Environ. Sci. Technol. **XXXX,** *xxx,* 000–000

Flying into the Future: Aviation Emissions Scenarios to 2050

BETHAN OWEN,* DAVID S. LEE, AND LING LIM
Dalton Research Institute, Manchester Metropolitan University, John Dalton Building, Chester Street, Manchester M1 5GD, United Kingdom

Received August 19, 2009. Revised manuscript received January 13, 2010. Accepted February 14, 2010.

This study describes the methodology and results for calculating future global aviation emissions of carbon dioxide and oxides of nitrogen from air traffic under four of the IPCC/SRES (Intergovernmental Panel on Climate Change/Special Report on Emissions Scenarios) marker scenarios: A1B, A2, B1, and B2. In addition, a mitigation scenario has been calculated for the B1 scenario, requiring rapid and significant technology development and transition. A global model of aircraft movements and emissions (FAST) was used to calculate fuel use and emissions to 2050 with a further outlook to 2100. The aviation emission scenarios presented are designed to interpret the SRES and have been developed to aid in the quantification of the climate change impacts of aviation. Demand projections are made for each scenario, determined by SRES economic growth factors and the SRES storylines. Technology trends are examined in detail and developed for each scenario providing plausible projections for fuel efficiency and emissions control technology appropriate to the individual SRES storylines. The technology trends that are applied are calculated from bottom-up inventory calculations and industry technology trends and targets. Future emissions of carbon dioxide are projected to grow between 2000 and 2050 by a factor in the range of 2.0 and 3.6 depending on the scenario. Emissions of oxides of nitrogen associated with aviation over the same period are projected to grow by between a factor of 1.2 and 2.7.

Introduction

Aviation currently contributes between 2 and 3% of total annual anthropogenic carbon dioxide (CO_2) emissions (*1*) but possibly as much as 4.9% of radiative forcing in 2005, including cirrus cloud effects (*2*). Aviation has grown strongly over recent decades with passenger transport in terms of revenue passenger kilometers (RPK) increasing at an average rate of 5.2% yr^{-1} over the period 1992−2005, despite world-changing events such as the first and second Gulf Wars and the World Trade Center attack, etc. (*2*). The future potential growth of emissions from this sector is of some concern since its impacts on climate arise from both CO_2 and non-CO_2 emissions and effects. Moreover, international aviation emissions which contribute approximately 60% of the total are not part of the Kyoto Protocol and lie outside the remit of internationally agreed emission reduction targets. Even though there have been significant improvements in fuel efficiency through aircraft technology and operational management this has been outweighed by the increase in air traffic.

Previously, some efforts have been made to formulate future aviation emissions scenarios (*3*) but these are now over 10 years old and were based on older IPCC scenario assumptions. Here, we present new aviation emission scenarios to 2050 that are designed to interpret the IPCC SRES storylines (*4*) under the four main families A1B, A2, B1, and B2 with a further outlook to 2100. In addition, a scenario has been calculated assuming that the ambitious technology targets of the Advisory Council for Aeronautical Research in Europe (ACARE) (*5*) are achieved. The emission scenarios presented here are time-variant and have been gridded so that impacts can be assessed with climate models including chemical transport models (CTMs). These aviation emissions scenarios form part of the European Commission sixth Framework project 'QUANTIFY', in which SRES-based emission scenarios have been developed in a consistent manner for the transportation sector as a whole (www.pa.op.dlr.de/quantify/).

Calculation of Baseline Fuel and Emissions

A global model of aircraft movements and emissions, 'FAST' (*6*), for a baseline year of 2000 has been used as the basis for calculation of new future emissions for scenario years 2020, 2050, and 2100 under the SRES marker scenarios (A1B, A2, B1, and B2). FAST has previously been used to calculate fuel, CO_2 and NO_x emissions for aviation and used in a variety of impact studies (*7*−*10*) and is also in use under the aegis of the International Civil Aviation Organization (ICAO)'s Committee on Aviation Environmental Protection (CAEP), along with other similar modeling systems. The emission scenarios are spatially resolved at 1° latitude × 1° longitude with a vertical discretization of 610 m (i.e., flight-level intervals of 2000 feet), every month. FAST combines a global aircraft movements database of scheduled and nonscheduled air traffic (*11*) with data on fuel flow provided by a separate commercial aircraft performance model, PIANO (*12*). Emissions of CO_2 are a simple function of fuel consumption, whereas NO_x emissions require an algorithm that corrects certification (ICAO databank) data for altitude (*13, 14*). Global aviation fuel from civil aviation using FAST was calculated to be 152 Tg for 2000. This is in broad agreement with other estimates of emissions (*15, 16*). The fuel burn derived from "bottom-up" inventories such as the FAST2000 inventory generally indicate lower fuel use than reported aviation fuel use by the International Energy Agency (IEA) (*17*). There are a number of reasons for this. First, the "bottom-up" inventories only indicate civil emissions, military emissions are much more difficult to estimate but Eyers et al. (*15*) calculated this to be approximately 11% of the total in 2002.

Second, many of these inventories including FAST2000 are idealized in terms of missions, in that great circle distances are assumed and no holding patterns. This leads to an underestimate of actual burn of about 10% (*15*). These various factors conspire to systematically underestimate aviation CO_2 emissions, which is why it is important to use the total fuel sales data and the more detailed bottom-up inventory total should be scaled accordingly. In this study the FAST2000 data has been normalized to the IEA total aviation fuel sales figure of 214 Tg yr^{-1} for 2000. This method of scaling to IEA fuel, while conventional (*3*), introduces some uncertainty in the location (both horizontally and vertically) of the NO_x emissions. In particular, military emissions will be emitted at different altitudes to civil aviation and a CTM user may consequently choose to omit the military portion of NO_x from their calculations. However, the uncertainties intro-

---

* Correpsonding author e-mail: B.Owen@mmu.ac.uk.

10.1021/es902530z

duced by scaling of the fuel use data are not significant for CO_2 emissions.

Aircraft movements and emissions from the baseline inventory can then be used as the basis of projections, using input data of growth in movements (regional) and assumed changes in technology based upon historical development and future anticipated changes. For the year 2020, the traffic projection of ICAO/CAEP is used (*18*). Post-2020, traffic demand for each scenario was calculated using a simple econometric model based on global GDP growth (*19*) as the principle driver although there is some decoupling from GDP under certain growth scenarios. Technology assumptions (on fuel efficiency and NO_x emissions) are then determined for each of the SRES scenarios to reflect the scenario storylines.

Scenarios of emissions out to 2100 are necessary for climate-response type calculations (*20*) and were developed from the 2050 scenarios. Uncertainty increases beyond 2050 which renders overly complex assumptions difficult to justify. Demand up to 2100 is modeled as described as for the period 2020−2050 but more simple technology assumptions were made and are provided in the scenario descriptions.

Aviation Demand in the Near-Term

The ICAO projection of global aviation traffic demand to 2020 (*18*) is a consensus forecast developed by Government and independent expert economists and transport planners, airframe manufacturers, engine manufacturers, and air transport organizations. The 20 year forecast produced by ICAO is very much “in view” in terms of the aviation industry, given the long development and production timeframes for aircraft. This forecast provides a breakdown of RPK and SKO (seat kilometers offered) by aircraft seat bandings and regional flows. The calculated growth factors for each aircraft size band and route group were then applied to the year 2000 baseline inventory activity data, producing an aviation activity data set for 2020. The overall global growth in SKO shown by the ICAO forecast is 4.1% yr^{-1} until 2020. In terms of aircraft types, an upward trend in the size of aircraft making up the global fleet is projected by the Forecasting and Economic Sub-Group (FESG) with aircraft of more than 300 seats contributing to approximately 11% of total SKOs in 2002 and 18% in 2020. The ICAO/FESG has recently completed a new forecast to 2026 (*21*) and the most recent consensus is that traffic growth to 2026 is likely to fall between 4.2 and 4.9% per year (*22, 23*). The use of the 4.3% annual average growth rate of the ICAO/CAEP6-FESG forecast is thus deemed an appropriate and pertinent forecast to 2020 for this study.

Long-Term Aviation Demand Modeling

In order to extend the traffic and emissions projections to 2050 (and beyond) a different methodology is required. A number of studies have shown a robust link between economic growth and the demand for transport (*24*) and for aviation in particular (*25*−*27*). Previously, in the IPCC 1999 Report a logistic-type statistical function of the ratio of RPK to GDP was used to model future global aviation demand (*28*) and a similar method has been employed here. Time series of global GDP growth from the UN World Bank and ICAO passenger demand statistics (*29*) have been used to 2006 to develop a logistic function (see the Supporting Information (SI) for details). The function is then applied with the SRES GDP growth assumptions.

The disaggregation of the global demand to regional flows has been undertaken taking account of the GDP growth assumptions, the relative maturity of aviation demand in the regions and interpretation of the IPCC SRES storylines.

Interpreting IPCC-SRES Emissions Scenarios for Aviation

The SRES scenarios were developed by the Intergovernmental Panel on Climate Change (IPCC), as four main family storylines: A1B, A2, B1, and B2. Each scenario family involves a storyline and a number of quantifications, including estimates on population and GDP.

The SRES storylines are described in terms of certain characteristics that imply that political and societal factors may change the way we travel in the future; for example, two of the scenarios (A1B and B1) are both globalization scenarios, whereas A2 and B2 are more regional scenarios where individual regions become more separate and there is less exchange between the regions. Within the SRES storyline literature there is no specific reference to aviation, other than for the A2 scenario: “*interregional passenger transport and trade flows low*” (*30*); and the B1 scenario: “*air traffic is mostly for intercontinental trips”* (*31*). Thus some interpretation of the general SRES trends and patterns for aviation was necessary. Further details are given in the SI.

Technology Trends: Fuel and NO_x Emissions

Fuel efficiency values in terms of kg fuel per SKO for each in-service aircraft over appropriate mission distances were determined from the FAST baseline inventory using the PIANO model (*12*) and real flight data. Since a global movement data set was used, it incorporates typical ranges of flight distances undertaken by the specific aircraft types. These fuel efficiency values by aircraft type form the basis, with a fleet-rollover model, of calculated future trends in global fleet fuel efficiency.

The fuel efficiency of the fleet to 2020 is calculated based on the retirement and replacement of older aircraft types with newer known aircraft types via a fleet rollover model (*32*). Aircraft currently in-service but not appearing in the 2000 fleet such as the B787 and A380 are estimated to have 20% better fuel efficiency that their current equivalents (*33*). Additional fleet-wide improvements in fuel efficiency are assumed from changes in air traffic management (ATM) and operational improvements (*34*). Total fleet-wide fuel efficiency improvements of approximately 1% yr^{-1} as kg/SKO from 2000 to 2020 are estimated from this work.

Projecting trends in fuel efficiency beyond 2020−2050 requires the consideration of some aircraft and engines that are not yet in production and thus more speculative assumptions. After 2020, additional aircraft not yet in production will enter the fleet and no specific fuel efficiency or emissions data are available for these. However, likely trends for new unknown aircraft in the longer term have been determined from the aeronautical industry ACARE technology goals (*5*) and the ICAO/CAEP Long-term Technology Goals (LTTG) (*35*) with the rate of implementation dependent on the scenario.

Implementation of Technology Trends into Scenarios

The assumptions made for fuel efficiency and emissions technology for each scenario were matched to the general storyline of the scenarios. Although the improvements in fuel efficiency and NO_x emissions are applied using fleet-wide assumptions, they have been derived from detailed bottom-up inventory and fleet-rollover analyses (details provided in the SI). The implementation is summarized as follows:

A1B. For aviation post-2020, the evolution of the fleet includes ACARE-type aircraft entering the fleet at a moderate rate, that is, 5% of new aircraft are ACARE-compliant in 2020, 25% in 2030, and by 2050, 75% of new aircraft entering into service are ACARE-compliant aircraft. Using these assumptions, fuel efficiency improvements for aviation under this

TABLE 1. Emission Inventory Results for base year, 2000 and for SRES Aviation Scenarios; SRES Total Anthropogenic; And Transport Emissions

year/Scenario	fuel	CO_2 (Tg)	NO_x (Tg)	total SRES CO_2 (Tg)	quantify transport total CO_2 (Tg)	quantify transport as % of total SRES (*5*)	aviation as % of quantify transport (*38*)
2000	214	677	2.9	25 287	5665	22%	12%
2020	336	1062	4				
2050A1	766	2418	7.5	58 701	16 284	28%	15%
2050A2	469	1481	5.4	60 472	9148	15%	16%
2050B1	426	1345	3.4	42 887	10 785	25%	12%
2050B2	435	1373	4.4	41 194	9861	24%	14%
2050B1ACARE	325	1025	2.6	42 887	10 785	25%	10%
2100A1	1605	5067	15.7	48 020	20 773	43%	24%
2100A2	956	3018	11	105 991	12 803	12%	24%
2100B1	375	1186	3	19 053	9656	51%	12%
2100B2	565	1783	5.7	50 689	9951	20%	18%
2100B1ACARE	229	723	1.8	19 053	9656	51%	7%

scenario were assumed to be approximately 1% yr^{-1} for the entire 50 year period (2000−2050). This matches the rate of fuel efficiency improvements seen in the industry over the past 10 years but this rate of improvement is assumed to be sustained to 2050 which is a generally optimistic outcome and consistent with the A1 storyline of technological improvement (previous future projections of fuel efficiency have assumed a declining rate of improvement with time, for example, IPCC projections assumed efficiency improvements would decline to 0.5% yr^{-1} post-2020−2100) (*28*). Improvements in NO_x technology under the A1 scenario are significant, commensurate with the generally high level of technological advancement and exchange. It is thus assumed that the medium term technology targets proposed by the CAEP are implemented by 2030 and achieved by all new aircraft entering the fleet after 2030.

A2. This scenario has the lowest overall demand and the lack of technological advances and international cooperation mean that the step-changes that would be required to develop ACARE-type aircraft are not achieved and fuel efficiency improvements after 2020 are slow, amounting to an overall improvement of 30% over 2000 values by 2050. Only marginal annual improvements in fuel efficiency (0.2% yr^{-1} post-2020−2100) and NO_x emissions technology are assumed.

B1. For this scenario, where local air quality would be an important driver for reducing NO_x emissions, significant improvements in NO_x technology are assumed, commensurate with achieving the long-term technology goals for NO_x proposed within CAEP and the ACARE NO_x improvements discussed by the aeronautical industry. Fuel efficiency improvements are based on the same assumption outlined for the A1 scenario to 2050 (1% yr^{-1} in kg/SKO) but increase again to 1.3% yr^{-1} (kg/SKO) in the period 2020−2100 as the possibility of more radical aircraft design and materials and alternative fuels become available. As with all the scenarios, for the period 2050−2100, the fuel efficiency improvements are speculative and top-down. The B1-ACARE scenario shares the same $EINO_x$ assumptions as B1 but with the fuel efficiency assumptions tightened further by assuming that the ACARE fuel efficiency goal is achieved by all new aircraft entering the fleet in 2020 (a 2.1% yr^{-1} improvement in kg/SKO). This scenario is effectively a parametric "what if", since it is clear that the ACARE targets are demanding, and it would be virtually impossible for all newly manufactured aircraft to meet the targets since this would require existing types to be re-engined; rather, in reality, ACARE opportunities only exist for new aircraft types. For the B1-ACARE scenario, post-2050, the rate of fuel efficiency obtained up to 2050 would be continued to 2100. The B1-ACARE scenario is akin to an aviation mitigation scenario as to achieve the fuel efficiency improvements described here, would probably require the technology to be driven by concerns over climate change. However, it should be noted that the B1 SRES total emissions scenario is not a mitigation scenario and has a 2100 temperature increase of around 2.6 °C in excess of the level commonly associated with "dangerous climate change" (*36*).

B2. The B2 scenario also shows some ecological credentials although with environmental policies being prominent only at a local level, the implementation of tougher NO_x emission standards through groups such as ICAO/CAEP are assumed to be less likely. The B2 scenario also lacks the technological advances evident in the B1 world. The B2

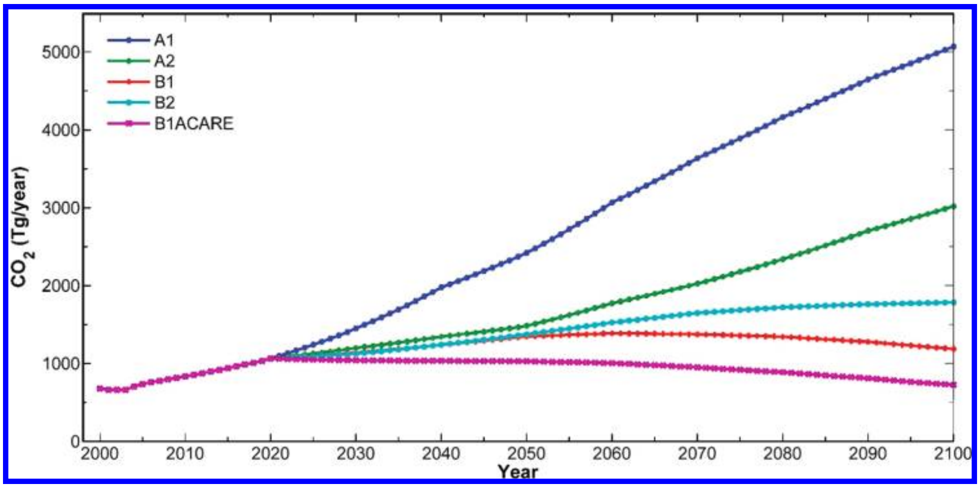

FIGURE 1. Time series of SRES aviation CO_2 emission scenarios (with outlook to 2100).

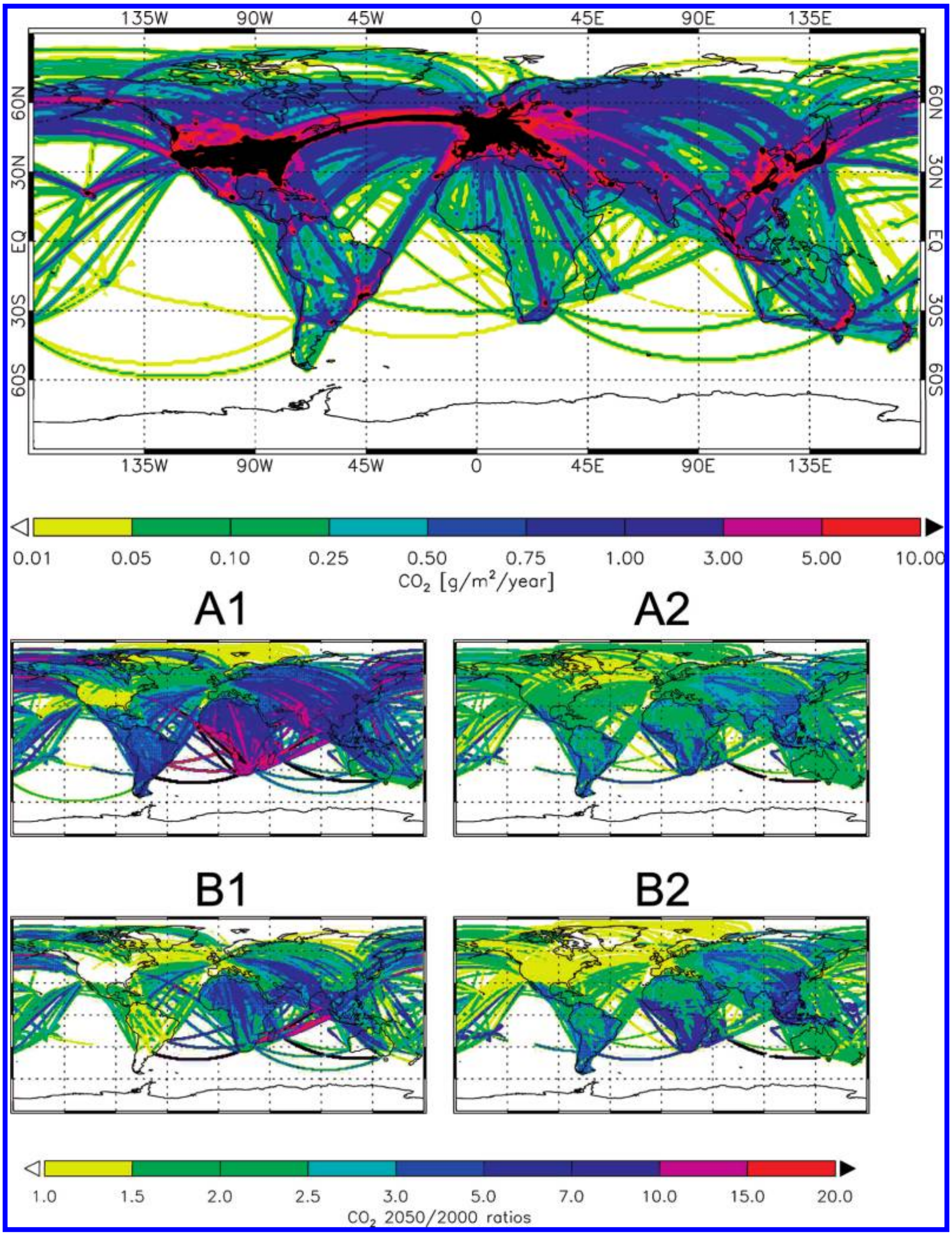

FIGURE 2. 2000 CO_2 emissions data from aviation and ratio to SRES 2050 emissions projections.

scenario is thus characterized by fairly slow improvements in NO_x technology between 2020 and 2050. Modest improvements in fuel efficiency similar to those used in the IPCC scenarios (*28*) of 1% yr^{-1} to 2030 and 0.6% yr^{-1} to 2050 (and then to 2100) are assumed.

RESULTS

Emission Scenarios to 2050. Global emissions of CO_2 and NO_x according to the methodology described above are summarized in Table 1. For the B1 scenario there is also a B1-ACARE variant (an aviation advanced technology scenario) which assumes more significant improvements in fuel efficiency. The projected trends over time of aviation CO_2 and NO_x emissions for each of the scenarios is shown in Figure 1. For the high growth A1 scenario, emissions of CO_2 grow by an average of 2.6% yr^{-1}. Emissions of NO_x for the A1 scenario grow by an average of 2.0% yr^{-1}. The B1-ACARE scenario represents a future with a more environmental outlook where demand is slower and fuel efficiency and NO_x technology improvements are both stronger. The emissions of CO_2 grow by an average of 0.8% yr^{-1} between 2000 and 2050. Emissions of NO_x for the B1-ACARE scenario decline by an average of 0.1% yr^{-1} between 2000 and 2050 as a result of the combined improvements of fuel savings and NO_x emission reductions.

The spatial distributions of the aviation scenarios in 2050 are shown in Figure 2 in terms of ratios to the base year of 2000. The spatial distribution for A1/B1 and A2/B2 scenarios is distinct, with the global scenarios A1/B1 showing greater growth of inter-regional demand compared with the more regionally focused scenarios A2/B2. The A1 scenario, which describes a future where developing and developed countries show greater economic equality, has the greatest growth in regions such as Africa and Latin America. The emissions in developing regions increase by factors of 15−20 and more in some cases for the A1 scenario between 2000 and 2050

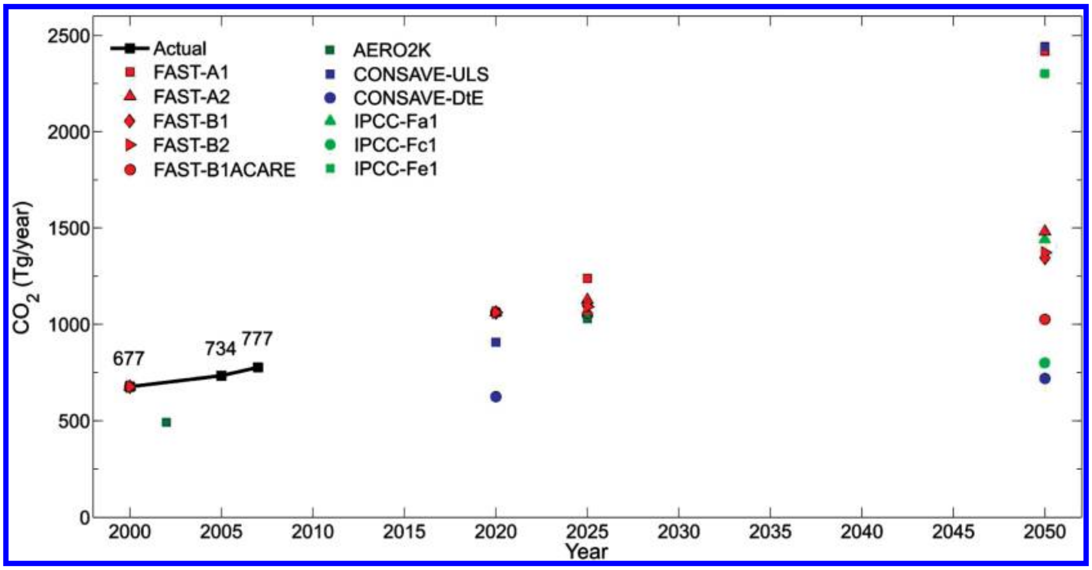

FIGURE 3. Comparison of range of emission estimates produced in this study (FAST-A1, high and FAST-B1ACARE, low) with other aviation emission estimates.

reflecting the emergence and strong growth of aviation in these regions. The SRES aviation scenarios produced here are compared with other aviation scenario data in the literature including the main IPCC 2050 scenarios (*28*) and the CONSAVE scenarios (*37*) in Figure 3 and are found to lie within a similar range.

Outlook to 2100. The emissions to 2100 are provided in Table 1. Assumptions post-2050 are necessarily more speculative and provide an outlook only. Post-2050 demand (inter-regional or intra-regional) is assumed to continue to grow linearly with GDP growth according to the scenario storyline. Assumptions for fuel efficiency were determined using broad-brush assumptions on fuel availability for the scenarios during the second half of the century and in the absence of any obvious trends for NO_x, all $EINO_x$ values remain at their 2050 values (trends in NO_x are therefore scaled to fuel and carbon dioxide emissions). For the high growth A1 scenario, emissions of CO_2 and NO_x grow by an average 1.5% yr^{-1} over the period 2050−2100. At the opposite end of the scenario range, emissions of CO_2 and NO_x for the B1-ACARE scenario decline by an average of 0.7% yr^{-1} between 2050 and 2100.

Discussion

Total global emissions from fossil fuel burning (from SRES) and from aviation (this study) are also given in Table 1 together with the total SRES QUANTIFY transport emissions data (*38*).

Aviation emissions grow by approximately a factor of 7.5 for the A1B marker scenario between 2000 and 2100, whereas transport emissions in this scenario grow by a factor of 4 for the QUANTIFY transport emissions (*38*). This increase in the share of aviation emissions at 2100 reflects the relatively slower transition to alternative nonfossil fuels compared with other transport modes, particularly road and rail transport. Aviation CO_2 emissions represent 3% of total fossil fuel CO_2 emissions in 2000 and between 3 and 11% in 2100.

Aviation is calculated to contribute 677 Tg of CO_2 in 2000, that is 12% of total transport CO_2 emissions. In 2100, aviation was calculated to contribute between 5067 and 723 Tg of CO_2 (A1B and B1-ACARE, respectively), compared with total SRES Transport of between 20 773 and 9656 Tg of CO_2 (A1B and B1, respectively, that is 24 and 7%, respectively).

The aviation scenarios presented in this study represent an update of the future aviation emission scenarios published in the IPCC Special Report on Aviation (*28*). The scenarios presented show a range of demand and technology outcomes that are broadly consistent with the storylines presented in the IPCC SRES emission scenarios and are plausible outcomes under the SRES economic growth assumptions used.

Emissions of CO_2 from aviation between 2000 and 2050 are projected to grow by between a factor of 2.0 and 3.6, depending on the scenario. Emissions of NO_x from aviation over the same period are projected to grow by between a factor of 1.2 and 2.7. By 2100, aviation CO_2 emissions under the high growth A1 scenario are a factor of 7.5 more than the 2000 aviation emissions. The B1 scenario CO_2 emissions are a factor of 1.7 more than the 2000 emissions. The B1-ACARE emissions are the lowest in 2100, and are only a factor of 1.1 more than the 2000 emissions. It should be noted that the B1-ACARE scenario differs from the SRES scenarios as it would require significant continuing improvements in fuel efficiency and some radical technological advances in the second half of the century probably as a result of some climate concerns and policy. Moreover, we have implemented achievement of ACARE targets for all newly manufactured aircraft as a “what if”, in practice this would be impossible.

The SRES scenarios by design do not include mitigation policies for climate change. If emissions from international aviation remain outside emission reduction targets set for climate change mitigation the aviation emissions presented here may occur while emissions from other sectors are rapidly reduced. Emissions from aviation would thus become far greater contributors in the future to global greenhouse gas emissions and climate change. While aviation is not currently one of the main drivers of global warming, the growth trajectory of the industry suggests it could become a significant factor over the coming decades.

The SRES scenarios have been interpreted for aviation with other transport modes as part of the QUANTIFY project (*38*), which will allow different transport modes to be compared and their climate impacts to be modeled in a consistent fashion.

Acknowledgments

We gratefully acknowledge the financial support by the European Commission as part of the Integrated Project “QUANTIFY - Quantifying the Climate Impact of Global and European Transport Systems” funded under the sixth Framework Programme for Research as well as the support from our home institution.

Supporting Information Available

Details on modeling the traffic demand for the SRES storylines, a description of the SRES scenarios and further details on projecting future emission trends. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) IEA. *CO_2 Emissions from Fuel Combustion 1971−2001*; International Energy Agency Organisation for Economic Co-Operation and Development: Paris, 2007.

(2) Lee, D. S.; Fahey, D. W.; Forster, P. M.; Newton, P. J.; Wit, R. C. N.; Lim, L. L.; Owen, B.; Sausen, R. Aviation and global climate change in the 21st century. *Atmos. Environ.* **2009**, *43*, 3520–3537.

(3) IPCC. Aviation and the Global Atmosphere. In *Intergovernmental Panel on Climate Change*; Penner, E. Lister J., Griggs, D. H., Dokken, D. J., McFarland M., D. J., Eds.; Cambridge University Press: Cambridge, UK, 1999.

(4) IPCC. *Special Report on Emission Scenarios Working Group III of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2000.

(5) ACARE. *Strategic Research Agenda*; Advisory Council for Aeronautics Research in Europe: Brussels, 2002; Vol. 2.

(6) Lee D. S.; Owen B.; Graham A.; Fichter C.; Lim L. L.; Dimitriu D. *Allocation of International Aviation Emissions from Scheduled Air Traffic—present Day and Historical*; Report to UK Department for Environment, Food and Rural Affairs: London, 2005.

(7) Stordal, F.; Gauss, M.; Myhre, G.; Mancini, E.; Hauglustaine, D. A.; Köhler, M. O.; Berntsen, T.; Stordal, E. J. G.; Iachetti, D.; Pitari, G.; Isaksen, I. S. A. TRADEOFFs in climate effects through aircraft rerouting: forcing due to radiatively active gases. *Atmos. Chem. Phys. Discuss.* **2006**, *6*, 10733–10771.

(8) Sausen, R.; Isaksen, I.; Grewe, V.; Hauglustaine, D.; Lee, D. S.; Myhre, G.; Köhler, M. O.; Pitari, G.; Schumann, U.; Stordal, F.; Zerefos, C. Aviation radiative forcing in 2000: An update of IPCC (1999). *Meteorol. Z.* **2005**, *14*, 555–561.

(9) Gauss, M.; Isaksen, I. S. A.; Lee, D. S.; Søvde, O. A. Impact of aircraft NO_x emissions on the atmosphere—Tradeoffs to reduce the impact. *Atmos. Chem. Phys.* **2006**, *6*, 1529–1548.

(10) Fichter, C.; Marquart, S.; Sausen, R.; Lee, D. S. The impact of cruise altitude on contrails and related radiative forcing. *Meteorol. Z.* **2005**, *14*, 563–572.

(11) Michot, S.; Stancioi, N.; McMullen, C.; Peeters, S.; Carlier S. *AERO2K Flight Movement Inventory*; Project Report, EUROCONTROL, EEC Report EEC/SEE/2003/005: France, 2003; http://www.eurocontrol.int/eec/public/standard_page/DOC_Report_2003_030.html (accessed 07−23−09).

(12) Simos, D. *PIANO: PIANO User's Guide Version 4.0*; Lissys Limited: UK, 2004; (www.piano.aero).

(13) Gardner, R. M.; Adam, J. K.; Cook, T.; Deidewig F.; Falk, R.; Fleuti, E.; Herms, E.; Johnson, C. E.; Lecht, M.; Lee, D. S.; Leech, M.; Lister, D.; Massé, B.; Metcalfe, M.; Newton, P.; Schmitt, A.; Vandenbergh, C.; van Drimmelen, R. The ANCAT/EC global inventory of NO*x* emissions from aircraft. *Atmos. Env.* **1997**, *31*, 1751−1766.

(14) Deidewig, F.; Döpelheuer, A.; Lecht, M. Methods to assess aircraft engine emissions in flight. In *Proceedings of the 20th Congress of the International Council of the Aeronautical Sciences (ICAS)*; International Council on Aeronautical Sciences: Sorrento, 1996; pp 131−141.

(15) Eyers, C. J.; Addleton, D.; Atkinson, K.; Broomhead, M. J.; Christou, R.; Elliff, T.; Falk, R.; Gee, I.; Lee, D. S.; Marizy, C.; Michot, S.; Middel, J.; Newton, P.; Norman, P.; Plohr, M.; Raper, D.; Stanciou, N. AERO2k Global aviation emissions inventories for 2002 and 2025; QINETIQ/04/01113,: Farnborough, Hants, UK, 2005.

(16) Kim, B. Y.; Fleming, G. G.; Lee, J. J.; Waitz, I. A.; Clarke, J.-P.; Balasubramanian, S.; Malwitz, A.; Klima, K.; Locke, M.; Holsclaw, C. A.; Maurice, L. Q.; Gupta, M. L. System for assessing Aviation's Global Emissions (SAGE), Part 1: model description and inventory results. *Transp. Res.* **2007**, *D12*, 325–346.

(17) IEA. *Oil Information 2006, Table 9*; International Energy Agency: Paris, 2007; Vol. 749.

(18) CAEP/6-FESG. *Report of the Forecasting and Economic Sub-Group (FESG): Traffic and Fleet Forecast.* International Civil Aviation Organisation Committee on Environmental Protection Steering Group Meeting, Orlando, FL, June 2003.

(19) The International Civil Aviation Organisation Forecasting and Economic Analysis Sub-Group. *ICAO-FESG. Report 4: Long-Range Scenarios*; International Civil Aviation Organization Committee on Aviation Environmental Protection Steering Group Meeting: Canberra, Australia, January 1998.

(20) Sausen, R.; Schumann, U. Estimates of the climate response to aircraft CO_2 and NO_x emissions scenarios. *Clim.c Change* **2000**, *44*, 27–58.

(21) ICAO/CAEP Forecasting and Economic Sub-Group (FESG) CAEP/8 Traffic and fleet forecasts Paper presented to CAEP Steering Group 19/08/08. ref. CAEP-SG/20082-IP/02

(22) ICAO News Release. http://www.icao.int/icao/en/nr/2009/pio200908_e.pdf (accessed August 5, 2009).

(23) http://www.oagaviation.com/trends-chart-jul.jpg (accessed August 5, 2009).

(24) Schafer, A.; Victor, D. G. The future mobility of the world population. *Transp. Res., Part A* **2000**, *34* (Issue 3), 171–205.

(25) Vedantham, A.; Oppenheimer, M. *Long-term Scenarios for Aviation: Demand and Emissions of CO_2 and NO_x Energy Policy*; Elsevier Science Ltd: Great Britain, 2003; Vol. 26, pp 625−641.

(26) Olsthoorn, X. Carbon dioxide emissions from international aviation: 1950−2050. *J. Air Transp. Manage.* **2001**, *7*, 87–93.

(27) Pulles, J. W. *Aviation Emissions and Evaluation of Reduction Options/AERO*; Ministry of Transport, Public Works and Water Management, Directorate-General of Civil Aviation: The Hague, The Netherlands, 2002.

(28) Henderson, S. C., Wickrama, U. K., Baughcum, S. L., Begin, J. L., Franco, F., Greene, D. L., Lee, D. S., Mclaren, M. L., Mortlock, A. K., Newton, P. J., Schmitt, A., Sutkus, D. J., Vedantham, A., Wuebbles, D. J. Aircraft emissions: Current inventories and future scenarios. In *Aviation and the Global Atmosphere*, Special Report of the IPCC 1999 Aviation and the Global Atmosphere, Chapter 9; Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J., McFarland, M., Eds.; Cambridge University Press: Cambridge, UK, 1999.

(29) ICAO World Traffic Data. http://www.airlines.org/economics/traffic/World+Airline+Traffic.htm (accessed January 24, 2009).

(30) Jiang, K.; Masui, T.; Morita, T.; Matsuoka, Y. Long-term GHG emission scenarios for Asia-Pacific and the world. *Technol. Forecast. Social Change* **2000**, *63* (2−3), 207–229, February−March.

(31) Vries, B. De; Bollen, J.; Bouwman, L.; Elzen, M. Den; Janssen, M.; Kreileman, E. Greenhouse gas emissions in an equity-, environment- and service-oriented World: An IMAGE-based scenario for the 21st century. *Technol. Forecast. Social Change* **2000**, *63* (2−3), 137–174, February−March.

(32) Greene D. L.; Meisenheimer L. *Commercial Air Transport Emission Scenario Model*; Oak Ridge National Laboratory Center for Transportation Analysis: Oak Ridge, TN, 1997.

(33) *UK Air Passenger Demand and Carbon Dioxide Forecasts*; UK Department for Transport: London, November, 2007.

(34) *ATM Global Environmental Efficiency Goals for 2050*; CANSO Civil Air Navigation Services Organisation: Hoofddorp, The Netherlands, 2008.

(35) *ICAO/CAEP Report of the Independent Experts on the NO_x Review and Medium and Long Term Technology Goals for NO_x*, Document 9887; ICAO Committee on Aviation Environmental Protection: Ottawa, ON, 2008; p 120, ISBN 978-92-9231-088-2.

(36) IPCC Assessment Report 4 Synthesis. In *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Core Writing Team; Pachauri, R. K., Reisinger, A., Eds.; IPCC: Geneva, Switzerland, 2007; p 104.

(37) Berghof, R., Schmitt, A., Eyers. C., Haag, K., Middel, J. Hepting, M. *CONSAVE 2050 Final Report Project*, No. GMA2-2001-52065; Constrained Scenarios on Aviation and Emissions: Cologne, July 2005.

(38) QUANTIFY website http://www.pa.op.dlr.de/quantify/ (accessed August 5, 2009).

ES902530Z