, Tyndall Centre Technical Report 28
- Boardman, B., Killip, G., Darby S. and Sinden, G, (2005) **Lower Carbon Futures: the 40% House Project**, Tyndall Centre Technical Report 27
- Dearing, J.A., Plater, A.J., Richmond, N., Prandle, D. and Wolf , J. (2005) **Towards a high resolution cellular model for coastal simulation (CEMCOS)**, Tyndall Centre Technical Report 26
- Timms, P., Kelly, C., and Hodgson, F., (2005) **World transport scenarios project**, Tyndall Centre Technical Report 25
- Brown, K., Few, R., Tompkins, E. L., Tsimplis, M. and Sortti**,** (2005) **Responding to climate change: inclusive and integrated coastal analysis**, Tyndall Centre Technical Report 24
- Anderson, D., Barker, T., Ekins, P., Green, K., Köhler, J., Warren, R., Agnolucci, P., Dewick, P., Foxon, T., Pan, H. and Winne, S. (2005) **ETech+: Technology policy and technical change, a dynamic global and UK approach**, Tyndall Centre Technical Report 23
- Abu-Sharkh, S., Li, R., Markvart, T., Ross, N., Wilson, P., Yao, R., Steemers, K., Kohler, J. and Arnold, R. (2005) **Microgrids: distributed on-site generation**, Tyndall Centre Technical Report 22
- Shepherd, D., Jickells, T., Andrews, J., Cave, R., Ledoux, L, Turner, R., Watkinson, A., Aldridge, J. Malcolm, S, Parker, R., Young, E., Nedwell, D. (2005) **Integrated modelling of an estuarine environment: an assessment of managed realignment options**, Tyndall Centre Technical Report 21

- Dlugolecki, A. and Mansley, M. (2005) **Asset management and climate change**, Tyndall Centre Technical Report 20
- Shackley, S., Bray, D. and Bleda, M., (2005) **Developing discourse coalitions to incorporate stakeholder perceptions and responses within the Tyndall Integrated Assessment**, Tyndall Centre Technical Report 19
- Dutton, A. G., Bristow, A. L., Page, M. W., Kelly, C. E., Watson, J. and Tetteh, A. (2005) **The Hydrogen energy economy: its long term role in greenhouse gas reduction**, Tyndall Centre Technical Report 18
- Few, R. (2005) **Health and flood risk: A strategic assessment of adaptation processes and policies**, Tyndall Centre Technical Report 17
- Brown, K., Boyd, E., Corbera-Elizalde, E., Adger, W. N. and Shackley, S (2004) **How do CDM projects contribute to sustainable development?** Tyndall Centre Technical Report 16
- Levermore, G, Chow, D., Jones, P. and Lister, D. (2004) **Accuracy of modelled extremes of temperature and climate change and its implications for the built environment in the UK**, Tyndall Centre Technical Report 14
- Jenkins, N., Strbac G. and Watson J. (2004) **Connecting new and renewable energy sources to the UK electricity system**, Tyndall Centre Technical Report 13
- Palutikof, J. and Hanson, C. (2004) **Integrated assessment of the potential for change in storm activity over Europe: Implications for insurance and forestry**, Tyndall Centre Technical Report 12
- Berkhout, F., Hertin, J., and Arnell, N. (2004) **Business and Climate Change: Measuring and Enhancing Adaptive Capacity**, Tyndall Centre Technical Report 11
- Tsimplis, S. et al (2004) **Towards a vulnerability assessment for the UK coastline**, Tyndall Centre Technical Report 10
- Gill, J., Watkinson, A. and Côté, I (2004). **Linking sea level rise, coastal biodiversity and economic activity in Caribbean island states: towards the development of a coastal island simulator**, Tyndall Centre Technical Report 9
- Skinner, I., Fergusson, M., Kröger, K., Kelly, C. and Bristow, A. (2004) **Critical Issues in Decarbonising Transport**, Tyndall Centre Technical Report 8
- Adger W. N., Brooks, N., Kelly, M., Bentham, S. and Eriksen, S. (2004) **New indicators of vulnerability and adaptive capacity**, Tyndall Centre Technical Report 7
- **Macmillan, S. and Köhler, J.H., (2004) Modelling energy use in the global building stock: a pilot survey to identify available data**, Tyndall Centre Technical Report 6
- Steemers, K. (2003) **Establishing research directions in sustainable building design**, Tyndall Centre Technical Report 5
- Goodess, C.M. Osborn, T. J. and Hulme, M. (2003) **The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events**, Tyndall Centre Technical Report 4
- Köhler, J.H. (2002). **Modelling technological change**, Tyndall Centre Technical Report 3
- Gough, C., Shackley, S., Cannell, M.G.R. (2002). **Evaluating the options for carbon sequestration**, Tyndall Centre Technical Report 2
- Warren, R. (2002). **A blueprint for integrated assessment of climate change**, Tyndall Centre Technical Report 1