Short-haul Flights and Climate Change: What are the Effects and Potential Alternatives?

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Keywords: climate change, short-haul flights, integrated analysis, door-to-door emissions, policy-making.

ABSTRACT: Despite the economic crisis airline traffic for budget airlines grew by at least 10% in the beginning of 2009 (Ryanair, 2009; Easyjet, 2009). The growth in aviation can be attributed to the shift from full service carriers to budget airlines and as the industry if set to continue to grow this has important implications for climate change. Most literature focuses on modes of transport independent of each other. Realistically total journeys consist of a combination of transport modes as a consequence of time, cost and accessibility and policy making should involve a holistic approach in order to tackle climate change. This research involves a scenario analysis which involves calculating door-to-door emissions using a combination of different modes of transport between several origins within the UK to a destination in Europe. This provides a comparable analysis between budget airlines and full-service airlines; between hub airports and regional airports and between alternative modes of transport. Results show that trains are the best alternative in the context of door-to-door emissions however, results also show the necessity of an efficient infrastructure to and from regional airports to mitigate emissions. This paper concludes with a set of policy recommendations using a holistic approach.

1 INTRODUCTION

The impact of aviation on climate change is unique compared to other industries as aircraft engine emissions inject directly into the atmosphere which as research has shown has a greater effect on the environment than if the gases were emitted from the ground. The commercial aviation industry has been a fast growing industry and concerns are also growing in how to address its environmental impacts (Whitelegg, 2000; Bows & Anderson, 2007). Scientific uncertainty in quantifying these effects into a meaningful numerical value which policy makers require to mitigate these emissions poses a great challenge especially when emissions from aviation continue to grow.

Despite inclusion into the Kyoto Protocol, restrictions are only considered for domestic air travel (Oberthur, 2003). However, the majority of flights within Europe are international flights. In 2005, approximately 70% of total flights from the UK were destinations within Europe (CAA, 2007). With an increase of short-haul flights alternative modes of transports are being suggested in order to reduce green house gas emissions (ghge). International flights are set to continue to grow especially with budget airlines entering the medium-haul markets.

Since 1999, UK air traffic growth has been above the global average (Bows & Anderson, 2007). The UK accounts for a large proportion of the world's total aviation activity with a fifth of all international air passengers flying to or from a UK airport (DfT, 2003). The number of international passenger movements by air between 1995 and 2005 is illustrated in Figure 1:

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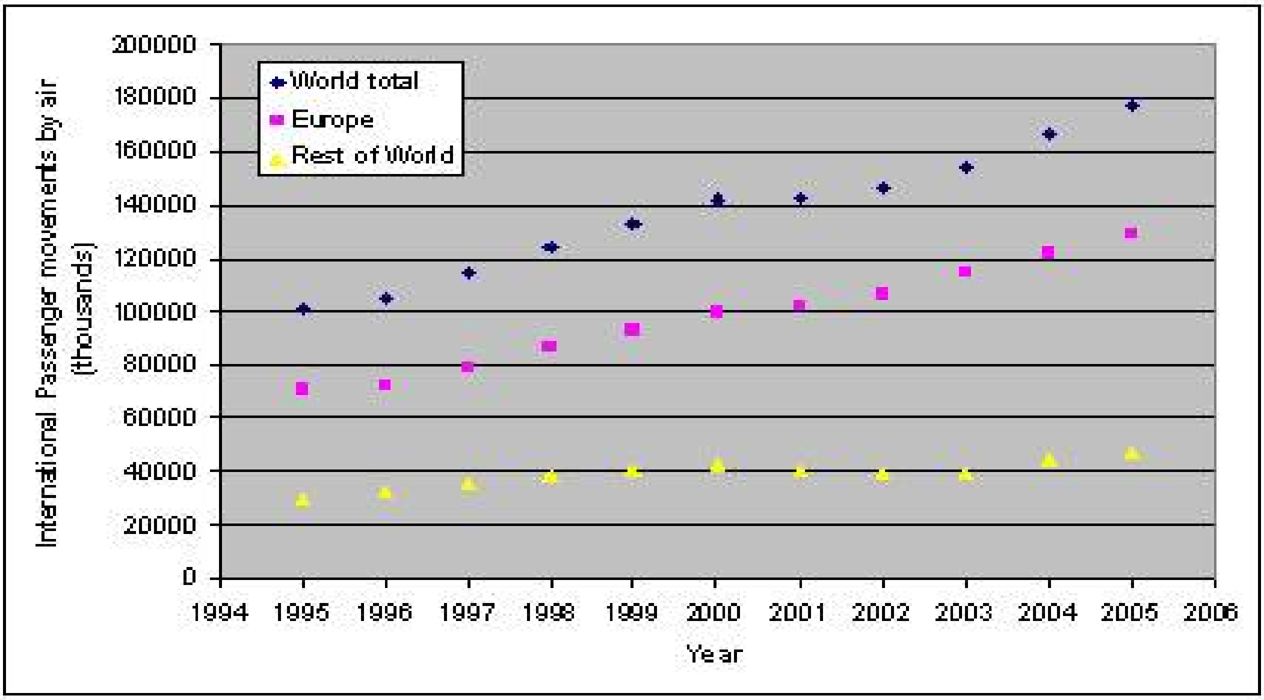

Figure 1. UK international passenger movements by air: 1995-2005 (DfT, 2006).

From Figure 1, the majority of international passenger movements are to and from Europe (approximately 70%) which is considered in this paper as short-haul. Furthermore, it shows that the increase of international passenger movements within the UK is attributed to short-haul flights. The number of international passengers from 2002 to 2005 increased by 31 million, 23 million additional passengers flying to Europe and about 8 million to the rest of the world.

It can be argued that this cause of growth can be attributed to the success of the low cost model used by budget airlines. Figure 2 (obtained from a report done by the CAA in 2006) illustrates the number of airport pairs from 1986 to 2005 comparing full-service airlines and budget airlines flown within the EU. It shows that from the mid 1990s airport pair numbers continued to grow rapidly for budget airlines relative to full-service airlines. This growth can be attributed to the increasing use of regional airports as well as using London (hub) airports. Between 1995 and 2005 the total traffic at regional airports grew from 46.6m to 94.7m, an average annual growth rate of 7.3% (CAA, 2006).

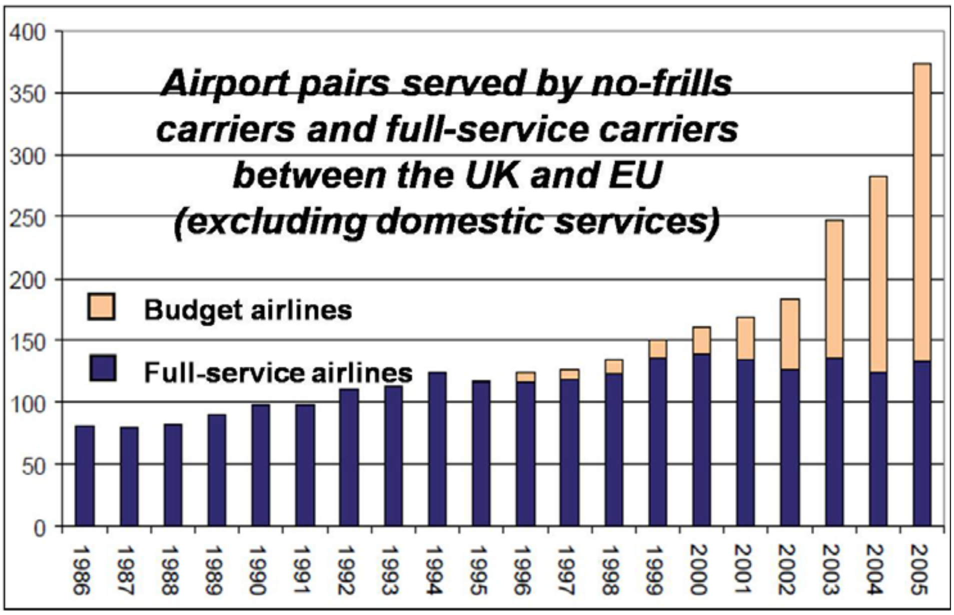

Figure 2. Airport pairs served by budget airlines between the UK and EU (excluding domestic services (CAA, 2006) (NB: CAA refers to budget airlines as 'no-frills' and also note this is for the EU and not all of Europe).

This paper analyses the effects of the changes within and its effect on climate change. The scope of the study consists of calculating the shift from full service airlines to budget airlines. This not only involves a change of airline, load capacity etc. but most importantly a shift of origin and destination airports i.e. hub versus regional. Most importantly, this research goes further and uses a holistic approach by calculating the door-to-door emissions from origin through to destination in the form of case studies. Literature read focuses on modes of transport independent of each other. Realistically, total journeys consist of a combination of transport modes as a consequence of time, cost and accessibility. Givoni and Banister (2006) discuss the potential benefits of airline and railway integration, through a mixture of substitution (i.e. replacing short-haul flights with high-speed rail) and complementation (better rail infrastructure to reach airports). However, their model was focused on Heathrow and discussed the potential benefits to hub airports if complementation was implemented. Finally, alternatives consisted of calculating different modes of transport i.e. substitution for the entire journey in each case study.

2 METHODOLOGY

A scenario analysis calculating the $CO_{2equivalent}$ of emissions for different combinations and sequences of modes of transport, including both full-service and budget airlines from regional and hub airports which are then compared and analysed. The scenario analysis uses a case study of holiday travellers travelling from the UK to the popular holiday destination Barcelona.
The scenario analysis considers three points of origins (Bristol, Bournemouth, Newcastle Upon Tyne). From each origin, holiday travellers have the following options to reach Barcelona via:

- a full-service airline flying from Heathrow airport (which included combinations of other modes of transport getting to and from the airport) to Barcelona airport (hub airport);
- a budget airline from Stansted (which included combinations of other modes of transport getting to and from the airport) to a regional airport in Girona and from there to Barcelona;
- regional airports (which included combination of other modes of transport getting to and from the airport) to a local airport in Girona and from there to Barcelona;
- alternative modes such as car, train, and coach for the entire journey.

The assumption of door-to-door was from each origin's train station to Barcelona train station. The budget airline Ryanair was used. The reasons for these different scenarios included to compare the emission differences between:

- Shifting from full-service carriers from Heathrow to budget airlines from Stansted
- Flying from regional airports versus flying from Stansted.
- Different combinations of modes of transport to and from the airport, to see if complementation could be feasible rather than complete substitution.
- Comparing the effects of flying versus potential alternatives over the ground.

The analysis is on the basis of a Boeing 737-400, a representative aircraft type for short-haul flights (Jardine, 2005). The emissions for a B737-400 are obtained from the Emissions Inventory Guidebook (EEA, 2001). Both the 'landing and take-off' (LTO) and 'climb cruise and descend' (CCD) distances are used to obtain the CO_2 emissions for the flight. The total CO_2 emissions from the LTO cycle of the B737-400 are equal to 2599.7 kg CO_2. The total CO_2 emissions from the CCD cycle of the B737-400 depends on the quantity of fuel burnt, which is a function of the distance flown. From the amount of fuel used, the CO_2 emissions can be calculated. Each kg of fuel burnt produces 3.15 kg of CO_2 (Jardine, 2005). The total $CO_{2equivalents}$/passenger.km for a short-haul flight can therefore be calculated as follows:

$$EPP = \frac{\left(LTO_{co2} + CCD_{co2}\right) \times RFI}{N_{seats} \times LF \times d} \qquad (1)$$

where EPP is kg of $CO_{2equivalent}$/pass.km; the LTO_{CO2} and CCD_{CO2} are in kg of CO_2; RFI is the radiative forcing index; N_{seat} is the number of seats an aeroplane contains; LF is the load factor and d is the distance. The RFI factor of 1.9 is used to convert the CO_2 emissions of the aircraft into

$CO_{2equivalent}$ emissions and this figure is obtained from research on radiative forcing from aviation conducted by Sausen et al. (2005).
The difference between budget and full service airlines were seat capacity and load factor:
- A full-service airline has 160 seats and an average occupancy of 70% (ELFAA, 2005)[8].
- Ryanair has 189 seats (Boukhari, 2007) and an average occupancy of 83% (ELFAA, 2005)

The emissions and assumptions associated with each mode of transport can be found in Table 1.

Ground-surface mode	Load factor	CO_2 equivalent/p.km	Reference
Petrol car	1.58	0.20949	Lenzen (1999)
Train	50% full	0.038	ECCM (2007)
Coach	Not listed in reference	0.1	National Express (2005)

Table 1. $CO_{2equivalent}$ values used for ground-surface modes of transport.

The following assumptions were used to calculate emissions from ground-surface modes of transport: the UK trains systems consists of 85% electric and 15% diesel trains, this composition was also used for Spanish train systems; the load factor for trains was 50%; the petrol car occupancy was of 1 person. (Note: the occupancy for the figure shown for a coach in Table 1 is unknown).

In total, there are 9 different scenarios with regard to full-service carriers to Barcelona and 3 different scenarios using alternative modes of ground-transport for the entire journey (see Figure 3). For budget airlines, there are 20 different scenarios generated by travelling from Bristol and Bournemouth to Barcelona. Newcastle Upon Tyne has 24 scenarios, since it is the only origin where its regional airport has a train connection (see Figure 4).

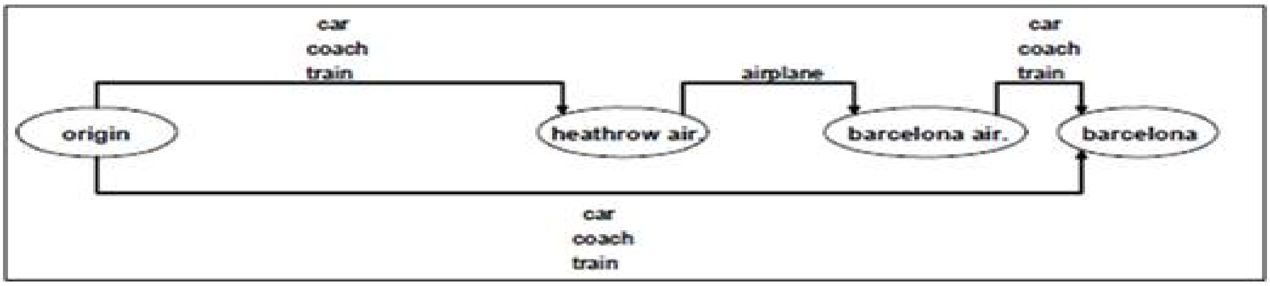

Figure 3. Different scenarios travelling to Barcelona via full-services airlines.

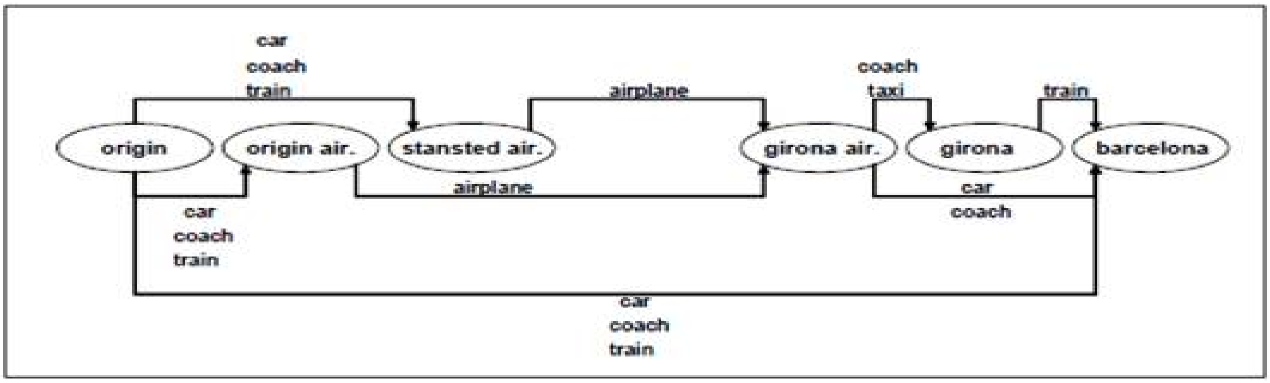

Figure 4. Total number of scenarios for travelling to Barcelona with budget airlines.

[8] This data is obtained from a report of the European Low Fares Airline Association, which might be biased towards presenting data on budget airlines in favour of full-service airlines.

3 RESULTS

Figure 5 shows the results for all the different transport scenarios from Bournemouth, Bristol and Newcastle Upon Tyne to Barcelona. Scenario 1, 2 and 3 show the $CO_{2equivalent}$ for travelling via car, train and coach to Barcelona, respectively. Scenarios 4 – 11 show the different options travelling via the regional airports. Scenario 12 – 23 show the different options travelling via Stansted and scenario 24 – 32 show the different scenarios flying with full-service airlines.

Figure 5 suggests that the $CO_{2equivalent}$ is reduced if the market shifts from full-service airlines to budget airlines from regional airports. In addition, the scenario analysis shows that not only the air flight mode (regional, hub with budget or full-service) is an important determinant in total emissions, but also the different modes of transport to and from the airport have an important effect. The differences between the worst and best emission performance are large within each of the different methods of travelling. The worst performing scenarios for each of the three origin destinations (scenario 30 in Figure 5) is to drive by car to a hub airport and take a full carrier to Barcelona (374, 316, 313 kg $CO_{2equivalent}$ for Newcastle Upon Tyne, Bournemouth and Bristol respectively). The fact that the full-service airline arrives closer to the destination does not outweigh the additional $CO_{2equivalent}$ emissions from driving to the departure airport and the additional $CO_{2equivalent}$ emissions from the flight in comparison to using a budget airline.

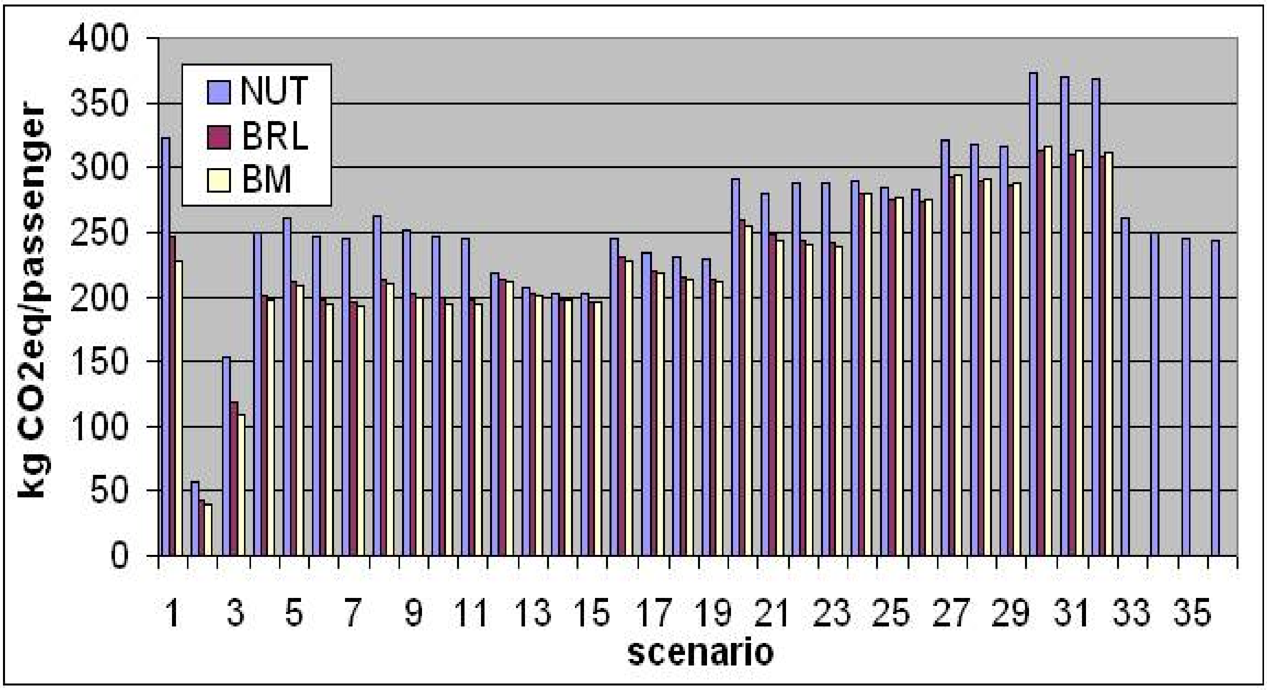

Figure 5. Total $CO_{2equivalent}$ for one passenger for different scenarios travelling from the UK to Barcelona.

However, the best performing scenarios are different for the different origins. For Bournemouth and Bristol the best combination of transport modes consist of a bus to the regional airport and a train from Girona to Barcelona (193 and 196 kg $CO_{2equivalent}$, see scenario 7 in Figure 5), while for Newcastle Upon Tyne it is better to take the train from Newcastle Upon Tyne to Stansted and fly from there (187 kg $CO_{2equivalent}$, see scenario 15 in Figure 5) i.e. complementing the flight with train as the ground-transport. Furthermore, these results suggest that from a holistic perspective, reducing emissions in relative terms does not mean that there is one suitable mode of getting to and from the airport using existing infrastructure. Instead, different combinations might be required for different journeys whereby the location of the regional airports in comparison to the origin and destination is a major factor.

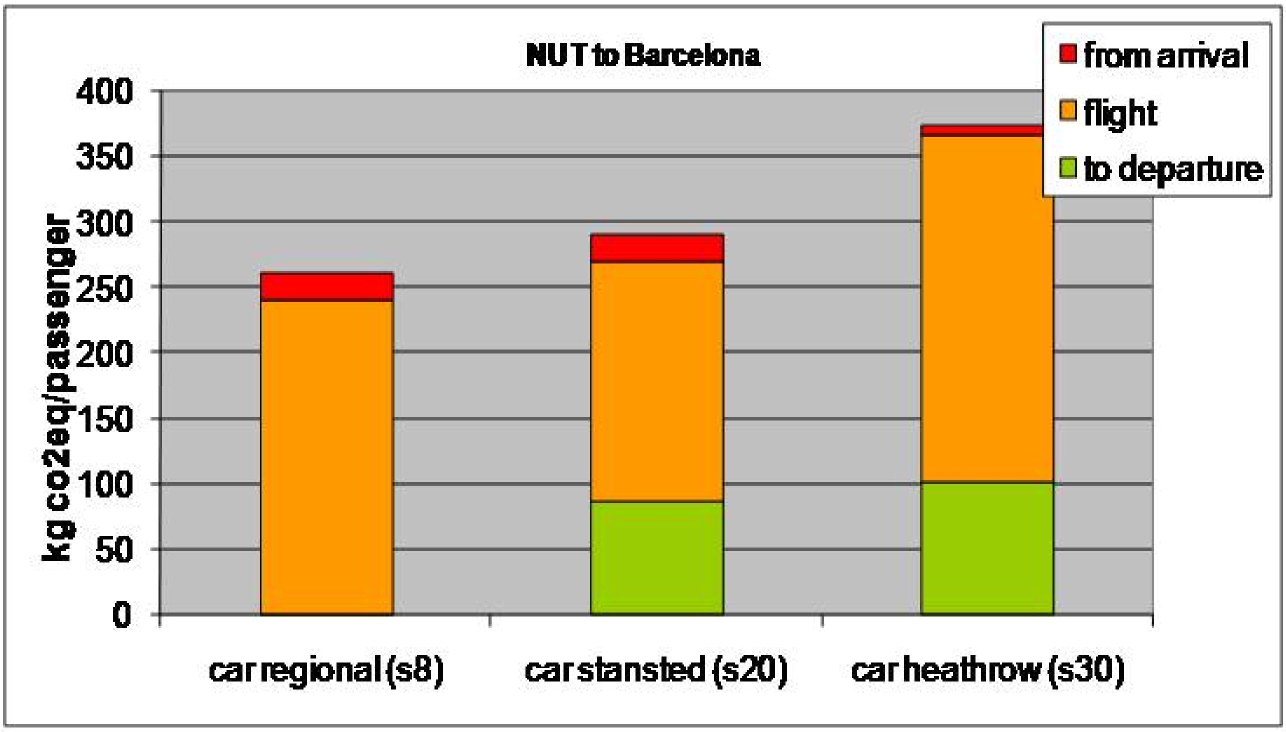

Figure 6. Total CO_{2eq} for one passenger travelling by car from Newcastle Upon Tyne to and from airports flying from the UK to Barcelona.

The results can also be used to compare the effects on $CO_{2equivalent}$ emissions from 1) the journey from the origin to the departure airport, 2) the flight itself and 3) from the arriving airport to the destination. Figure 6 compares three different scenarios from Newcastle Upon Tyne to Barcelona whereby holiday travellers drive to and from the airports by car. For a budget flight from the regional airport (scenario 8 in Figure 5), this means that the $CO_{2equivalent}$ emissions mainly take place from the arrival airport to the destination, while for budget or full-service airlines from London the emissions take place in the journey to the departure airport (scenario 20 and 30 in Figure 5). However, part of the emissions saved by using a regional airport are offset by the longer flight distance. In total, however, there is a 30% $CO_{2equivalent}$ emissions saving if flown from a regional airport, while there is a 22% saving for flying with budget airlines in comparison to full-service airlines. These results suggest that the shift towards regional airports can save $CO_{2equivalent}$ emissions, however the connection to and from the regional airports is crucial.

4 CONCLUSIONS AND RECOMMENDATIONS

Policy making should endeavour to tackle climate change by not looking at industries as sole entities but through an integrated approach. Trains are the best alternative in the context of substitution from door-to-door. There is a need for an efficient infrastructure to and from regional airports to reduce emissions. Regional airports may save emissions in comparison to full-service airlines via hubs however, this requires good public transport infrastructure. My final conclusion is that policy-making should focus on complementation of different modes of transport and to emphasise that these results show that there is no single combination of different modes which is suitable for all journeys – it depends on the distance of the origins and destinations relative to the airports.

Recommendations for further work include the following:

- Calculating the $CO_{equivalent}$ emissions by using more sophisticated and reliable method, which would be able to consider more accurately the effects of CO_2 emissions in the air (RFI was used as a quick and simple method in order to take into consideration the total impact of aviation).
- Emissions at airports – factoring in the contribution of emissions while waiting at airports, train stations, coach stations etc.
- Indirect emissions – a full life cycle analysis. Chester & Hovarth (2009) showed that the indirect emissions from onroad was an additional 63%, 155% for rail and 31% for aircraft systems.

- Cost and time – to see what effect this has on using a combination of different modes of transport and how factoring in reducing emissions from journeys can be effected by cost and time issues.
- Factoring other environmental impacts – climate change is not the only impact aviation has on the environment – noise and local air quality issues are also taken into consideration, but how are the trade-offs or comparing different impacts decided? What are the common indicators in comparing these in order to make decision-making less difficult?

Finally, in terms of policy it is crucial to consider high uncertainty, which is associated with these analyses. These uncertainties are partly the result of the scientific measures associated with analysing the effects of emissions on climate change. These uncertainties cannot be ignored, however need to be simplified in order to be able to form a basis for policy. Scientists focus on quantifying uncertainty in data for policy makers, however there is also uncertainty in applying this data. If an agreement is made at Copenhagen 2009 to cap international aviation emissions this is a positive step forward in tackling the impact of aviation on climate change.

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Exploring the uncertainties involved in calculating temperature response from the transport sector

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Keywords: climate response, transport, uncertainty

ABSTRACT: Simple climate models (SCMs) are useful tools for evaluating the climate impacts of anthropogenic emissions. As with any modelling exercise, it is important to identify and quantify the uncertainties in model results. For this study, the SCM, LinClim (Lim et al., 2007), was used to explore the sensitivity and uncertainties of various parameters involved in calculating global mean temperature response from the transport sector. The three main aspects of uncertainties explored in this paper are the effects due to the application of different background emission scenarios; the effects from the application of different carbon-cycle parameters and finally, the effects of tuning LinClim to different General Circulation Models (GCMs). Uncertainties in emissions scenarios and carbon-cycle parameters were investigated using transport emissions obtained from the EU Sixth Framework Project QUANTIFY (Quantifying the Climate Impact of Global and European Transport Systems); background scenarios from the Special Report on Emissions Scenarios (SRES); and carbon-cycle parameters derived from MAGICC (Wigley and Raper, 2001), the SCM used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). Temperature response for the emission scenarios was then calculated using LinClim, by applying tuning parameters (climate sensitivity parameter, λ and lifetime of the temperature perturbation, τ) of different GCMs. The results highlighted that for the scenario A1B-AIM, the uncertainty parameter that gave rise to the highest range of CO_2 temperature response from the transport sector was the LinClim tuning parameters (0.27 K by 2100). The potential range of temperature response due to CO_2 transport emissions for the same scenario was 0.36–0.63 K, which represented ~13–19% of temperature rise due to all anthropogenic sources.

1 INTRODUCTION

Simple climate models have been used in many climate impact studies (e.g. in IPCC), and vary in complexity but are always more computationally efficient than GCMs. They can be used to investigate impacts from large perturbations such as all anthropogenic sources (IPCC, 2007), or small perturbations such as the aviation sector (Lee et al., 2009). The computational efficiency of SCMs make them ideal tools for determining the climate impacts of a wide range of emissions scenarios, and the results from such studies help policymakers to devise and assess possible mitigation strategies. It is therefore important that any SCM results include uncertainty ranges, to give a better, more complete picture to the policymakers.

Typically, SCMs use emissions as input to calculate atmospheric concentrations of greenhouse gases (GHGs) or precursors from which global radiative forcing (RF) may be calculated. Then, climate responses such as global mean temperature and sea level rise can be computed from these RF. Each step within this modelling exercise, from emissions forecasts to their potential impacts are bound by various uncertainties. In this study, the simple climate response model, LinClim (Lim et al., 2007, Lee et al., 2009), is used to explore the sensitivity and uncertainties involved in calculating temperature response of the carbon dioxide (CO_2) perturbation from the transport sector. LinClim has previously been used in the assessment of aviation (Lee et al., 2009) and shipping (Lee et al., 2007) impacts. The model has now been adapted to also account for climate impacts from road

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transport. For this study, we constrained our analysis to uncertainties due to background emission scenarios, carbon-cycle parameters and LinClim tuning parameters.

2 BACKGROUND CO2 EMISSIONS AND CONCENTRATIONS

Background CO_2 emissions for this uncertainty analysis were taken from the IPCC SRES. The SRES scenarios follow four main storylines (A1, A2, B1, B2), each driven by different assumptions on "*demographic development, socio-economic development and technological change*". Six integrated assessment models (AIM, ASF, IMAGE, MARIA, MESSAGE, MiniCAM) were then used to generate future GHG emissions based on these four storylines. The A1 storyline was further split into three groups characterized by the assumptions on technological developments: A1B (balanced), A1FI (fossil fuel intensive) and A1T (non-fossil energy sources). In total, 40 SRES scenarios were developed, with *"no single most likely, 'central', or 'best-guess' scenario"*. Six "*marker*" scenarios, which were considered by the SRES team as "*illustrative of a particular storyline*" were selected for use in large-scale climate models. However, these marker scenarios (A1B-AIM, A1FI-MiniCAM, A1T-MESSAGE, A2-ASF, B1-IMAGE and B2-MESSAGE) "*are no more or less likely than any other scenarios*" (IPCC, 2000).

Therefore, to fully capture the broad range of assumptions within the SRES storylines and modelling methodologies, the full suite of SRES scenarios should be used when calculating climate impacts using SCMs. However, for this study which focuses on uncertainty analysis, the A1B storyline was used as illustration of the possible range in temperature response due to CO_2 emissions from transport. Quantitatively, by the year 2100 for scenario A1B, the difference between the highest (20.6 Pg C/yr) and lowest scenarios (10.5 Pg C/yr) was 10.1 Pg C/yr. The marker scenario, A1B-AIM, produced a total anthropogenic CO_2 estimate of 13.5 Pg C/yr (IPCC, 2000).

The resulting background CO_2 concentrations from various A1B scenarios were modelled using MAGICC 5.3, the SCM used in IPCC AR4 (IPCC, 2007). MAGICC has a built-in carbon-cycle model that considers oceans, atmosphere and terrestrial carbon reservoirs. It also includes terrestrial feedbacks from temperature and atmospheric CO_2 concentration and three levels of model sensitivity (low, mid and high). The model sensitivity is dependent on the net flux due to land-use changes and CO_2 fertilization coefficient (Wigley, 1993). The temporal development of CO_2 concentrations for the A1B scenarios, under the assumptions of mid-range carbon-cycle with feedbacks is shown in Figure 1. At 2050, the difference between the highest (A1B-ASF) and the lowest (A1B-MESSAGE) CO_2 scenarios was 94 ppmv. This difference increased to 207 ppmv by the year 2100 (~56% of present day CO_2 levels), with A1B-ASF remaining as the highest scenario (924 ppmv) and A1B-AIM (717 ppmv) the lowest scenario.

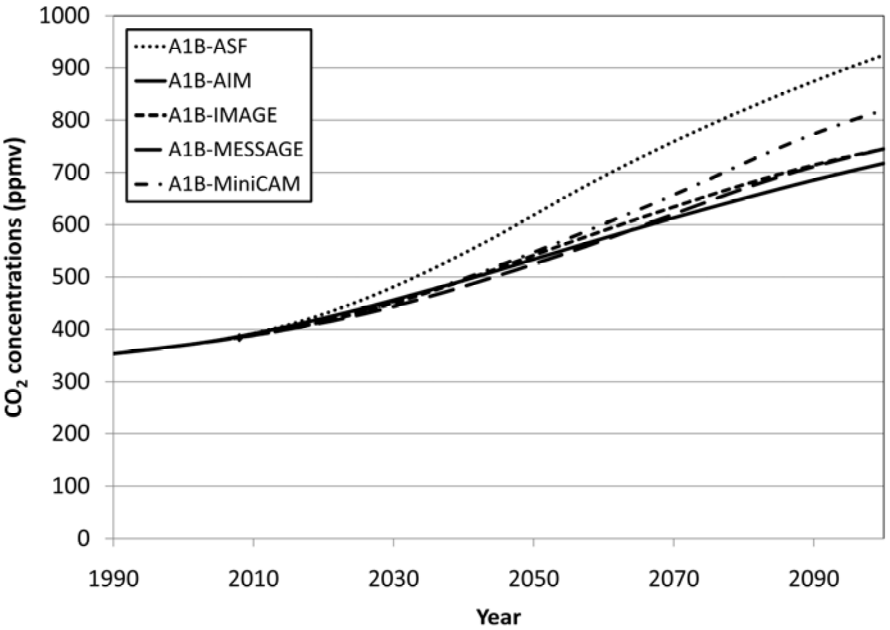

Figure 1: CO_2 background concentrations for A1B storyline (MAGICC 5.3, with feedbacks and mid-range carbon-cycle model)

The marker scenario A1B-AIM was also used as an illustration of the range of values various MAGICC carbon-cycle settings has on the background CO_2 concentrations (Figure 2). The range of uncertainty for carbon-cycle setting is not as high as those due to variations in emission scenarios. At 2050, the CO_2 concentrations range from 556 ppmv to 498 ppmv (difference of 58 ppmv) and at 2100, 773 ppmv to 609 ppmv (difference of 164 ppmv). As expected, there is a noticeable difference in CO_2 concentrations when feedbacks were included.

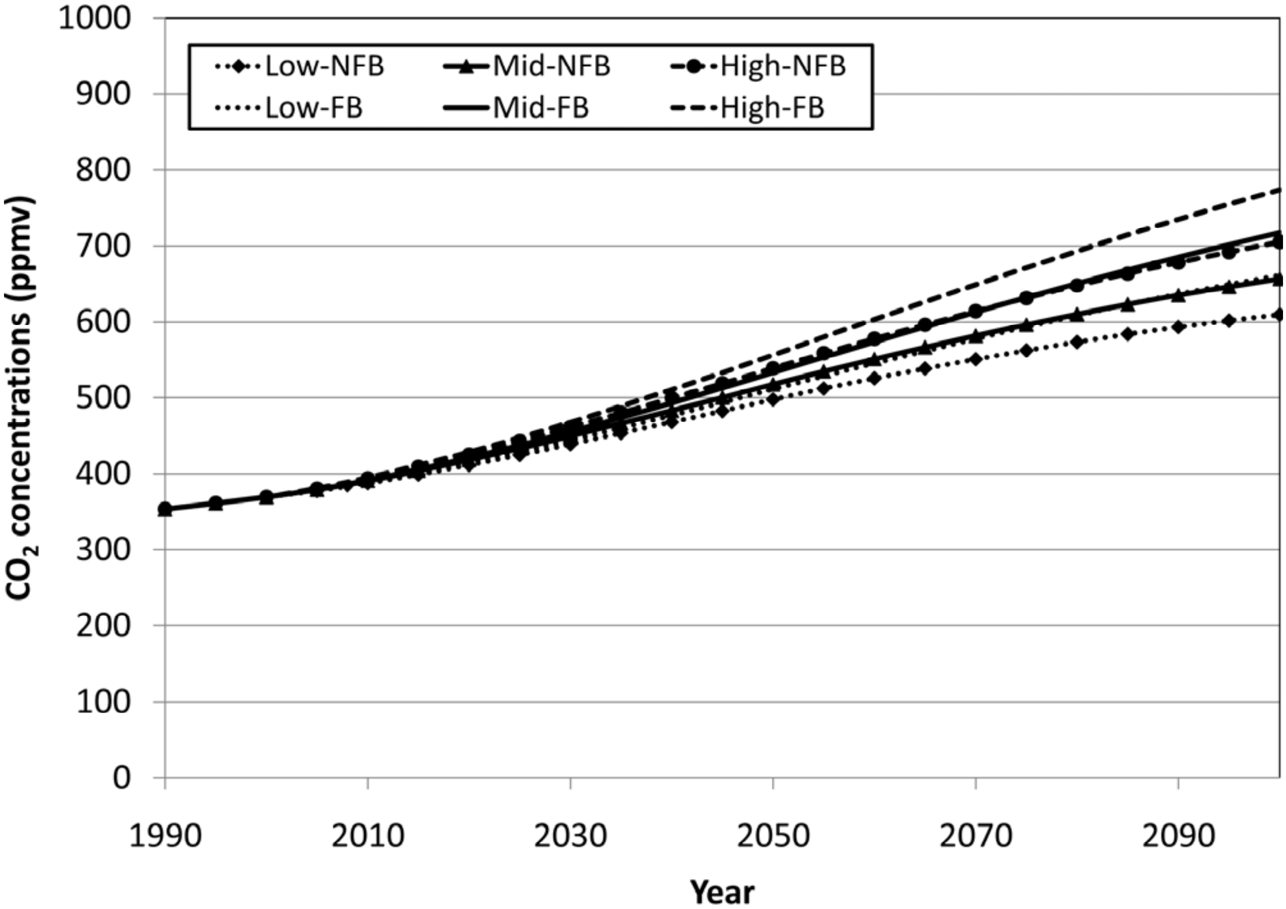

Figure 2: CO_2 background values for different carbon-cycle setting (Low, Mid, High; NFB – without feedbacks and FB – with feedbacks) for scenario A1B-AIM

3 TRANSPORT SECTOR CO2 EMISSIONS AND CONCENTRATIONS

Emissions of CO_2 from the transport sector were taken from the project QUANTIFY. The transport emissions were divided into three broad categories: land transport (road, rail and inland shipping), maritime shipping, and aviation. These emissions were developed to be consistent with the SRES storylines of A1B, A2, B1 and B2. A mitigation aviation scenario (B1ACARE), which followed the SRES B1 storyline, was also generated.

This study only considered emissions from the main transport categories of road, maritime shipping, and aviation. Figure 3 illustrates the total CO_2 emissions from these categories by SRES storylines. Scenario A1B had the highest transport CO_2 emissions for all forecast period (2000 to 2100). Transport CO_2 emissions for A2, B1 and B2 for years 2015 to 2085 were in the same range of 2 to 3 Pg C/yr. Beyond this period, scenario A2 continued to rise to 3.4 Pg C/yr, while scenarios B1 and B2 remained relatively constant. As expected, scenario B1ACARE, which included a mitigation scenario for aviation, had lower CO_2 emissions and followed the trend of its parent B1 storyline. By the year 2100, transport represented ~41% of total background CO_2 emissions for scenario A1B, ~12% for A2, ~62% for B1 and ~20% for B2. At 2100, the difference between the highest (A1B) and lowest scenarios (B1ACARE) was 3.1 Pg C/yr.

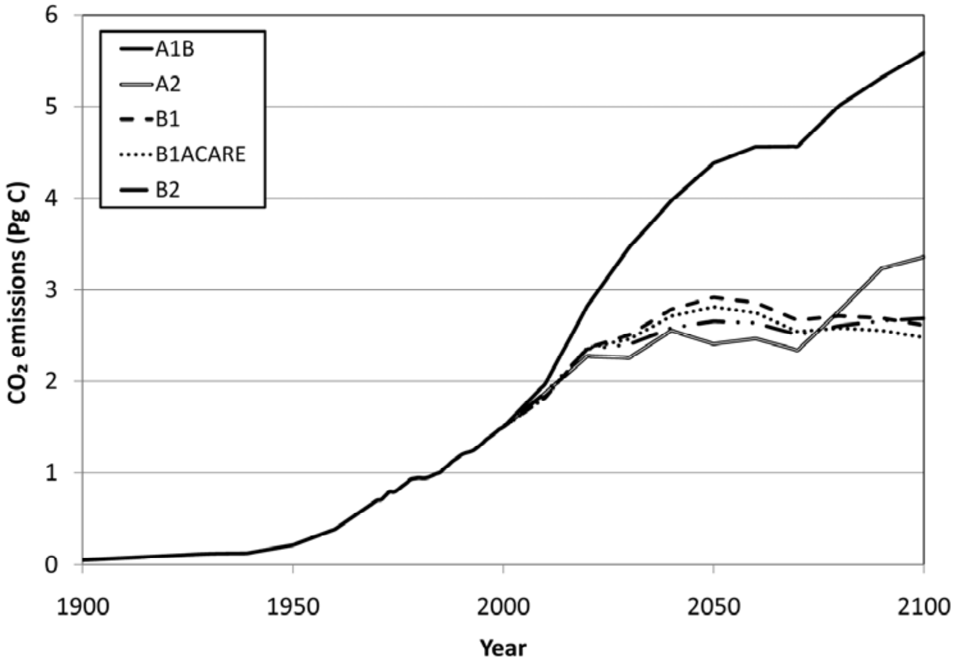

Figure 3: Total CO_2 transport emissions (road, maritime shipping and aviation) by SRES storylines

Figure 4 shows the split by transport category for scenario A1B, which is used as illustration for this study. Road sources were the largest contributors to CO_2 transport emissions; 76% at 2000, 71% at 2050 and 51% at 2100. The shipping and aviation emissions were very similar in magnitude, with each category contributing 0.18 Pg C/yr at 2000, 0.7 Pg C/yr at 2050 and 1.4 Pg C/yr at 2100. However, shipping had a longer history of CO_2 emissions when compared to aviation.

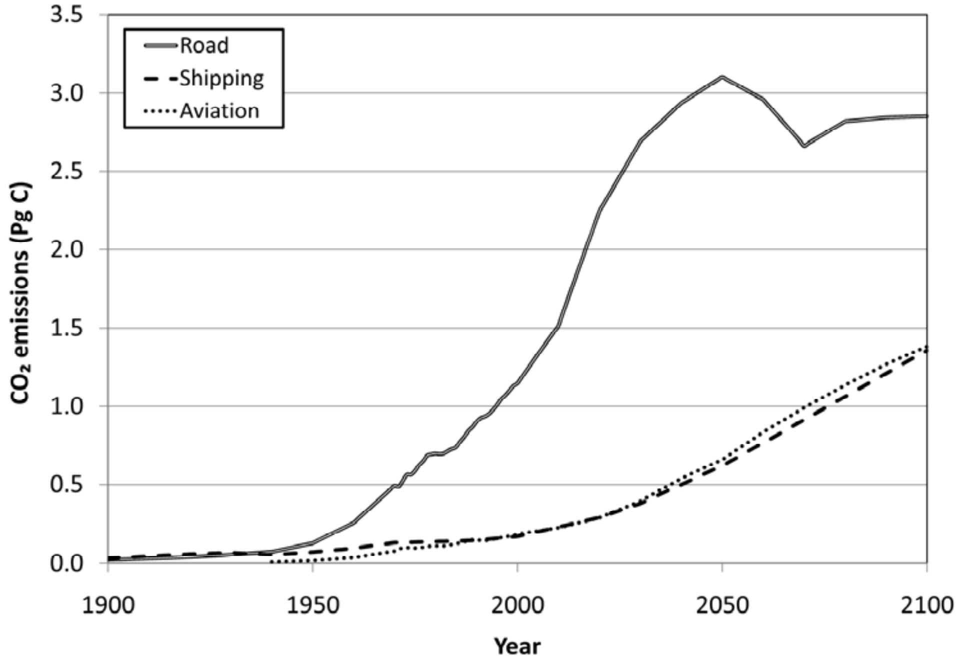

Figure 4: CO_2 emissions split by transport category for scenario A1B

Transport CO_2 concentrations were calculated explicitly from the emissions using LinClim's carbon-cycle model (Lim et al., 2007). The model is an impulse response function that approximates the results of the carbon-cycle model of Maier-Reimer and Hasselmann (1987). Figure 5 shows the results for scenario A1B by transport category. Between years 2000 to 2100, road transport accounted for 63–76% of total transport CO_2 concentrations, while shipping was 13–18%, and aviation was 11–19%. Assuming mid-sensitivity carbon-cycle with feedbacks, the total CO_2 transport concentrations represented 4–17% of background CO_2 concentrations; with road transport contributing 3–11% and shipping and aviation 0.07–3% each.

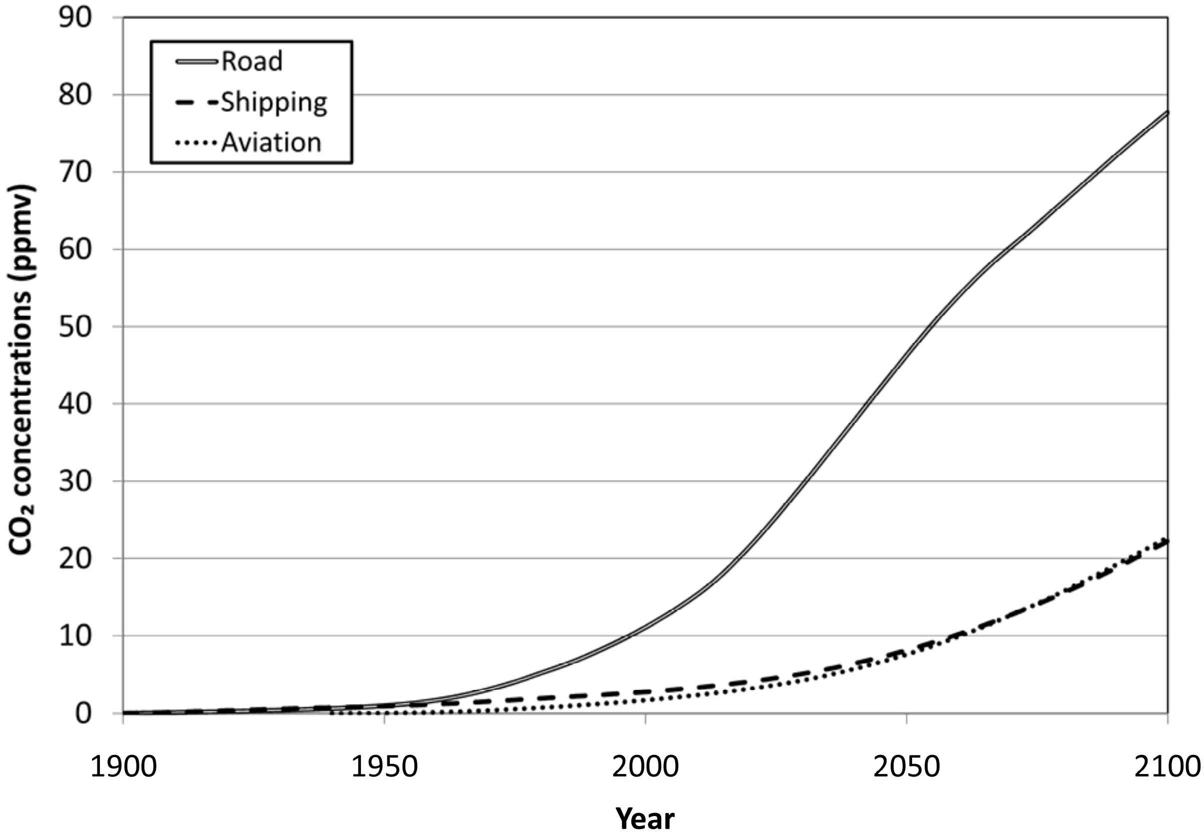

Figure 5: CO_2 concentrations split by transport category for scenario A1B

4 TRANSPORT SECTOR CO2 RADIATIVE FORCING (RF) AND TEMPERATURE RESPONSE (ΔT)

Carbon dioxide RF in LinClim is calculated according to the simple function used in IPCC AR4 (Lim et al., 2007, IPCC, 2007). The resulting RF is then used in an impulse response function, which estimates the temperature response (ΔT) due to a specific perturbation. Temperature response is not only dependent on RF, but also two other parameters, the climate sensitivity parameter (λ) and lifetime of the temperature perturbation (τ). These parameters are derived or "*tuned*" to a specific GCM. Therefore, ΔT calculated by LinClim will emulate or evolve in the manner of its parent GCM. By default, LinClim uses tuning parameters from the GCM ECHAM4/OPYC3. To explore the uncertainty in calculating ΔT from transport, tuning parameters from other GCM were also developed. These parameters were derived using five sets of GCM temperature data from MAGICC 5.3. The five GCMs were NCAR's CCSM3 and PCM, Hadley Centre's HadCM3 and HadCM2, GFDL-CM2.0 and CSIRO's Mk3.0.

4.1 *Uncertainties due to background emissions (A1B storyline)*

Table 1 shows RF summary for the A1B storyline calculated for each transport category using background CO_2 concentrations shown in Figure 1. The total transport CO_2 RF represented 13–19% of background RF in 2050 and 11–19% in 2100. At 2100, road sources had the biggest CO_2 RF difference, 0.14 W/m^2, between the highest (A1B-AIM) and lowest (A1B-ASF) scenario. Shipping and aviation, which had similar range of CO_2 concentrations (Figure 5), also had similar RF difference, 0.04 W/m^2. The ΔT results calculated by LinClim using ECHAM4/OPYC3 tuning parameters are also summarized in Table 1, with the temporal evolution depicted in Figure 6. The uncertainty range by 2100 was approximately 0.09 K. Over the 2000–2100 periods, road sources consumed 67–75% of the total transport ΔT budget, while shipping 14–24% and aviation 9–15%. Shipping had a higher ΔT compared to aviation because of its longer emissions history.

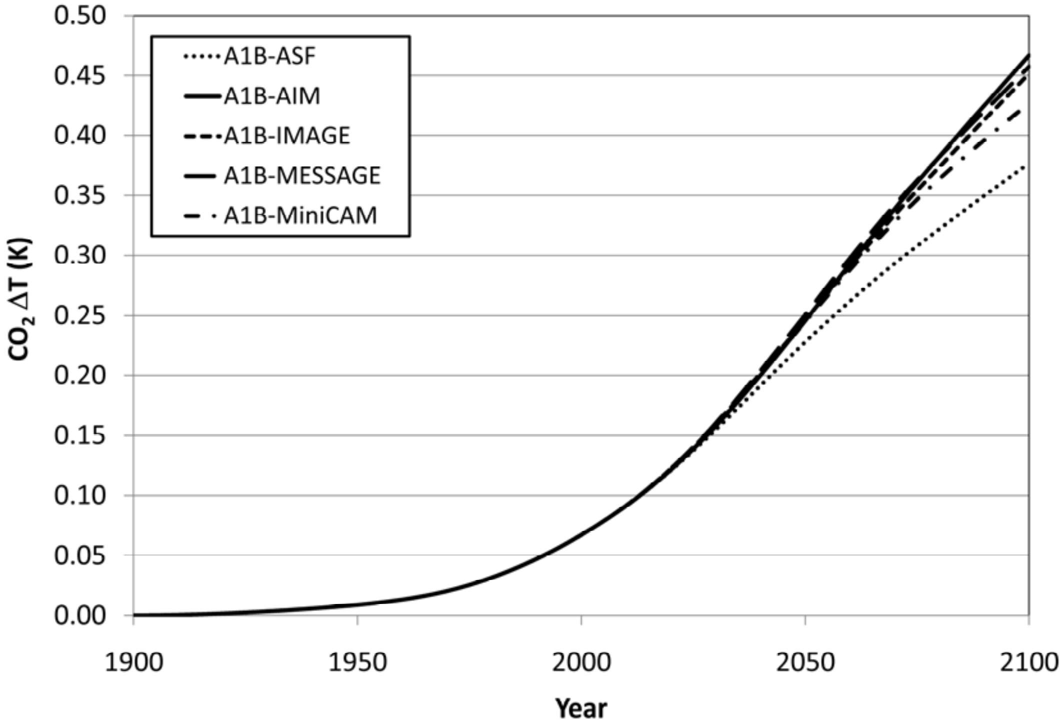

Figure 6: CO_2 total transport ΔT using background concentrations for A1B storyline as depicted in Figure 1

4.2 *Uncertainties due to background concentrations (carbon-cycle settings, A1B-AIM scenario)*

The total transport RF at 2050 and 2100, calculated using background CO_2 concentrations shown in Figure 2, are summarized in Table 1. Transport accounted for 17–22% of background RF in 2050 and 16–27% in 2100. High carbon-cycle with feedbacks on background concentrations resulted in the lowest transport RF. Figure 7 shows the range of ΔT results (tuned to ECHAM4/OPYC3) due to these RF variations. The transport CO_2 ΔT predictions for different carbon-cycle settings varied by 0.02 K in 2050, increasing to 0.09 K by 2100 (Table 1). The split between transport categories was similar to that reported in Section 4.1.

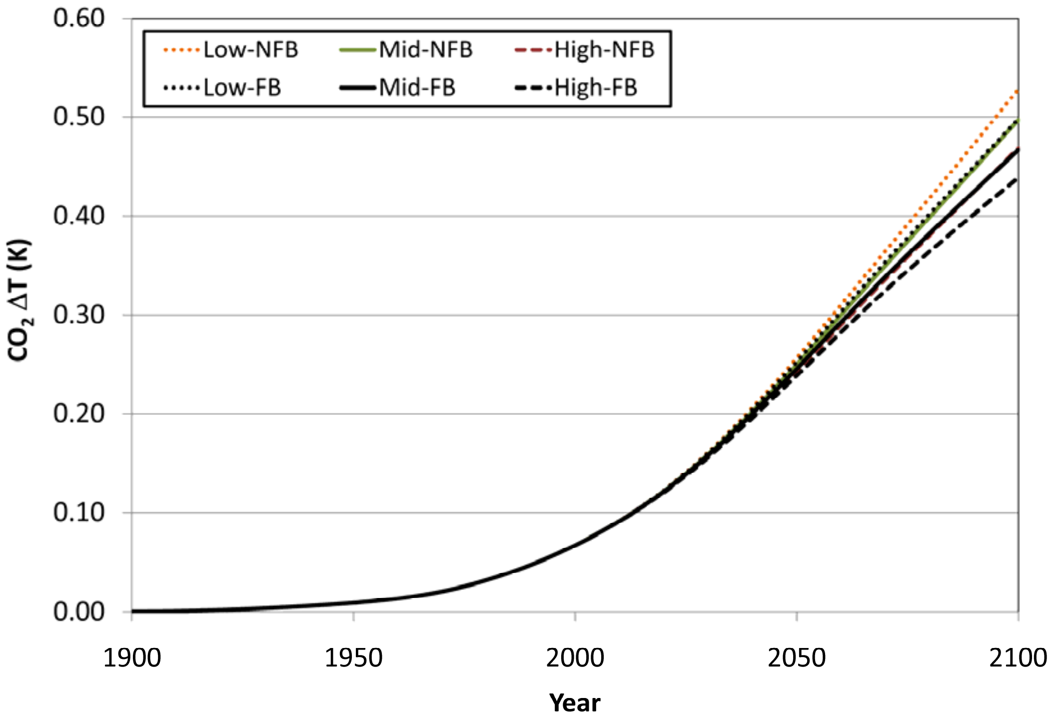

Figure 7: CO_2 total transport ΔT using background concentrations for scenario A1B-AIM as depicted in Figure 2

4.3 *Uncertainties due to tuning parameters, λ and τ (A1B-AIM scenario)*

Figure 8 shows the ΔT range calculated by LinClim when tuned to different GCMs. The RFs used to produce these ΔT were taken from the A1B-AIM scenario, Mid-FB background concentrations (Figure 2). A significant difference between the highest (CSIRO-Mk3.0) and lowest (ECHAM4/OPYC3) CO_2 ΔT was already observed in the year 2000. This uncertainty range of 0.11–0.067 K increased to 0.22–0.37 K in 2050 and 0.36–0.63 K in 2100 (Table 1). However, the tuning parameters from CM2.0 produced the highest ΔT in 2100, while CCSM3 the lowest. The split within the individual transport categories was again similar to that reported in Section 4.1.

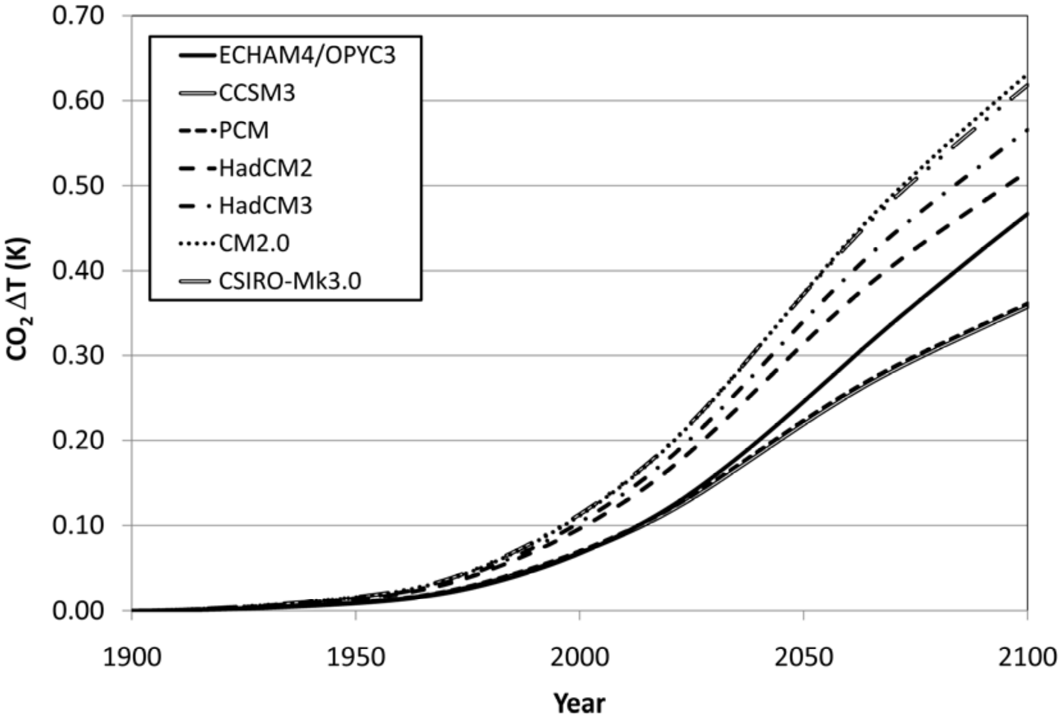

Figure 8: CO_2 total transport ΔT using different GCM tuning parameters for scenario A1B-AIM as depicted in Figure 2

5 SUMMARY AND FURTHER WORK

In this paper, we explored the uncertainty ranges involved in calculating CO_2 temperature response from the transport sector. A summary of the main results is shown in Table 1. The results demonstrated that considering only three uncertainty parameters for the scenario A1B-AIM, by the year 2100, the CO_2 temperature response from transport could range between 0.36–0.63 K. This represented ~13–19% of background temperature response. The uncertainty parameter that produced the highest range of temperature response was the tuning parameters (0.27 K by 2100), while background CO_2 emissions and carbon-cycle settings gave rise to uncertainty range of ~0.09 K by 2100.

Table 1: Summary of main results

Uncertainty parameters	Storyline/Scenario	RF (W/m^2)		ΔT (K)	
		2050	2100	2050	2100
Background emissions	A1	0.55 – 0.67	0.73 – 0.95	0.23 – 0.25	0.38 – 0.47
Background concentrations (carbon-cycle settings)	A1B-AIM	0.62 – 0.69	0.88 – 1.13	0.24 – 0.26	0.44 – 0.53
LinClim tuning parameters	A1B-AIM	-	-	0.22 – 0.37	0.36 – 0.63

This preliminary work demonstrated the importance of including uncertainty ranges to SCM results, especially if the results are to be used for policymaking. In the future, this work will be extended to include the full suite of SRES scenarios, to use tuning parameters from other AR4 GCMs and to also investigate other likely uncertainties in temperature response calculations.

6 ACKNOWLEDGEMENTS

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