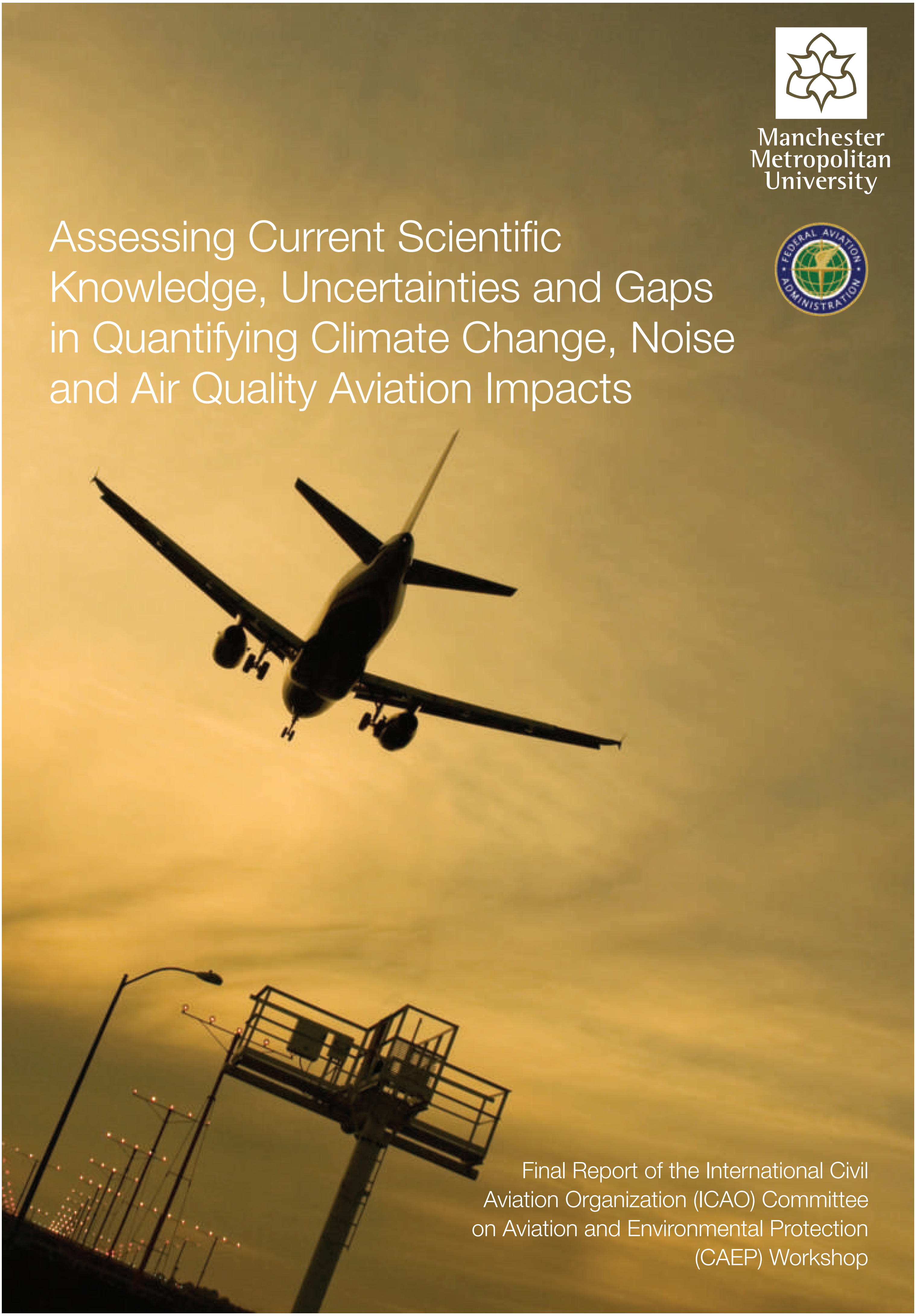

Manchester Metropolitan University

Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts

Final Report of the International Civil Aviation Organization (ICAO) Committee on Aviation and Environmental Protection (CAEP) Workshop

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Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts

Final Report of the International Civil Aviation Organization (ICAO) Committee on Aviation and Environmental Protection (CAEP) Workshop

29 October – 2 November 2007, Montreal, Canada

Edited by L. Q. Maurice and D. S. Lee

Foreword

Jane Hupe

The International Civil Aviation Organization (ICAO) develops a range of standards, policies and guidance material for the application of integrated measures to address aircraft noise and engine emissions mainly through its Committee on Aviation Environmental Protection (CAEP).

CAEP is composed of 22 members, 13 observers and approximately 400 experts who are involved in its overall activities, thus forming a unique international expertise forum for the study and development of proposals to minimize aviation's effects on the environment. The experts cooperate in a consensus building process, based on sound data and knowledge and a profound respect for different views and needs, to achieve globally accepted solutions to the aviation environmental challenge.

To enlarge its knowledge base and bring new facets to the work of the Committee, thereby allowing it to keep track of the top research developments, CAEP organizes workshops regularly to seek further advice on timely and emerging new areas, like the impacts of aircraft noise and aircraft engine emissions on health and wellbeing.

This workshop is a successful example of how CAEP gathers the best available expertise and delivers it to the aviation community in order to support decision making. The results of this workshop have provided critical input to ICAO and will allow further developments in this field.

ICAO would like to express its sincere gratitude to the United States and the United Kingdom for their financial support, to the organizing committee for all the effort put into the planning of the workshop and the excellent experts who participated and contributed in the discussions.

Jane Hupe, Secretary of Committee on Aviation Environmental Protection (CAEP),
International Civil Aviation Organization

Acknowledgements

Many individuals worked extremely hard to make this workshop a reality. The panel co-chairs and panellists themselves were of course the heart of the workshop, and their exceptional contributions are noted throughout their report. And of course, this historic gathering would not have been possible without the efforts of the workshop planning committee.

The workshop co-chairs would also like to acknowledge additional contributions. First, the United Kingdom and United States graciously provided financial support for the workshop.

Dr Stuart Jacobson, the Associate Director of the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) – a US Federal Aviation Administration (FAA)/US National Aeronautics and Space Administration (NASA)/Transport Canada sponsored Centre of Excellence project – and Dr James Hileman, Research Engineer at the Massachusetts Institute of Technology (MIT), led a team of graduate students who provided magnificent support during the workshop and report preparation. They included Douglas Allaire, Christopher Kish, Stephen Lukachko, Anuja Mahashabde and Christopher Sequeira of MIT, Steven Barrett of the University of Cambridge, Agnieszka Skowron of Manchester Metropolitan University, and Ying Zhou of Harvard School of Public Health. Without their expertise, grace and patience with the workshop chairs and co-chairs, the workshop and its report would not have been possible.

Dr Nick Miller of Harris, Miller, Miller & Hanson, Inc., aviation environmental consultants, graciously stepped in and assisted with documenting the Noise Panel work after one of its co-chairs, Larry Finegold, became seriously ill.

Ms Aimee Fisher of the US Federal Aviation Administration (FAA) provided impeccable staff support, compiling all inputs and addressing hundreds of comments.

Dr Lourdes Maurice

Prof. David S. Lee

And of course, thanks also go to the wonderful Committee on Aviation Environmental Protection (CAEP) Secretariat staff who made a very complicated undertaking appear effortless.

Dr Lourdes Maurice, Chief Scientist Energy and Environment, Federal Aviation Administration and Workshop co-chair

Prof. David S. Lee, Manchester Metropolitan University and Workshop co-chair

Executive summary

During the 7th Meeting of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP), held in Montreal, Canada in February 2007, CAEP members and observers agreed that a scientific workshop would be organized to assess the state of knowledge and gaps in understanding and estimating noise, air quality and climate impacts of aviation. The CAEP agreed that a small group would be formed to plan and execute the workshop, facilitated by the CAEP Secretariat. This should include carefully crafting the questions posed to the science community in order to best inform CAEP.

The Workshop on 'Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts' (hereafter referred to as the 'Impacts Workshop') was held in Montreal, Canada at ICAO Headquarters, 29–31 October 2007. It was structured along the lines of panels in three subject areas: noise, ar quality and climate impacts of aviation. The experts from each area were also involved in discussion on all issues associated with trade-offs and interdependencies among these impacts. The panels were reconstituted during the last breakout session to comprise experts from all subject areas in order to facilitate the interdependencies and trade-offs discussions.

The objective of the workshop was to critically review knowledge and methodological requirements important to the comprehensive evaluation of aviation environmental impacts in a decision-making context. Participants were asked to:

1. review the current state of knowledge of aviation environmental impacts and best practice approaches for assessing these impacts;

2. examine key issues, gaps and underlying uncertainties in the comprehensive evaluation of aviation environmental impacts; and

3. advise ICAO/CAEP on how existing knowledge and best practice approaches may be used to inform policy decisions, and to suggest near term steps that can be taken to improve the knowledge and approaches.

Ultimately, the participants were asked to address the following question:

> Given current ICAO/CAEP practices, and given what is available and ready (or nearly ready) to use in the world, what are the best next steps for ICAO/CAEP to take with modelling and analysis of aviation environmental impacts?

Conclusions from the workshop are envisaged to facilitate CAEP's future development of cost-benefit or other analyses approaches for assessing the environmental health and welfare impacts of aviation environmental policy and would, in due course, lead to refining associated interdependencies and trade-offs analyses taking environmental impacts into account.

The workshop was possibly unique in that it brought together international experts from the noise, air quality and climate science communities to address the state of knowledge and uncertainties. The interdependencies session, in which the three communities were mixed, was also very productive.

Air quality

The workshop noted that degradation of air quality caused by aviation may directly impact upon human health. Moreover, it can also affect crop productivity and ecosystem response. In reality, aviation impacts on air quality are no different to those from other sources, as no pollutant has as yet been identified as being unique to the sector.

Currently, the main driver for air quality assessment of aviation sources is one of regulatory compliance, risk assessment and planning consent. The current process of CAEP air quality *impacts* assessment is focused on emissions inventories. High quality inventories of emissions for both the airport and non-airport locality are necessary, up to a regional scale, depending on the pollutant being studied. CAEP efforts to intercompare models are laudable, but panellists noted that intercomparing models is not adequate for validation; comparison with experimental data is critical. The workshop noted that dedicated measurement campaigns with more technically sophisticated instrumentation would be needed and encouraged states to support such campaigns.

The workshop ultimately concluded that while the development of detailed emissions inventories is critical, such inventories are not enough in and of themselves for air quality *impacts* assessment. Dispersion modelling and health risk analyses must be employed in order to determine the source-receptor relationships for direct/indirect (or primary/secondary) air pollutants that will be unique for every airport studied.

The workshop noted the substantial progress made on emission characterization and for many years, the International Civil Aviation Organization (ICAO) Landing-Take-Off (LTO) Certification process has facilitated high quality characterization of aircraft NO_x emissions. However, the situation is not so satisfactory on the issue of particle emissions about which many health impacts are currently concerned. Characterization of particle emissions and consideration of their impacts is technically and scientifically demanding, but critical to addressing the environmental impacts of aviation.

Cost-effectiveness analyses (CEA) and cost-benefit analyses (CBA) are potentially valuable tools for use in assessing the air quality impacts of aviation. The methods are mature and well accepted and CAEP could immediately make use of these analyses to inform assessments.

Noise

The CAEP process of assessing aircraft noise *impacts* is primarily based on the number of people exposed to significant noise as measured by day-night sound level, or DNL, which is not an assessment of *impacts per se*. This approach of quantifying people exposed should be modified to focus more specifically on the health effects or outcomes of aircraft noise exposure. For noise, the most appropriate definition of health is that of the World Health Organization (WHO), which indicates that health is "a state of complete physical, mental, and social wellbeing and not merely the absence of disease, or infirmity."

There are currently well documented exposure-response relationships for a number of health effects which can be applied presently by CAEP to the overall aircraft noise assessment process, except for sleep structure and coronary heart diseases (CHD). However, because air traffic has evolved from fewer operations with loud aircraft to more frequent operations with quieter aircraft, an update to exposure-response curves may be needed to better reflect current and projected air traffic operations. The workshop also noted that the applicability of and ability to generalize existing noise effects research data and related exposure-response relationships and thresholds to all countries is questionable and must be addressed.

As for air quality, CEA and CBA are potentially valuable tools for use in assessing the impacts of aircraft noise. However, the Noise Panel discussions noted that primary emphasis for aircraft noise impact assessment should focus on expanding exposure analyses. Noise panellists generally felt that economical assessment of noise impacts is challenging. Economists presented the state-of-the-practice in noise impact valuation, based on housing value loss or contingent valuation surveys. But many among the Noise Panel expressed their concern that such economic impact models fail to capture the full extent of noise effects, such as the value of cardiovascular effects and the effects of sleep disturbance on worker productivity and worker accidents. Some panellists noted that DALY (disability-adjusted life years) and QALY (quality-adjusted life years) analyses, which are very well developed for air quality impacts, were also applicable to noise and had been used to compare noise and air quality impacts in airport analyses. However, other panellists felt that these methodologies were not yet widely agreed upon for noise impacts. Ultimately, panellists noted that most of them did not have economic expertise and that CAEP should seek further advice.

Climate

Quantification and assessment of the climate impacts of aviation (and for that matter, any other source) possibly represents the greatest challenge but arguably the most pressing need, given the long time-scales of response. Similarly to air quality issues, quantification of emissions alone is a first step, but in isolation is of limited use in assessing climate impacts and related metrics. A range of modelling techniques and concepts is necessary in order to assess the climate impacts. Most of these techniques and concepts are routinely applied to estimate the climate impacts of emissions from other sources.

Although workshop climate panellists readily agreed that inventories were not sufficient to quantify impacts, they could not readily agree on a single best approach to defining climate impacts. An 'impact chain' can be qualitatively developed; however, when attempting to quantify impacts within the framework for assessing impacts the challenges are significant. Most of the expertise of the workshop was restricted to defining certain key indicators of aviation impacts such as global mean or regional radiative forcing or temperature response. Such modelling of 'physical' impacts is complex and requires considerable scientific and intellectual resources to undertake this to a consensual level. The following steps from regional and global indicator geophysical responses through to resource/ecosystem/energy/health/societal responses and subsequent social welfare and costs responses represent a considerable challenge for society as a whole and is certainly not restricted to the debate over one sector's impacts on climate.

The workshop noted that although the climate impact of CO_2 emissions is most certain, aviation's emissions impacts are "more than those from just CO_2. Understanding of other effects, such as the balance between O_3 production and ambient CH_4 destruction from aviation NO_x emissions, climate impacts due to soot particles and aerosols, and the different scales of radiative forcing and temperature response remain a challenge but are solvable in the near future through dedicated design simulations and analyses.

The time-scales of response was a theme that was often referred to. Emissions of CO_2 will have a radiative impact over a time-scale of a century or more, while those from non-CO_2 effects will be shorter. However, this is not the full picture, since other metrics such as global mean temperature response or sea level rise have much longer time-scales, *even for non-CO_2 effects*, because of the thermal inertia of the coupled atmosphere-ocean climate system.

Because of the complex chemical and physical responses induced by aviation on climate and their different time-scales, there has been considerable interest in developing metrics. Such metrics should be distinguished by their purpose and usage, such that relatively straightforward quantitative metrics of current response (e.g. radiative forcing) may be of limited use as policy metrics addressing different impacts. Metrics appropriate to the policy being formulated will need to be developed. This is not to say that this subject is too immature to be utilized, for example, consideration of Global Warming Potential (GWP), Absolute Global Warming Potential (AGWP) and Global Temperature Change Potential (GTP) is increasingly finding its way into the scientific literature. Such relatively simple formulations have the advantage of relative simplicity and transparency: what require ongoing consideration are the inputs from more complex models and the application of such metrics to particular questions posed.

Considerable difficulties are involved in assessing the socio-economic responses to changes in the climate system. Although there is a large body of literature on damage assessment, the panellists noted there was no scientific consensus on the best approach or the values/metrics involved. Appropriate approaches are also dependent on the question being asked and it is difficult to provide generic advice to CAEP that would cover a range of potential questions. Applying a number of approaches is helpful, but each has drawbacks. The Climate Panel noted that there was not good representation of such impact assessment expertise available (with the notable exception of one international expert on this subject), but there was consensus across the panel that monetary evaluation of climate impacts, even though it is routinely applied, may well be beyond what the majority of panellists felt comfortable with and would find credible, given the complexities and uncertainties of input assumptions. Understanding that policymakers may nevertheless wish to examine such data, it is critical to always show a range of different metrics, with quantified uncertainties. It is also critical to compute impacts for a range of time horizons and leave how different results are weighed up to the policymaker.

Interdependencies

The workshop concluded that intrinsic physical interrelationships exist between noise, air quality and climate. Interdependencies are important and trade-offs are routinely made (e.g. modern aircraft design and mitigation strategies). There was strong consensus that CEA was not appropriate for assessing interdependencies between noise, air quality and climate impacts. The workshop agreed that CBA could in principle enable such comparisons. However, while CBA modelling and metrics exist in principle for noise, air quality and climate individually to various levels of maturity (but less so for climate), there are no generally agreed credible approaches to compare interdependencies. A number of states are pursuing efforts to develop such approaches and the panellists noted we can look forward to new findings and experiences that can inform future efforts.

Ultimately, it is clear that there is not one simple, single answer. Multiple metrics are important (e.g. health outcomes, quality of life, to some degree monetization) to address interdependencies. How questions are posed and different approaches to assessments may produce different rank orders, but multiple metrics inform the decision process. No single or multiple process or metric can replace the decision maker; additional data will just serve to inform policy decisions more fully.

For health and welfare effects, there is widespread consensus, thanks largely to the efforts of the World Health Organization on approaches to monetized air quality impacts; however, a consensus does not exist among the noise community, although techniques are available. Monetization has been done for climate, but there is not a single widely accepted approach. CAEP may wish to assess climate and other non-quantifiable impacts in terms of an added (non-quantified) cost/benefit to a CBA between air quality (AQ) and noise.

CAEP states its environmental goals in terms of mitigation of noise and emission *impacts*. However, these impacts have not been characterized and estimated beyond inventories and people exposed to 'significant' noise. CAEP should seek to move towards truly defining impacts in order to provide meaningful guidance and direction on defining environmental needs, goals, and targets to achieve those goals.

The workshop suggested that CAEP move towards a transparent, policy analysis framework that: 1) assesses noise, air quality and climate as well as their integration, 2) integrates the latest relevant knowledge from the physical and social sciences, and 3) is open to various stakeholders (e.g. researchers, decision makers and parties affected by those decisions). However, doing so will take time and careful consideration, and will probably require substantial investment.

The way forward on scientific advice

The workshop organizers noted that effective future efforts to address aviation environmental impacts cannot be undertaken in isolation, nor at a single UN Agency level alone. The range of stakeholders involved necessitates wider coordination, not least of all accounting for the efforts of the individual scientists and scientific organizations who so freely and generously gave of their time to make the workshop a success. However, bringing all of this expertise into CAEP would not be easy, nor necessarily wise.

The workshop chairs suggest that CAEP form a small virtual group of individuals representing the relevant science communities to develop proposals for future possibilities that will facilitate improved scientific understanding and ultimately facilitate policy-relevant advice to be provided to ICAO and member states with regard to environmental protection. The intent behind a virtual group is that such an approach will increase the likelihood of engaging top scientists. The virtual group should also include participation of stakeholders (that is, CAEP members and observers) to ensure that the focus remains on policy-relevant science.

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Chapter 1 Introduction

During the 7th Meeting of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP), held in Montreal, Canada in February 2007, CAEP members and observers agreed that a scientific workshop would be organized to study the state of knowledge and gaps in understanding and estimating noise, air quality and climate impacts of aviation. Conclusions from such a workshop were envisaged to assist CAEP in focusing more specifically on understanding and addressing the environmental health and welfare impacts of aviation. The results from the workshop were also envisaged to facilitate CAEP's future development of cost-benefit or other analysis approaches for assessing the environmental health and welfare impacts of aviation environmental policies, and would, in due course, lead to refining associated interdependencies and trade-offs analyses taking environmental impacts into account.

The CAEP agreed that a small group would be formed to plan and execute the workshop, facilitated by the CAEP Secretariat. This should include carefully crafting the questions posed to the science community in order to best inform CAEP. Individuals participating in the workshop planning committee included:

Mr Dan Allyn, International Coordinating Council of Aerospace Industries Associations
Dr Mohan Gupta, United States
Professor David Lee, United Kingdom
Professor Patrizio Massoli, Italy
Dr Lourdes Maurice, United States
Mr Ted McDonald, Canada
Ms Celia Alves Rodrigues, ICAO/CAEP
Mr Saleem Sattar, Canada
Ms Nancy Young, International Air Transport Association (IATA)

Dr Maurice and Professor Lee jointly led the planning committee and also served as workshop general chairs. The CAEP Research Focal Points (RFPs) as well as Science Focal Points (SFPs)[1] participated in the workshop planning. Australia and Japan also provided support. The CAEP Secretariat provided logistical support, in addition to participating in the planning committee.

The Workshop on 'Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts' (hereafter referred to as the 'Impacts Workshop') was held in Montreal, Canada at ICAO Headquarters, 29–31 October 2007.

The Impacts Workshop was structured along the lines of panels in three subject areas: noise, air quality and climate impacts of aviation. The experts from each area were also involved in discussion on all issues associated with trade-offs and interdependencies among these impacts. The panels were reconstituted during the last breakout session to comprise experts from all subject areas in order to facilitate the interdependencies and trade-offs discussions. Each panel comprised two panel co-chairs, invited members and observers. The size of each panel ranged between twenty and thirty participants.

The co-chairs for the Noise Impacts Panel were Larry Finegold (United States) and Dr Michel Vallet (France). The co-chairs for the Air Quality Impacts Panel were Professor Michael Pilling (United Kingdom) and Professor Jack Spengler (United States). The co-chairs for the Climate Impact Panel were Professor Ivar Isaksen (Norway) and Professor Don Wuebbles (United States). The panel co-chairs were intermingled to lead the interdependency groups. Participating panellists are shown in Appendix A, 'Workshop participants'.

It was important that CAEP members and observers (referred to as Workshop Stakeholders) were invited to observe the workshop and help provide context for the panel members, who may not have much experience with CAEP. However, the objective of the workshop was to gather international scientists to identify the main knowledge gaps in relation to climate, air quality and noise impacts of aviation. Hence, it was important to ensure that there was an appropriate balance of numbers between the Workshop Stakeholders and the scientific experts. A request for expression of interest to attend as an observer was forwarded to Workshop Stakeholders. About twenty individuals, representing ICCAIA, IATA, the European Commission (EC), the United Kingdom and the United States attended as observers who distributed themselves between the three panels. In addition, the co-rapporteurs of CAEP working groups and task forces were invited to attend, and one of the co-rapporteurs of ICAO/CAEP Working Group 1 (Noise) participated. A list of Workshop Stakeholders is also shown in Appendix A.

The Planning committee, General Chairs, and Panel Co-Chairs had agreed on a draft workshop agenda, which was refined as the workshop planning progressed and is given in Appendix B, 'Workshop agenda'. Official recorders were provided by Manchester Metropolitan University (MMU), the University of Cambridge and the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) Centre of Excellence. Recorders were graduate students or research assistants experienced in the various subject areas.

The planning committee, general chairs, and panel co-chairs prepared briefing papers and brief introductory presentations for each subject area. This documentation was provided to the participants prior to the workshop. The panel co-chairs also compiled a library of relevant background documentation. These references were made available to participants via an ICAO secure website (https://icaosec.icao.int/Users/). Access to the website by CAEP members and observers can be obtained through ICAO/CAEP.

[1] Rick Miake-Lye (climate and air quality), Claus Bruning (climate and air quality), Malcolm Ko (climate and air quality), David Lee (climate), François Coulouvrat (supersonic noise), Yoshikazu Makino (supersonic noise), Vic Sparrow (supersonic noise).

The objective of the workshop was to critically review knowledge and methodological requirements important to the comprehensive evaluation of aviation environmental impacts in a decision-making context. Participants were asked to:

1 review the current state of knowledge of aviation environmental impacts and best practice approaches for assessing these impacts;

2 examine key issues, gaps and underlying uncertainties in the comprehensive evaluation of aviation environmental impacts; and

3 advise ICAO/CAEP on how existing knowledge and best practice approaches may be used to inform policy decisions, and to suggest near term steps that can be taken to improve the knowledge and approaches.

In sum, the participants were asked to address the following question:

> Given current ICAO/CAEP practices, and given what is available and ready (or nearly ready) to use in the world, what are the best next steps for ICAO/CAEP to take with modelling and analysis of aviation environmental impacts?

The specific questions addressed by the Air Quality, Noise and Climate Panels, as well as the questions addressed by the Interdependency Panels are given in Appendix C, 'Workshop questions', as well as within individual chapters as appropriate.

This report provides a summary of findings and recommendations by the participants of the workshop in order to inform CAEP. The report seeks to advise CAEP on how existing scientific knowledge may be used to inform policymakers, and near term (next 1–2 years) steps that can be taken to improve this knowledge. Chapter 2 offers a summary of the background of current ICAO/CAEP policy-making practices focused on mitigating aviation climate, local air quality and noise impacts provided to workshop participants. It places these current practices in context through a brief (and, as such, not comprehensive) summary of regulatory decision-making processes within representative organizations charged with environmental stewardship. It also outlines the roles and responsibilities of ICAO/CAEP, recent analyses to support aviation environmental policy decisions, and reviews development activities intended to advance these analysis capabilities. Chapter 2 also highlights current environmental impact assessment practices focused on air quality, noise and climate effects undertaken outside of ICAO/CAEP. Chapters 3, 4 and 5 focus on findings and recommendations of the Air Quality, Noise and Climate Panels, respectively. Chapter 6 summarizes the findings and recommendations of the interdependencies breakout groups. Summary and overarching recommendations are found in Chapter 7.

Chapter 2 Background

ICAO's activities in the environment field are primarily focused on those problems that benefit most from a common coordinated approach, on a worldwide basis, namely aircraft noise and the impact of aircraft engine emissions. Most of this work is undertaken through the CAEP, which consists of members from states (countries) and observers from states, intergovernmental organizations, and non-governmental organizations representing aviation industry and environmental interests. The current CAEP structure includes separate working groups to address the technical aspects of noise and emissions reduction and mitigation, and aircraft operations. In addition, a support group provides information on aviation activity forecasting and economics, and task groups address modelling and databases, and market-based measures. For the most part, CAEP has considered noise, air quality and climate separately, but is cognizant of the interrelationships among these impacts and is taking steps to move towards a comprehensive analytical approach.

In 2001, the ICAO Assembly endorsed the concept of a 'balanced approach' to aircraft noise management (ICAO, 2004a). This consists of identifying the noise problem at an airport and then analysing the various measures available to reduce noise through the exploration of three principal elements, namely reduction at the source (quieter aircraft), land use planning and management, and noise abatement operational procedures and operating restrictions, with the goal of addressing the noise problem in the most cost-effective manner. ICAO has developed policies on each of these elements, as well as on noise charges.

With regard to emissions, aircraft are required to meet the engine certification standards adopted by the ICAO Council, which are contained in Annex 16, Volume II to the Convention on International Civil Aviation (ICAO, 2004b). These standards were originally designed to respond to air quality concerns in the vicinity of airports. As a consequence, they establish limits for emissions of oxides of nitrogen (NO_x), carbon monoxide (CO) and unburned hydrocarbons (UHC), all for a reference landing and take-off (LTO) cycle below 915 metres of altitude (3000 ft). There are also provisions regarding smoke and vented fuel. In 2001, the ICAO Assembly asked the Council to promote the use of operational measures as a means of limiting or reducing the impact of aircraft engine emissions. Subsequently, an ICAO circular was published on operational opportunities to minimize fuel use and reduce emissions. The circular includes information on aircraft ground level and inflight operations, as well as ground service equipment and auxiliary power units. Separately, ICAO is also pursuing analysis of, and guidance on, the application of market-based measures aimed at reducing or limiting the environmental impact of aircraft engine emissions, particularly with respect to mitigating the impact of aviation on climate change. The ICAO Assembly encouraged states and the ICAO Council, taking into account the interests of all parties concerned, to evaluate the costs and benefits of the various measures with the goal of addressing aircraft engine emissions in the most cost-effective manner, emphasizing the need for states to take action in a consistent manner regarding both domestic and international aviation emissions (ICAO, 2004a).

Before a given policy or stringency measure is adopted, CAEP's terms of reference require it to assess the technical feasibility, the economic reasonableness and the environmental benefits of the options considered, taking into account interdependencies between noise and emissions and among emissions. Historically, CAEP has measured economic reasonableness strictly in terms of the cost to implement the measure and environmental benefits in terms of changes in fuel burn, emission inventories and/or number of people exposed to noise. Additional information on selected CAEP studies can be found in the ICAO Environmental Report 2007 (ICAO, 2007b), namely, the 'Analysis of Market-Based Measures for CAEP/5' (p. 147), and the 'Analysis of Local Air Quality Charges for CAEP/6' (p. 86).

More recently, CAEP has recognized the need to develop better methodologies to address interdependencies. The report from the 7th Meeting of CAEP noted that:

> The meeting acknowledged the growing complexity associated with assessing noise and emissions effects of aviation, especially when considering impacts and their influence on benefits-costs, as well as the case for CAEP to get a better understanding of these impacts and the benefits of environmental mitigation based on establishing the value of such reductions in addressing the stated problem (and) endorsed the consideration of a transition to a more comprehensive approach to assessing actions proposed for consideration by the 8th meeting of CAEP. (ICAO/CAEP, 2007a)

The report also noted:

> For CAEP to fully assess interdependencies and analyses of the human health and welfare impacts, CAEP would need to do three things. First, it would need to employ tools that were capable of looking not only at one aviation environmental parameter in isolation, but also at the effect that changing one aviation-related environmental parameter has on other aviation environmental parameters. Second, CAEP would need to frame the impacts of these parameters on common terms, so that it can understand the implications of the interdependencies and make policy decisions taking those implications into account. Third, CAEP should establish the benefit of environmental mitigation as part of a comprehensive assessment. (ICAO/CAEP, 2007a)

Below is a listing and brief description of models that either have been used in past CAEP work and/or are undergoing further development and evaluation to determine their suitability for future CAEP analyses. These models, which have various uses and levels of accuracy, are described under four categories: 1) aircraft noise, 2) air quality, 3) global emissions, and 4) economics and interdependencies. Additional information on these models can be found in the ICAO Environmental Report 2007 under 'Overview of Analytical Capabilities for CAEP Work' (ICAO, 2007b; p. 191).

Air quality models

The following models have been developed by CAEP members for estimating aircraft emissions inventories for operations in the airport vicinity (although several models are also used for global emissions estimates). Although they are called air quality models (and many have dispersion capabilities), CAEP analyses have only estimated emission inventories, not the changes in air quality or the ultimate health and welfare impacts of aviation emissions. The models typically take as inputs the number of operations for specific aircraft types and then use type-specific aircraft and engine performance information and estimated trajectory information to calculate emissions inventories as a function of space and time.

Atmospheric Dispersion Modelling System (ADMS)-Airport
ADMS-Airport has a flight performance pre-processing tool for calculating aircraft emissions. It determines aircraft emissions based on aircraft performance according to aircraft type, weight, airport elevation and aircraft engine. ADMS is linked to EMIT (EMissions Inventory Toolkit), which provides a complete system for the management and manipulation of emissions inventories, including a comprehensive review of the impacts of aircraft, traffic (road and rail), industrial, commercial, and domestic sources

Aviation Environmental Design Tool/Emissions and Dispersion Modelling System (AEDT/EDMS)
Part of the US FAA suite of environmental tools, AEDT/EDMS is a combined emissions and dispersion model for assessing air quality at civilian airports and military air bases. The model is used to produce an inventory of emissions generated by sources on and around the airport or air base, and to calculate pollutant concentrations in these environments. AEDT/EDMS also generates input files for use with US Environmental Protection Agency's AERMOD dispersion model, AERMET meteorological pre-processor and AERMAP terrain pre-processor.

Airport Local Air Quality Studies (ALAQS-AV)
Developed by EUROCONTROL as a test bench tool that can be used to evaluate the impact of various emission inventory and dispersion calculation methods and parameters, ALAQS-AV is an airport air quality toolset based on a Geographical Information System that includes an emissions inventory tool. ALAQS-AV considers four categories of airport emission sources: aircraft, Ground Support Equipment used for aircraft handling, stationary sources (i.e. power/heating plants, fuel farms, etc.) and road traffic (airside and landside).

Lagrangian Simulation of Aerosol Transport for Airports (LASPORT)
Developed in 2002 on behalf of the Federal German Airports Association (ADV), LASPORT is a system for the calculation of airport-induced pollutant emissions and concentrations in the atmosphere. It utilizes the Lagrangian particle model LASAT.

Aircraft noise models

The following models have been developed by CAEP participants for estimating aircraft noise contours around airports. The models typically take as inputs the number of operations for each aircraft type at a given airport, and population data, and then use individual aircraft noise performance data (e.g. noise-power-distance curves) to estimate the number of people exposed to different levels of aircraft noise. Of the three major environmental impacts (noise, climate and air quality), it is noise for which CAEP comes the closest to directly evaluating the impacts (versus stopping at emissions inventories, for example). However, to truly compute impacts is arguably necessary to compute the number of people 'affected' by noise, which may exceed those inside a particular noise contour. Doing so would entail using the dose/response relationships and computing the affected numbers across the whole population. This is further discussed in Chapter 4, 'Aviation noise impacts'.

Aviation Environmental Design Tool/Integrated Noise Model (AEDT/INM)
Part of the US Federal Aviation Administration (FAA)/National Aeronautics and Space Administration (NASA) and Transport Canada suite of environmental assessment tools, AEDT/INM is a computer program developed to assess changes in noise impacts resulting from: 1) new or extended runways or runway configurations; 2) new traffic demand and fleet mix; 3) revised routings and airspace structures; 4) alternative flight profiles; and 5) modifications to other operational procedures.

Aviation Environmental Design Tool/Model for Assessing Global Exposure to the Noise of Transport Aircraft (AEDT/MAGENTA)
Part of the US FAA/NASA/Transport Canada suite of environmental assessment tools, AEDT/MAGENTA is a model developed, within the ICAO/CAEP framework, to estimate global noise exposure caused by civil aircraft operations. The model computes, under any specified noise certification and fleet transition scenario, the noise exposure contours around a large number of civil airports and counts the number of people exposed. Input data include aircraft noise and performance characteristics and aircraft traffic forecasts. Outputs include noise-exposed population estimates by airport together with regional summaries.

The Civil Aircraft Noise Contour Model (ANCON 2)
ANCON is the model used to produce the annual aircraft noise exposure contours published by the UK Department for Transport. It is also used to produce noise exposure forecasts for use in airport planning studies.

The European Harmonized Aircraft Noise Contour Modelling Environment (ENHANCE)
The ENHANCE model aims at improving the quality of noise contours mainly by improving the quality of the input data used by these models. An interface/pre-processor combination is used to enable full 4-D trajectories, taken from either smoothed radar data, or from an ATC simulator, to be used for noise calculations. Thrust profiles, which are generally missing in the input data, are calculated by the pre-processor from these trajectories.

JCAB Aircraft Noise Prediction Model
The Civil Aviation Bureau of the Ministry of Transport of Japan (JCAB) model uses several basic data inputs including: 1) noise-distance data, which determines the value of LAmax to source-receiver distance according to engine thrust values for various aircraft types; 2) altitude profiles, showing the transition of flight altitude and engine thrust; and 3) flight tracks, which are flight paths projected onto the ground. This model usually calculates noise predictions in a simplified form of WECPNL (WECPNLj) on the basis of information on airport and flight operations, and depicts the noise contours. In the calculation, it first determines a flight altitude and an engine thrust value at minimum distance on the flight route from an observation point. Next, it calculates noise exposure due to the flight using noise-distance data. The model corrects for distortion due to excess ground attenuation, based on elevation angle looking up at the aircraft. It also takes flight route dispersion into account. WECPNLj is calculated by adding up all energy contributions of noise exposure calculated for all types of aircraft and flight operations with the corrections.

SONDEO
Developed by Anotec Consulting, the SONDEO model can estimate noise contours surrounding an airport, as well as the number of people exposed within that contour. The noise contour module (NCM) calculates noise contours of LDEN and Lnight according to ECAC Document 29 (3rd edition). The population module is capable of overlaying the noise contours from NCM on population maps, so as to determine the number of people exposed to certain levels of noise. From the total number of people exposed, the percentage of highly annoyed people is derived.

Global emissions models

The following models have been developed by CAEP members for estimating global aircraft emissions inventories (although some models are also used for estimating emissions in and around airports). As with the air quality models, CAEP analyses have only estimated emission inventories, not the changes in climate nor the ultimate health and welfare impacts of these global aviation emissions. The models typically take as inputs the number of operations for specific aircraft types and then use type-specific aircraft and engine performance information and estimated trajectory information to calculate emissions inventories as a function of space and time.

Advanced Emission Model (AEM)
Developed in the late 1990s by EUROCONTROL, AEM is a standalone system used to estimate aviation emissions (CO_2, H_2O, SO_x, NO_x, HC, CO, Benzene, VOC) and fuel burn. It is able to analyse flight profile data, on a flight-by-flight basis, for air traffic scenarios of almost any scope (from local studies around airports to global emissions from air traffic).

AERO2k
Developed as a European Commission Fifth Framework Programme project, AERO2k is a global inventory tool for estimating aviation fuel use and emissions. In addition to the previously provided gas phase species of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HCs) and NO_x, AERO2k provided additional parameters (e.g. particle emissions and km travelled/grid cell) that are now needed for the climate modelling community. The initial output from AERO2k took the form of global gridded data (1 degree latitude × 1 degree longitude × 500 ft cells) of fuel used, emissions and distance flown in each cell for a 2002 inventory and a 2025 forecast. For CAEP work, however, AERO2k tool uses CAEP standard format input data in order to calculate global emissions for current years and for future policy scenarios.

Future Aviation Scenario Tool (FAST)
The FAST model was originally developed for the UK Department of Trade and Industry (DTI) and has subsequently been used in the European Commission Framework Programme projects, TRADEOFF and QUANTIFY. The FAST model was used in TRADEOFF to calculate global civil aviation emissions for 1992 and projections for 2000 (based on 1992 traffic), so that the data could be used to evaluate the impacts of aviation NO_x emissions on O_3 and CH_4, contrails and cirrus cloud enhancement. It has been used in QUANTIFY for a revised inventory for 2002 and scenario projections in 2050.

Aviation Environmental Design Tool/System for Assessing Aviation's Global Emissions (AEDT/SAGE)
Part of the US FAA suite of environmental tools, AEDT/SAGE is a computer model used to predict aircraft fuel burn and emissions for all commercial (civil) flights globally in a given year. The model is capable of analysing scenarios from a single flight, up to airport, country, regional and global levels. AEDT/SAGE is able to dynamically model aircraft performance, fuel burn and emissions, capacity and delay at airports, and forecasts of future scenarios.

Economics and interdependencies

The following models have been developed by CAEP members for estimating the impacts of potential policies on aviation industry economics, and to different extents, the interdependent effects of policies on air quality, climate change and community noise. To date, all CAEP analyses to support decision making have been based on cost-effectiveness analysis (CEA), whereby different policies are judged on the basis of industry costs and changes in emissions inventories or number of people impacted. Estimates of the ultimate health and welfare impacts of aviation noise and emissions have not been considered, nor has there been an explicit accounting of potential interdependencies among environmental impacts.

Aviation Emissions and Evaluation of Reduction Options Modelling System (AERO-MS)
Developed by the Dutch Civil Aviation Authority, AERO-MS is a tool for analysing the complex environmental and economic effects of policy measures to reduce aircraft engine emissions at the local, regional and/or global levels under different scenarios. AERO-MS was specifically designed to consider the environmental impacts of global aircraft engine emissions at cruise level. While focusing on the global

perspective, in view of the spatial detail considered, the modelling system is also able to assess the impacts of emissions on a regional and local scale. AERO-MS has been used for various CAEP analyses, including the CAEP/5 economic analysis of various market-based measures that might be used to reduce carbon dioxide (CO_2) emissions from aviation.

Campbell-Hill Noise Cost Model
This is also known as the FESG Noise Cost Model. It is used in CAEP/5, the Noise Cost Model estimates aircraft-related operating costs and capital expenditures that would result from noise certification (stringency) and phase-out scenarios. The ability of the model to execute airplane transactions in the case of phase-out makes it a unique tool to assess such scenarios.

FESG NO_x Cost Model
This model was used to assess the costs to the manufacturers and operators for the NO_x stringency options that were evaluated as part of the CAEP/6 work program. (The CAEP Forecast and Economic analysis Support Group (FESG) should be contacted for additional information on the CAEP/6 cost-effectiveness analysis of the NO_x stringency options and related modelling methods and assumptions.) The NO_x Cost Model can be used to quantify the mitigation costs (manufacturer and operator costs) for NO_x stringency policy options aggregated to the global level. Currently, some additional development work is underway to update the tool for compatibility with newer baselines and to show costs on a regional level.

US/Canada Comprehensive Environmental Tools Suite
The US FAA Office of Environment and Energy, in collaboration with Transport Canada and NASA, is developing a comprehensive suite of software tools that will allow for thorough assessment of the environmental effects and impacts of aviation. The main goal of the effort is to develop a new, critically needed capability to characterize and quantify the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operational and market scenarios. The three main functional components of the Tools Suite are as follows.

- *Environmental Design Space (EDS)*, which is used to estimate aircraft CAEP/8 performance trade-offs for different technology assumptions and policy scenarios;
- *Aviation Environmental Design Tool (AEDT)*, which takes as input detailed fleet descriptions and flight schedules, and produces estimates of noise and emissions inventories at global, regional and local levels;
- *Aviation Environmental Portfolio Management Tool (APMT)*, which serves as the framework within which policy analyses are conducted and provides additional functional capabilities.

APMT functional capabilities include an economic model of the aviation industry that takes as inputs different policy, and market scenarios and existing and potential new aircraft types (the latter from EDS or other sources). It then simulates the behaviours of airlines, manufacturers and consumers, producing a detailed fleet and schedule of flights for each scenario year for input to AEDT. APMT also takes the outputs from AEDT (or other similar tools) and performs comprehensive environmental impact analyses for global climate change, air quality and community noise. These environmental impacts are quantified using a broad range of metrics (including, but not limited to, monetized estimates of human health and welfare and impacts, thereby enabling both cost-effectiveness and cost-benefit analyses). Additional information is in the 'ICAO Environmental Report 2007' (ICAO, 2007b) and on the FAA website.

Decision-making practices outside of CAEP

Regulatory agencies in many world regions use economic analysis to guide policy decisions through an explicit accounting of the costs and benefits associated with a regulatory change (e.g. cost-benefit analysis, or CBA). CBA requires that the effect of a policy relative to a well-defined baseline scenario be calculated in consistent units, typically monetary, making costs and benefits directly comparable.

Although CBA is the recommended basis for assessing policy alternatives in many governments (see, for example, EPA, 2000a, p. 59; FAA, 1998, pp. 2–3; OMB, 2003, p. 11; OECD, 1995, p. 23; UK HM Treasury, 2003, p. 22), other forms of economic analysis are used in the absence of adequate information to quantify costs and/or benefits. A common method is cost-effectiveness analysis (CEA). In most cases, the difference between CEA and CBA is in the treatment of benefits. Rather than comparing policies with differing costs and benefits and using benefits net of costs as a decision metric, policies are compared on the basis of cost when similar benefit outcomes are expected. The idea is to achieve the least cost for a given benefit. In practice, some analysis is carried out under the heading of CEA where benefits are quantified in terms of a physical measure, such as tons of NO_x reduced or numbers of people exposed to noise. However, if there is a nonlinear relationship between the intermediate physical measure of the benefits and the ultimate health and welfare benefit (as is often the case), then CEA can be misleading. Further, even when the intermediate physical measure is a good surrogate for the ultimate health and welfare effects, the most cost-effective policy could still be unwarranted (i.e. economically inefficient) if the policy costs exceed the benefits returned to society. "Cost-effectiveness analysis does not necessarily reveal what level of control is reasonable, nor can it be used to directly compare situations with different benefit streams" (EPA, 2000a; p. 178).

While CBA can be used to evaluate whether a program results in an overall improvement for society, policy analysis almost always requires assessing which segments of the economy or parts of society receive the benefits and which segments bear the costs. This is broadly termed distributional analysis (DA). Sometimes DA is required by specific legislation, such as bylaws designed to offer special protection to segments of society deemed to be vulnerable, for example, children, the elderly, or minorities. This also could be used to assess the feasibility of a particular policy solution, knowing that policies are more likely to be successful when costs are equitably distributed as opposed to heavily concentrated on one segment of society, be it individuals or businesses.

Since many governments specify that environmental economic policy analysis include quantitative measures of the costs and benefits, a number of academic, government, and industry research efforts have focused over the past 30–40 years on developing and refining the techniques of quantifying costs and benefits of environmental policies. Likewise, a significant fraction of environmental economic research has been performed to improve understanding of the situations from which environmental problems arise and to define optimal policy mechanisms (see, for example, Kolstad, 2000 and Freeman, 2003). Below is a brief review of some current practices for assessing policies aimed at mitigating air quality, noise and climate impacts due to aircraft operations.

Air quality

Aircraft engine emissions that are important for assessing air quality impacts on health and welfare include primary particulate matter (PM), nitrogen oxides (NO_x), unburned hydrocarbons (HC), sulphur oxides (SO_x), and carbon monoxide (CO). There is a generally consistent technique used worldwide (but not yet within CAEP) to assess air quality impacts beginning with estimation of an emissions inventory, evaluating the chemical changes in the atmosphere that result from emissions release, and finally concluding with a determination of how such changes may impact health and welfare. In application, incidence of health and welfare outcomes can be valued for the purposes of CBA. However, while the methodology is common in general, details in modelling and data can differ.

One recent example describes current practice in an aviation context. Under legal mandate, the US FAA and the US EPA, in collaboration with the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), evaluated health impacts stemming from changes to air quality as a result of commercial aviation activity in the US (Section 753, US Public Law 109-58, Energy Policy Act of 2005; see EPACT, 2007 and Ratliff, 2007). Three steps composed the EPACT analysis. First, the FAA Emissions and Dispersion Modelling System (EDMS) (CSSI, 2007) was used to estimate emissions inventories for selected airports based on the landing and take-off cycle. The impact of EDMS emissions inventories on pollutant concentrations were then evaluated using the EPA Community Multiscale Air Quality modelling system (Byun and Schere, 2006). Finally, changes in the incidence of health responses, such as chronic bronchitis and premature mortality, were estimated using concentration response functions (CRFs) drawn from the epidemiological literature. In this case, the Environmental Benefits Mapping and Analysis Program (Abt, 2005), which assesses ambient PM (from both primary PM emissions, and secondary PM from precursor emissions such as NO_x and SO_x) and ozone effects, was used to calculate incidence of health endpoints. Several recent US EPA rulemakings have employed similar practices for health impact analyses in other contexts including: the Tier 2/Gasoline Sulphur Rule (EPA, 1999); Clean Diesel Trucks, Buses, and Fuel: Heavy-Duty Engine and Vehicle Standards Highway Diesel Fuel Sulphur Control Requirements (EPA, 2000b); Control of Emissions from Non-road Diesel Engines (EPA, 2004); and the Clean Air Interstate Rule (EPA, 2005b), among others (e.g. EPA, 2005a; EPA, 2006; EPA, 2007a; EPA, 2007b; EPA, 2007c).

Many similarities can be found in the methodologies employed by the EU Clean Air for Europe (CAFE) program to assess the health impacts of ambient PM and ozone. Emissions are evaluated by the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) and converted to concentrations using the Regional Air Pollution Information and Simulation (RAINS) model (Amann *et al.,* 2004). The Health Impact Assessment (HIA) block (CAFE, 2005b) within the CAFE CBA model (CAFE, 2005a; CAFE, 2006) estimates health endpoint changes using CRFs. The CAFE CBA then applies a monetary valuation to determine the economic cost of related health impacts. Recent applications of EU CAFE health impact practices include the Thematic Strategy on Air Pollution (EC, 2005a), as well as the Impact Assessment documents for the Thematic Strategy on Air Pollution and the Directive on Ambient Air Quality and Cleaner Air for Europe (EC, 2005b). Like the US EPA analyses, these assessments considered the health impacts of ambient $PM_{2.5}$ (from both primary PM emissions, and secondary PM from precursor emissions such as NO_x and SO_x) and ozone for twenty-five EU countries.

Noise

Aircraft noise impacts both the health and wellbeing of residents near airports. Noise effects include annoyance, sleep disturbance, learning and motivation in children, and health impairment (WHO, 2004). These effects tend to overlap in their meanings, for example, annoyance can be a result of sleep disturbance, and current research is focused to some extent on the definition of more separable outcomes. Measures of annoyance and sleep disturbance are the most widespread assessment of aircraft noise impacts (Miedema, 2007). Both EU and US agencies have recommended methods to estimate metrics for annoyance and sleep disturbance (EC, 2003; EU, 2002; Miedema and Oudshoorn, 2001; EPA, 1974; Finegold, Harris and Von Gierke, 1994; FICAN, 1992). Annoyance is typically measured using a correlation relating a cumulative noise metric and the percentage of people highly annoyed. Differences exist in the treatment of sleep disturbance by EU and US agencies. A 2004 EC position paper (EC, 2004) recommends the use of the sleep awakening response function developed by Passchier-Vermeer (Passchier-Vermeer, 2003) based on the Lnight metric and gives a worst case scenario when all night-time events have a sound exposure level (SEL) of 58.8 dBA. Lnight averages total night-time noise energy. Conversely, the US Federal Interagency Committee on Aviation Noise (FICAN) recommended the use of a sleep awakening dose-response relationship based on single event SEL instead of an averaged metric. This relationship intends to estimate the "maximum percent of the exposed population expected to be behaviourally awakened" (FICAN, 1997). In 2000, the American National Standards Institute (ANSI) adopted a new relationship for sleep awakenings from noise, which also used the SEL metric (Michaud *et al.,* 2007).

Developments in assessing noise impacts continue. The World Health Organization is updating their guidelines for night-time noise and its effects on sleep based on the Lnight and LAmax metrics (WHO, 2005). ANSI is also revising their recommendations concerning noise-induced awakening (ANSI, 2007). These reports have yet to be released.

Aircraft noise can have a direct economic impact. A common method of determining economic effects is to statistically assess the decrease in housing values caused by aircraft noise vs. other aspects of the house and its environment which may impact price. In economic terminology, this is a *revealed-preference method*; housing sales data are analysed to statistically evaluate the effect of aviation noise level on the price of housing (Nelson, 2004). These assessments are often referred to as *hedonic price analyses*. The estimated percentage change in housing values for each decibel increase in noise is typically called the *noise depreciation index* (NDI). NDI values vary by location, but tend to be in the range of 0.3–2.3% for cities in the US, Canada, Western Europe and Australia (Navrud, 2002).

Another method for assessing the economic impact of noise on housing values is to survey a given population and statistically determine a monetary trade-off for noise reduction (Carson, Flores and Meade, 2001). In economic terminology, this is a *stated-preference* method and results in the estimation of willingness-to-pay for a unit change in noise level. Compared to hedonic price analyses, fewer stated-preference surveys have been conducted concerning aircraft noise (Navrud, 2002).

Climate

Aviation emissions that perturb the Earth's radiative balance include CO_2, H_2O, NO_x, SO_x and soot resulting in direct warming or cooling effects or indirect effects such as increased contrail formation or aviation-induced cirrus formation, and modification of atmospheric ozone chemistry and methane concentrations. The effects are diverse in terms of time-scales and spatial variation, ranging from long-lived and spatially homogeneous CO_2 forcing, to short-lived perturbations with high regional variability such as contrails or NO_x-related ozone impacts (IPCC, 1999).

Modelling approaches for estimating climate impacts depend on the context of the application and are determined by trade-offs between factors such as complexity and spatial resolution versus computational constraints. Atmosphere-ocean general circulation models (AOGCMs) coupled to a chemistry package represents one extreme of the spectrum, being the most comprehensive models that aim to simulate with high fidelity. Such models are computationally expensive and challenging for applications involving century-long time-scales. Moreover, determining a climate signal (e.g. temperature response) from aviation emissions in such models is very difficult, presently requiring many decades of simulation or multi-ensemble runs. Generally, in such models, the chemical of physical impact (e.g. contrails) can be determined and the resultant radiative forcing calculated. Reduced-order climate models involving parameterizations derived from AOGCMs are often better suited for investigating future trends in climate impacts on a large spatial scale for a range of emissions scenarios. For example, the IPCC Fourth Assessment Report used a more simplified climate model (Model for the Assessment of Greenhouse-Gas Induced Climate Change – MAGICC), tuned to outputs from nineteen different AOGCMs, for making projections of climate change for different emissions scenarios (IPCC, 2007a).

In the aviation context, several different approaches have been proposed for estimating future climate impacts of aviation activity using reduced-order models. Hasselmann *et al.* (1997) proposed a general framework (not specific to aviation) for CO_2 impacts based on impulse response models derived from carbon cycle models and GCMs. Sausen and Schumann (2000) extended this approach to assessing impacts of aviation CO_2 and NO_x (O_3 effect) emissions on radiative forcing, globally averaged temperature and sea level. Shine *et al.* (2005) propose a simplified energy balance model along with carbon cycle impulse response functions to estimate temperature change to explicitly capture the effects of the climate sensitivity parameter on impact estimates.

Radiative forcing estimates for non-CO_2 effects such as short-lived NO_x on O_3, contrails, aviation-induced cirrus, sulphates, soot, H_2O, NO_x on CH_4 and O_3 are calculated from specific models for the effect, for example, Chemical Transport Models (CTMs), cloud coverage models and then the outputs used for the calculation of radiative forcing (RF) in radiative transfer models. The most recent updates to non-CO_2 RF estimates from IPCC (1999) are provided by the TRADEOFF project in Sausen *et al.* (2005). It is possible to estimate the climate response in terms of global mean temperature change of both CO_2 and non-CO_2 effects under the framework proposed by Sausen and Schumann (2000).

The FAA Aviation Environmental Portfolio Management Tool (APMT) also uses impulse response models along with a simplified energy balance model to provide climate impacts for CO_2 and non-CO_2 effects in terms of physical metrics (e.g. RF, global temperature change) and monetary metrics (e.g. global GDP loss and net present value of damages) (Marais *et al.*, 2008). LinClim is another simplified climate module that assesses global radiative forcing and temperature impacts of aviation CO_2, O_3, CH_4, sulphate, soot and contrails effects (Lim *et al.*, 2007). Regional assessment of aviation impacts has recently been addressed using the AirClim model. AirClim employs 3-D aircraft emissions profiles along with pre-calculated atmospheric data to estimate surface temperature changes and addresses the CO_2, H_2O, CH_4, O_3 and contrails effects (Grewe and Stenke, 2007). All three models, APMT, LinClim and AirClim, may be viewed as extensions of the Sausen and Schumann (2000) framework.

Given their computational efficiency, reduced-order models are also useful in scoping climate impact estimates through probabilistic methods and sensitivity studies. This is important from a policy and decision-making perspective, since these models can provide initial impact estimates for proposed policies under several different future projections of anthropogenic activities with estimated confidence intervals that account for some of the uncertainties in the modelling process, which can then be supported with more complex and complete models.

Summary

In 2004, ICAO adopted three environmental goals.

1 To limit or reduce the number of people affected by significant aircraft noise.

2 To limit or reduce the *impact* of aviation emissions on local air quality.

3 To limit or reduce the *impact* of aviation greenhouse gas emissions on the global climate.[2]

These goals have the common objective of reducing aviation environmental health and welfare impacts. However, assessments done to date by CAEP do not necessarily consider the ultimate impact of noise and emissions. Recognizing the complexity, the breadth of the subjects related to the impact of aviation on the environment, advice on the scientific understanding of the environmental impact of aviation is crucial to CAEP. Workshop participants worked from the information discussed above. That information provided the basis upon which workshop participants built to advise on the latest scientific understanding for addressing the environmental health and welfare impacts of aviation.

[2] This follows directly from the Kyoto Protocol's mandate (article 2.2).

Chapter 3 Aviation impacts on ambient air quality

General background

Commercial air travel is expected to double in the next 20 years. This will result in substantial changes in the industry, including the expansion of existing airports and the conversion of military aviation, general aviation and small regional airports to accommodate commercial operations. Beside an increase in the size of the commercial fleet, new business models using less expensive smaller aircraft have the potential not only to increase aircraft and ground emissions at existing airports but to create aviation-related emission patterns where they currently do not exist.

Improving the capacity to conduct quantitative health risk assessments of airport-related activities does not need to be justified by future needs alone. There is increased attention on airports as contributors to regional air quality and local risk. Air pollution exposure health risk assessment has been well established and practised for years. The guidelines established by the US Environmental Protection Agency (EPA) have been reviewed by its Science Advisory Board, the Office of Management and Budget and several committees of the National Research Council. Similar guidelines have been provided internationally, for example, by WHO (WHO, 2007). It is accurate to say that quantitative assessments of airport-related air pollution risk are not available for many airports in the US and the rest of the world. However, it is important to note that the health exposure risk due to airport emissions is being increasingly assessed in a number of recent studies (e.g. RIDEM, 2008).

Airport authorities and state environmental agencies are more frequently being challenged to account for airport operations on air quality both in the nearby communities and at the regional level. Aircraft engines emit primary particulate matter, as well as gaseous precursors of secondary particles that are formed downstream of the engine. They are sources of nitrogen oxides, carbon monoxide, and a variety of hydrocarbon emissions, including many that act as ozone precursors and specific compounds such as polycyclic aromatic hydrocarbons (PAHs), and a number of volatile compounds that include contaminants designated as Hazardous Air Pollutants (HAPs, e.g. benzene). Many of the pollutants are also emitted from gasoline and diesel-fuelled ground support equipment and power generation. In addition, airports are important trip generators for various land-based mobile sources and have a variety of stationary sources from restaurants, maintenance, fuelling and de-icing operations.

Aviation emission rates for selected gas-phase pollutants and smoke are available from aircraft emissions certification measurements by aircraft type, weight and aircraft engine at various set thrust points within the LTO cycle (ICAO, 2007a). These emission rates have been incorporated into various models to produce an inventory of emissions generated by sources on and around the airport (or airbase). Note that CAEP air quality analysis is limited to inventory of emissions only. Although not required by the CAEP, some emission models have extended their capability within limited scope to disperse the air pollutants that are directly emitted at the airport, and hence calculate pollutant concentrations in the local and regional environments.

Through CAEP, there has been an effort to harmonize aviation emission factors. Yet methodologies and models for developing airport emissions inventories and conducting air quality analysis for exposure and health risk assessments have not been standardized. While various models are available for dispersion of inert and reactive air pollutants, their performance, in an airport context, for assessing impacts on compliance with air quality standards, on the contribution to regional air pollution or on the impact on human health exposure risk has received limited attention.

State of current practice

Aircraft and airport sources are known to directly emit a number of pollutants such as carbon monoxide, hydrocarbons, nitrogen oxides, particulate matter, and sulphur oxides. The direct emission of these air pollutants is not unique to aircraft/airport activities, but also arises from a variety of sources, such as ground transportation and power generation. Once released in the atmosphere, aircraft/airport emissions disperse, transform and interact with the background air in similar ways to emissions from other sources. There are well established widespread measurement and modelling methods that are in routine practical use to quantify air quality and health impacts of air pollutants that can be readily applied to the aviation transport sector. However, as stated earlier, within the CAEP context, air quality analysis is limited only to inventory of direct emissions of air pollutant emissions. Figure 3.1 shows a generalized scheme of the processes needed to link direct emissions to the health impacts analysis.

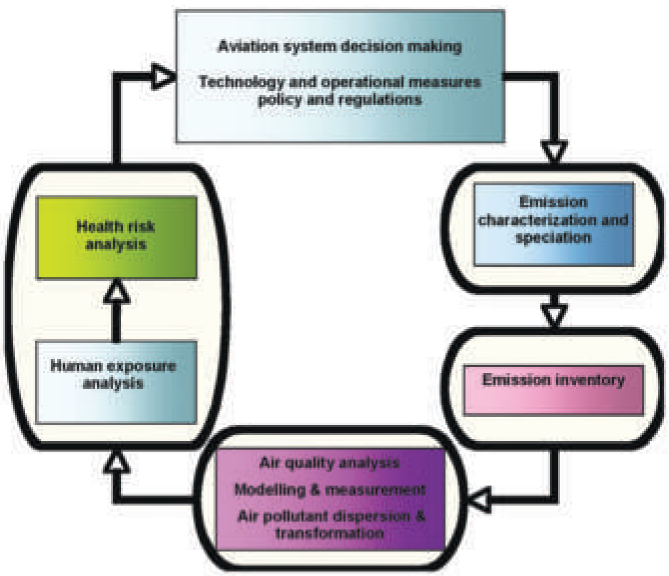

Figure 3.1 General scheme displaying the linkage between emissions and decision making guided by air quality-related health impacts.

Airport air quality impact assessments are required for regulatory compliance impact assessment of proposed development (expansion) and to address community and health risk concerns. Using only emissions as a metric is insufficient for air quality assessments of airports, because they are a poor proxy for human exposure due to primary or secondary pollutants. Instead, it is necessary to quantify the impacts of emissions over local (several hundred metres to a few kilometres) and regional scales (up to 100s or even 1000s of kilometres) with a combination of air quality modelling and ambient measurement approaches.

Airports are complex sources, generating vehicle trips on the passenger side of the terminal and emissions from stationary sources like restaurants and onsite power generation. Airports are distinguished by having aircraft emission sources that vary spatially and temporally as well as by engine type and power. Emissions occur both at the surface and aloft. The supporting ground operations on the tarmac side of airports include specialized vehicles as well as gasoline and diesel-fuelled fleets of buses, cars, vans and trucks. Further complicating the mix of emission sources that have to be characterized are refuelling, de-icing and maintenance operations.

The panellists agreed that not all airport-related sources of airborne contaminants have been adequately characterized. Focus to date has been on particles and nitrogen oxide (NO_x) emissions from aircraft engines. More information is needed concerning hazardous air pollutants including many volatile organic compounds (VOCs), semi-volatile organic compounds (polycyclic aromatic hydrocarbons (PAHs) and nitro-PAHs) and metals. Furthermore, health concerns for particles have broadened to question the differential toxicology of ultrafine particles (< 1.0 µm) and size-fractionated composition.

The framework linking emissions to health impacts shown in Figure 3.1 includes both local and regional air quality models and 'hybrid' representations, which incorporate both aspects. Coupled with focused monitoring of ambient air at the airport community scale as well as networks of regional measurement sites, these models can be used for 1) assessment of health risk exposure, 2) determination of compliance with ambient air quality standards, 3) identification of populations at risk, and 4) analysis of air quality impacts due to new construction and/or expanded/altered airport usage. Depending on the objectives, local and regional air quality models and monitoring programs will need to consider, to varying degrees of complexity, the spatial and temporal details of emission patterns both from airport and non-airport sources, geographic location, topography, meteorology of the source and impacted region, atmospheric evolution of directly emitted air pollutants and formation of secondary air pollutants through interaction of emissions with background air quality.

Local air quality models are typically applicable on a scale of tens of metres to kilometres. These models are generally based on dispersion from point, line and area sources. They include spatially and temporally distributed emissions sources from the airport and the surrounding region. The models typically provide hourly and annual averages. Background concentrations of pollutants are incorporated from monitoring data or from regional models. Local meteorological data are also needed. Only limited chemistry is needed for the conversion of NO to NO_2 by reaction with O_3. More detailed chemistry is needed for secondary particulate matter (PM), local ozone and carbonyl formation. Such chemistry is not currently included in models used for local air quality analyses.

Models are available that are generally considered to be of the appropriate quality and 'fit-for-purpose' in an operational context, for example, EDMS/AEDT (which uses AERMOD for pollutant dispersion), ADMS-Airport and LASPORT. These models have been developed for use in an aviation context and are used routinely for airport studies. They are particularly appropriate for predicting local compliance with air quality regulations and are more relevant to primary pollutants and in, some cases, locally impacted secondary pollutants, including NO_2. It is essential that airport emissions and dispersion models include appropriately detailed descriptions of other local sources, such as access roads.

Regional air quality models are able to quantify air quality impacts within the source proximity as well as at large distances (100s to 1000s km) from the source location. These models can simulate the atmospheric fate and transport of direct emissions, formation of secondary air pollutants (such as ozone, particulate matter) and their interaction with the background air quality. Regional air quality models are routinely used for analysis of compliance with ambient air quality standards (NO_2, O_3 and PM). Ozone is a secondary pollutant. It is formed from emitted NO_x and VOCs. Within the proximity of emission source, there is a decrease in localized ozone concentration due to titration against NO followed by its formation at larger spatial scales. Near the source region, both direct emissions as well as secondary formation due to gaseous precursors contribute to the net change in particulate matter brought by the emissions. However, regional impact of aviation on PM is primarily through the formation of secondary aerosol, with NO_x, SO_x and VOCs as the main precursors. These formation routes require model descriptions of detailed chemistry and microphysics.

The US EPA recognizes several fundamental components of methods for the characterization of model performance (EPA, 2005). In addition to items such as code verification, scientific peer review, etc., these components include "performance evaluations in the circumstances of the intended applications". Statistical-based assessments include various measures of differences between measured and modelled values as well as determination of correlations over time, space, and time and space combined as recommended by the American Meteorological Society Woods Hole Workshop (Fox, 1981). A useful guide for statistical evaluation of dispersion model performance has also been published by the American Society for Testing and Materials (ASTM, 2000). In Europe, COST Action 732 is targeting quality assurance and improvement of micro-scale meteorological models (COST, 2005).

The regulatory framework for considering air quality impacts of airports depend on prevailing standards, regulations and existing regional air quality. Compliance with short-term and annual NO_2 standards in the EU influence the modelling and measurement strategies for assessing European airports, while in the US the vast majority of non-attainment of the National Ambient Air Quality Standards (NAAQS) are the result of $PM_{2.5}$ (particle mass less than 2.5 micrometres) and ozone (O_3) (1 h and 8 h) violations.

The EPA-sanctioned methodology of applying continuous damage functions for PM and O_3 mortality and morbidity leads to the quantification of health and economic consequences of pollution sources even when existing ambient air quality is in compliance with established standards. A comparable methodology is used by UK Department of Environment, Food and Rural Affairs. A similar approach is widely used to assess cancer effects from HAPs with established potency factors. Continuous damage functions for assessing effects below standards do not currently exist for NO_2 exposures.

Findings

In this section, we focus our discussion on individual components that are essential for linking emissions to health impacts as shown in Figure 3.1.

Emissions

CAEP has provided a framework for characterizing and harmonizing emission tests for aircraft engines. These data are used for modelling aviation impacts using default emission indices, for idling, taxiing, take-off, ascent and descent. Some near-source runway measurements suggest that aircraft in actual practice deviate substantially from these default emission values. Furthermore, there are operating modes (e.g. less than 7% idle, deceleration) and emissions sources (e.g. tire smoke) for which emissions have not been characterized.

Particle emissions from aircraft engines leave the exhaust as a non-volatile component (black carbon soot) and a number of condensable gaseous particle precursor species that contribute to a volatile component later in the plume, or much later through regional processes in the atmosphere. As the exhaust mixes and dilutes with ambient air in the downstream plume, nitrogen oxides, sulphate (sulphuric acid) and organic condensable species undergo gas-to-particle conversion. New particles are formed through nucleation and growth, and the emitted non-volatile particles can become coated with nitrate, sulphate and organic species. The resulting aerosol increases in both mass and number due to the microphysical activity of these condensable species in the mixing aircraft plume. Experimental work is needed to characterize these processes and to inform the development of chemical and microphysical models of particle evolution in the downstream plume until it is dominated by local atmospheric processes. Both point concentration and plume geometry measurements are required, both concurrently and separately. A key issue is the time-scale on which gas-to-particle conversion processes become frozen relative to the time-scale of the plume dynamics. There is a strong contrast here with diesel surface vehicles, where plume 'freezing' takes place within seconds while most of the particle formation takes place at dilution ratios between about 3 and 30. For both diesel and aircraft emissions, the emissions continue to undergo dynamic evolution, including gas-to-particle conversion and agglomeration. These processes might be quite different for emissions trapped in vortices as compared to those occurring under typical dilution conditions of non-aircraft plumes. The processes are strongly influenced by local conditions, for example, meteorology, humidity, the concentration of background ammonia, the background particle surface area and other factors.

It is also necessary to characterize the evolution of the plume dynamics for incorporation in local air quality models. Issues include plume buoyancy and wake effects, which can affect local ground level concentrations of aircraft derived pollutants, and hence population exposure. Considerable progress has been made using LIDAR measurements of the evolving plume geometry. These measurements need extension and further confirmation; appropriate parameterizations are also needed for incorporation of these effects in models.

Measurements are also needed on diesel-fuelled ground support equipment, especially airport tugs, under variable load. The discharge of diesel emissions, which have a correspondingly complex mix of pollutants, has the potential to interact with aircraft plumes both chemically and microphysically.

Ambient monitoring

The main reason for current ambient air monitoring programs at airports is to determine compliance with ambient air quality standards. Monitoring also provides data for model evaluation and source apportionment. Coupled with more intensive measurements, monitoring of ambient air can be used to assess the accuracy of aircraft emissions inventories. Increasingly, ambient monitoring is becoming a major component of air quality analysis related to airport emissions. Recently, a number of completed studies have employed ambient monitoring to isolate and quantify the contribution from airport emissions to air quality (CARB, 2007; RIDEM, 2008; NJDEP, 2008; Westerdahl *et al.*, 2008).

Carslaw *et al.* (2006) discuss the analysis of monitoring data from sites close to London Heathrow (LHR). They constructed wind-rose plots of pollutant concentration to discriminate between different source types. Bivariate polar plots show both the wind direction and wind speed dependence of measured concentrations at a point. This technique is one of several that can help with source identification and apportionment in an airport setting. Figure 3.2a shows that NO_x concentrations near a road source clearly decrease with wind speed, which is typical of a non-buoyant ground level source. By contrast, in Figure 3.2b, measured concentrations close to the northern runway at Heathrow increase (or remain high) with increasing wind speed, which is indicative of the dispersion of a buoyant jet plume. Figure 3.2c shows a comparison with model results obtained using the ADMS-Airport model. A report (DfT, 2006) on emissions, modelling and monitoring at LHR describes the use of these and related analyses to assess and

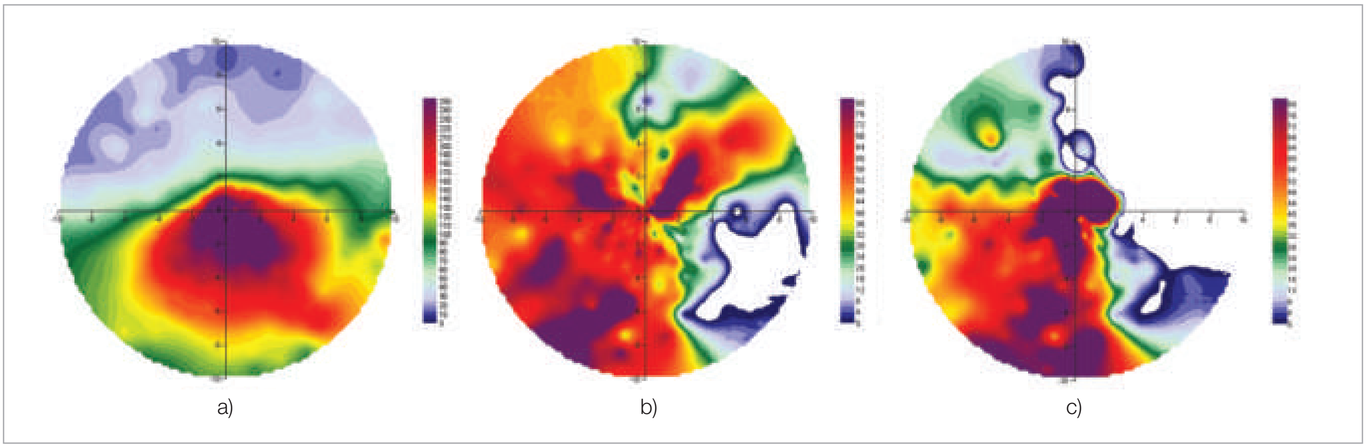

Figure 3.2 Bivariate polar plots using hourly measurements of NO_x, a) for a road source located to the south of the monitor; b) site 200 m north of the northern runway at Heathrow; c) model results using ADMS-Airport for the Heathrow site. The colours show the level of concentration and wind speeds increase from 0 m s^{-1} in the centre to 10 m s^{-1} at the circumference.

evaluate the performance of a number of air quality models, based on comparisons with monitoring data. Such an approach could form the basis of protocols for model evaluation at airports.

Focused, campaign-style measurements have been conducted near airports to determine pollutant concentrations and the special characteristics of aircraft sources. Westerdahl *et al.* (2008) measured a range of particle characteristics, NO_x and PAH near Los Angeles International Airport and assessed the impact of wind direction, demonstrating that concentrations of ultrafine particles from airport sources are elevated much further downwind than is the case for road traffic sources. Carslaw *et al.* (2008) used high frequency NO_x measurements to determine source apportionment, with respect to specific aircraft movements (Figure 3.3). Wood *et al.* (2008) reported measurements at Oakland International Airport and at Cleveland Hopkins International Airport. They showed that the NO is converted rapidly to NO_2 in exhaust plumes at low thrust, in a process which is unrelated to the conversion that occurs under ambient conditions from reaction with ozone.

A key component for air quality impact analysis are meteorological data. Local airport meteorological data are required for modelling use. While systems in current use at most airports serve the interests of aviation users, they often are not ideally designed (e.g. in terms of location, threshold, wind speeds) for the provision of model input data or analysis support for air monitoring programs.

Regional air quality monitoring data is needed as input for regional scale models and to assess the performance of these regional models as well. Ozone and PM can be evaluated against measurements from ground level monitoring stations. This is routine for ozone, but PM presents complications. There are both primary (direct) and secondary (indirect) sources of PM. Gaseous emissions of NO_x, SO_x and hydrocarbons lead to formation of secondary PM. Ideally, measurements should be made not only of the total PM concentration but also of its composition and size distribution. Note that such evaluations assess model performance for all regional sources and chemical and physical processing.

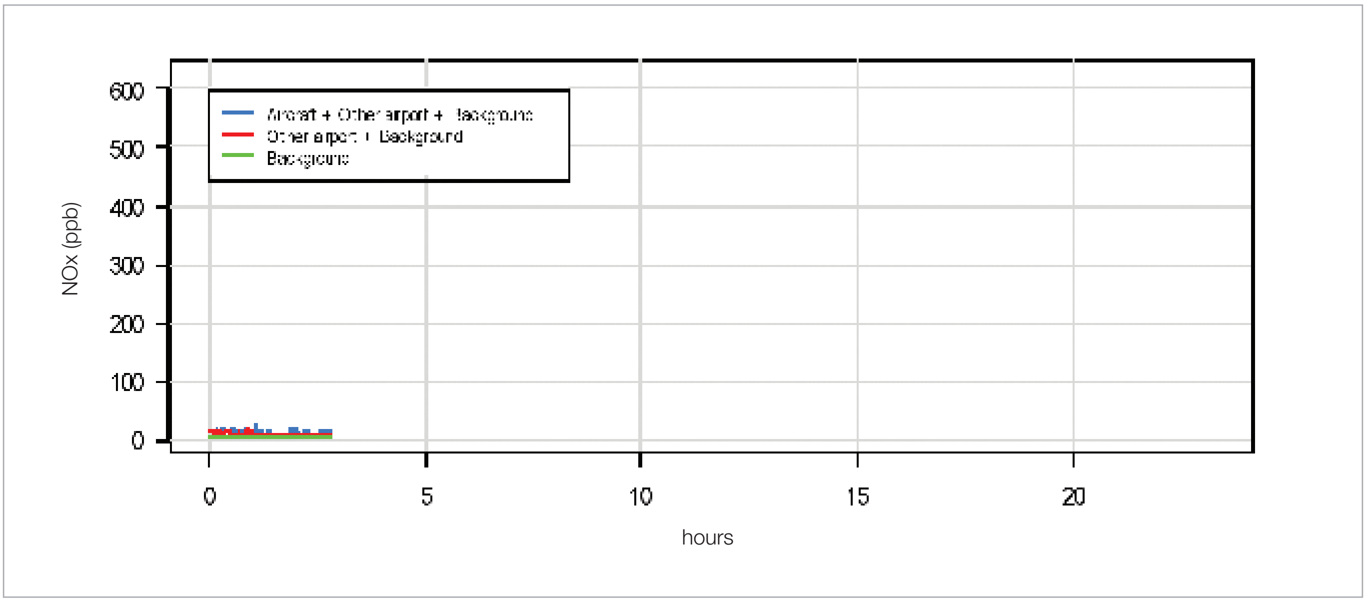

Figure 3.3 High frequency NO_x measurements at the same site as in Figure 3.2, with assignments to emissions sources.

Comprehensive health risk studies of airport impacts could be improved with ambient air monitoring. Measurements would need to consider time-scales relevant to various operational aspects to the health consequence of concern. Short time resolution might be important to differentiate the impact of specific sources or modes of operation on air quality. Longer time-integrated measurements might be more appropriate for estimating cancer risks, for example. Monitoring air quality in the local environment around airports will require a combination of instruments deployed at multiple locations. Monitoring campaigns might include the flexibility of relocating instruments to differentially isolate sources or operations. Novel sampling and statistical approaches, like those used by Ogulel *et al.* (2007), can be employed to attribute fresh and aged diesel and gasoline sources to local ambient particle concentrations.

Modelling

Local air quality modelling

Local-scale air quality modelling is generally performed by using dispersion models. These models have been developed for dispersion of emissions from point, area and volume sources, and have been extensively applied for dispersion of emissions from power plants, etc. Within the context of aircraft and non-aircraft airport emissions, further developments are needed to accommodate a number of issues, including the treatment of very light wind conditions and the appropriate incorporation of local road networks. Finer time resolution less than 1 h, for example, for treatment of odour and for HAP irritation effects and source resolution, poses problems particularly related to modelling of aircraft plumes. Modelling these effects in detail requires dispersion models that are able to resolve the temporal evolution of the plume (see e.g. Janicke *et al.*, 2007). Both plume rise and possible wake effects are inadequately understood and modelled. Current local models do not include chemical processes representative of air pollution and aspects of aerosol formation during the plume evolution.

The EDMS-AERMOD dispersion model is the only EPA recommended dispersion model for airport emissions-related regulatory analyses. The ADMS-Airport model was recently used to assess the impact of a third runway at London Heathrow. The approach and methodology provide a good example of the use of the application of such models (McHugh *et al.*, 2007). The focus is mainly on NO_2, but it also includes an assessment of direct emissions of PM_{10}. The modelling report includes a summary of the model set-up, comparisons with monitoring data and projections for 2015, 2020 and 2030. Other reports in the exercise cover emissions inventories for both the airport and roads and an assessment of population exposure.

To assess air quality health impacts, traditional air quality models need to be augmented with exposure models such as the US EPA's SHEDS model (EPA 2004b). The spatially and temporally resolved pollution contours of ambient concentrations of air pollutants are estimated by dispersion models. Actual population exposures may occur both outdoors and indoors. Ambient pollution will penetrate indoors as well as the building's ventilation system such that exposure may be modified but this will also depend upon the physical and chemical properties of the air pollutant. Furthermore, mobile populations are not in fixed locations. Therefore, airport assessments estimating risk need more comprehensive modelling approaches depending on the regulatory requirements and the interests of the stakeholders.

Regional modelling

Regional Chemistry Transport Models used in an aviation context include CMAQ, EMEP and CHIMERE. All of these models are Eulerian, although Lagrangian methods have also been used to model regional pollutants. The models operate on urban to national or even intercontinental scales, with resolution ranging from a few kilometres (2 to 4 km) to even ~100 km. Models such as CMAQ are run with nested scales and offer better definition of boundary conditions especially for urban areas, or in the vicinity of airports, while at the same time capturing the effects of potential long-range transport of air pollutants. In turn, they rely on global models for provision of the hemispheric background concentration of the targeted pollutants.

The models require meteorological data (temperature, pressure, wind speed, etc.) across the modelling domain at the same spatial and temporal scales as the air quality model. These data are generally provided from synoptic and local observations and require substantial and sophisticated processing using prognostic meteorological models such as MM5, WRF, etc. In addition to input data on airport emissions, they require emissions inputs across the modelling domain from all other anthropogenic and biogenic sources. Further, traditional representation of aviation emissions (during LTO cycle) within regional-scale air quality models included several simplified assumptions where all emissions were assumed to be in the surface layer. There is a need to include a 4-D representation of aviation emissions in regional-scale models, as was recently shown by Baek *et al.* (2007). Detailed chemical mechanisms are also needed, and these usually represent a lumped or a condensed version of the actual chemical reactions that take place in the atmosphere. Model evaluation is generally achieved via comparison with ground-based monitoring stations. Ideally, monitoring data for evaluation of PM should include total PM mass, size distribution and composition.

Examples of aviation applications include air quality assessments using CMAQ of the Hartsfield-Jackson (ATL), O'Hare, Chicago (ORD) and T.F. Green, Providence (PVD) airports (Arunachalam, 2007; Arunachalam *et al.*, 2008). Figure 3.4 shows the domain of the CMAQ runs to assess air quality impacts at the three airports. Model runs harmonize results from 36 km grids over much of North America, through 12 km grids and down to 4 km grids around the airports of interest. Figure 3.5 shows annual $PM_{2.5}$ concentrations projected for Georgia and the metropolitan Atlanta regions from commercial aviation operations at Hartsfield International Airport. Results are shown for 36 km and 12 km grid resolution. The predictions from a local-scale dispersion model (AERMOD) at various census-tract receptors are also shown as diamonds on these plots. In general, higher $PM_{2.5}$ impacts are seen at a 12 km model resolution than at a 36 km resolution. At all three airports, secondary components can contribute up to 60% of the total $PM_{2.5}$ in the modelled locations of maximum contributions from aircraft emissions. Both nitrate and secondary organic aerosol show local decreases near the airports, but increase downwind of the airports, showing the importance of secondary PM formation from aircraft emissions. This study showed that LTO aircraft emissions from an airport can have air quality impacts as far as ~300 km away from the airport.

Models such as CMAQ are capable of multi-pollutant integrated impact assessment, especially when reductions in a primary emissions species (such as NO_x) can lead to reductions in a secondary pollutant (such as particulate matter), but also to a local increase in another secondary pollutant, ozone, because of a reduced rate of reaction of ozone with NO, coupled with ozone increases on larger distance scales. This capability makes the use of regional models, while computationally intensive, highly conducive to performing comprehensive assessment of air quality impacts of aviation emissions, including cost-benefit analysis.

Figure 3.4 Multiscale CMAQ air quality modelling domain (Arunachalam *et al.,* 2008).

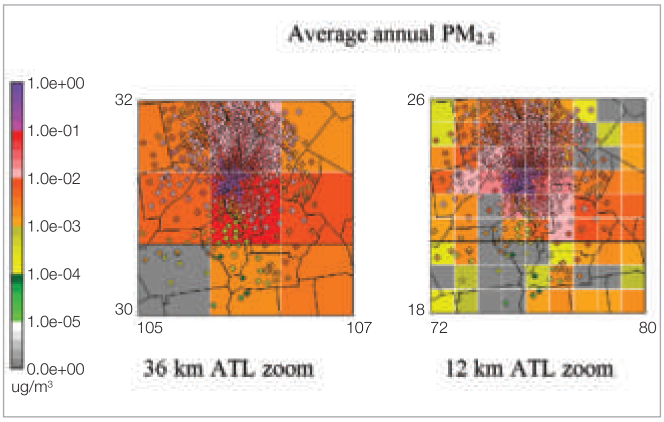

Figure 3.5 Impact of Hartsfield-Jackson (ATL) airport emissions: CMAQ results with AERMOD Overlay (from Saravanan Arunachalam's presentation at CAEP Workshop, October 2007).

Health risk assessment

The workshop discussions demonstrated clearly that CAEP's remit must expand beyond engine emissions to cover the full impact chain extending into air quality analysis, exposure, attributable health effects and aggregated impact indicators. Future health effects assessments should consider:

- incorporating population exposure models (e.g. US EPA's SHEDS model of human activity patterns) into the analysis and linkage of exposure models with air quality models;
- differentiating the impacts of airside aviation sources from non-aviation landside sources using measurement and modelling data;
- incorporation of noise stress into air quality impact assessments as a possible modifier of effects (Jarup *et al.*, 2008).

Within the current limited scope of CAEP's remit, it is not possible to establish the goals and targets that can guide development of impact mitigation options, or to realize the intended benefits of technological and operational advances, or to assess environmental policy options. Finally, without understanding the environmental impacts associated with individual and groups of air pollutant emissions, it will not be possible to understand relative trade-offs associated with multiple options. It is essential to relate emissions to impacts in order to develop and implement mitigation options.

Recommendations

The Air Quality Panel noted that the CAEP process of assessing the air quality impacts of aviation is primarily based on an emission inventory of aviation sources. Panellists noted this does not allow the determination of local and regional *impacts* of these emissions based on actual or modelled air concentrations of all airport-related pollutants and subsequent impacts upon human health and welfare. An assessment of impacts needs expansion beyond emissions inventories to cover the full impact chain extending to air quality, exposure, attributable health effects and aggregated impact indicators. Well established air quality health *impacts* assessment methodologies exist. Workshop participants suggested that CAEP should follow (to the degree practicable) existing definitions, terminology and state-of-the-art procedures and good practices established in the environmental health impact assessment field. Specific recommendations under the auspices of emissions, ambient monitoring, air quality modelling, and comprehensive airport assessments are further discussed below.

Emissions

Considerable progress has been made in measurement programs and techniques. These need to be exploited to provide necessary input into air quality and health risk assessment models. Emphasis should be placed on:

- measurements at the engine exit plane under various modes of operation;
- characterization of particle size and composition at the exit plane and in the evolving plume;
- characterization of PAH and nitro-PAH components and

gaseous HAPs, as well as ultrafine particulate matter as potential source markers;
- characterization of the dynamics of the evolving plume, e.g. using LIDAR;
- understanding the importance of ambient conditions and airport operations on aircraft emissions concentrations and properties.

Ambient monitoring

Ambient monitoring of air pollutants is currently primarily used to establish compliance. These data can be used for source apportionment as well as model evaluation and development. Model performance would be greatly aided through improved links to monitoring and measurement data. Protocols are needed for monitoring (including mobile platforms) around airports. These ambient measurements around the airport sites need to be linked with representative background levels of air pollutants established by large-scale measurement networks.

CAEP should develop and publish case studies of airport air quality assessments that are examples for various applications:

- Source apportionment of airside source characteristics
- Model evaluation
- Evaluation of emissions inventories
- Health risk impacts assessments
- Establishing an air monitoring network for trends and impact analysis.

Air quality modelling

Available local air quality models are generally based on a modified Gaussian dispersion approach, with modifications to incorporate airport-specific issues, such as parameterized representations of plume dynamics. These models should also include appropriate representation of processes that are responsible for chemical and microphysical transformation during the plume evolution. Further developments are needed and stronger links should be made with measurement and monitoring programs. Specifically, algorithms for plume dispersion can be enhanced using aircraft LIDAR measurements. Assessments of uncertainty and model performance using monitoring data require urgent attention and the development of appropriate protocols.

Regional-scale Chemistry Transport Models are needed to distinguish between primary and secondary contributions to air quality impacts of aviation emissions. This ability is critical for developing policies for effective air quality management in the aviation context. To examine the impacts of aircraft and airport emissions on ozone and PM, regional air quality models require both gridded background emissions as well as meteorological data. These models have been under development over the last several decades. While ozone formation is modelled reasonably well, the formation of secondary PM (such as nitrate, sulphate and secondary organic aerosol) is relatively less well understood and modelled. Performance would be improved through speciated PM monitoring programs that should be linked to model evaluation and development.

There is also a need for a hybrid modelling approach where both local- and regional-scale models are linked to properly capture both sub- and large-scale changes in air quality due to aviation emissions.

It is in the interests of ICAO/CAEP to ensure that formal evaluation procedures are developed and implemented for local-scale and regional-scale models within an aviation context. Model evaluation includes code verification of physical and chemical transport, transformation and removal processes, statistical comparison of measurements to modelled estimates, and determination of errors through uncertainty analysis. Model intercomparison is not an adequate substitute for detailed evaluation against the field data.

Comprehensive airport assessments

Better characterization is needed of all relevant sources and an understanding of how the pollution profile (and their toxicity) changes as a function of:

- airport location and ambient conditions (temperature, pressure, weather, ambient regional air pollution);
- operating modes for the various sources;
- contemporary weather conditions;
- transport distances.

Future health effects assessments should consider:

- incorporating population exposure models into the analysis and linkage of exposure models with air quality models;
- differentiating the impacts of airside aviation sources from non-aviation landside sources using measurement and modelling data;
- incorporation of noise stress into air quality impact assessments as a possible modifier of effects (Jarup *et al.*, 2008).

Promoting more comprehensive airport air quality assessment will require the scope of CAEP's expertise to be reconsidered to include other disciplines (e.g. air quality analysis using measurements and modelling, health risk analysis, benefit-cost analysis, air pollution epidemiology, exposure assessment), the right participation (stakeholders and representation of impacted populations), and the right procedures and processes to establish accurate, balanced and informative synthesis. Collaboration with stakeholders provides an alternative to expansion of the expertise within CAEP. For example, there are lessons to be learned form the impact assessment conducted by RIVM (2003) for Schiphol Airport and the risk evaluation conducted by the Clean Air Strategic Alliance in Alberta, Canada (Clean Air Strategic Alliance, 2006).

Chapter 4 Aviation noise impacts

Introduction

Aircraft noise affects people. It can interrupt or interfere with speech and communication, disrupt sleep, adversely affect academic performance, may induce detrimental cardiovascular effects, and can result in various levels of annoyance. The adverse effects can produce sufficient levels of annoyance throughout a community that citizens living around airports may mobilize to demand relief, and may take actions that inhibit airport operation or that slow or prevent efforts to expand air transport capacity. Hence, it may be in states' interest to limit the adverse effects of aircraft noise, not only for the benefit of the health and welfare of its citizens, but to permit increases in air transport capacity as they become necessary to serve the larger economic needs of the society.

Terminology

Any discussion of aircraft noise and its relationship to people benefits from unambiguous definitions of terms. The following definitions have been used consistently throughout this chapter. Note that this is an editorial addition to this report on the Noise Panel discussions to assist the reader. The Noise Panel did not fully discuss or reach complete consensus on these definitions and, in fact, ultimate responsibility for the definitions should probably lie with each member state.

Effect/effects/noise effects – These are measurable and quantifiable results of human exposure to aircraft noise. They may be measurable with proper use of appropriate instrumentation (as blood pressure is measurable with a sphygmomanometer), with a specific procedure (as speech interference can be measured through listening to and identifying randomly selected words against different levels of background noise), with surveys (as annoyance can be measured through administering a properly designed questionnaire), or with other scientific methods.

Exposure – The amount of aircraft noise at a given location or experienced by a population.

Metric – A number used to quantify an effect or an exposure. For example, it could be a probability of incidence of high blood pressure at a given exposure, a decibel value that quantifies an exposure, the percentage of people annoyed by a given exposure, the number of people living at a given exposure.

Adverse effects/adverse noise effects – The level of exposure at which an identifiable risk to public health or welfare occurs. (The Noise Panel did not reach a complete consensus on the levels of exposure that induce various health effects and welfare effects, according the 1948 WHO definition, as quoted in Chapter 2, 'Background'. This report defines adverse effect as a risk to either health or welfare.)

Impact – 'Impact' constitutes a policy decision. Because scientifically acquired information cannot always identify when adverse effects become a significant risk to public health or welfare, 'impact' must be a policy selected degree or level of adverse effect identifying the threshold of significant risk. For example, the ICAO concept of "people affected by significant aircraft noise" is a measure of the exceedance of the adopted goal to "limit or reduce the number of people affected by significant aircraft noise." In this case, if the goal is to be pursued with actions, a policy decision is necessary to quantitatively identify when 'significant aircraft noise' occurs. The impact (e.g. people exposed to significant aircraft noise) may be defined either directly in terms of the adverse effect (such as X% of people highly annoyed) or in terms of a metric of exposure that correlates with that level of adverse effect (Y dB LDEN). Then to determine the magnitude of the impact, the number of people affected (e.g. highly annoyed or living above Y dB LDEN) must be determined.

Background

Since the introduction of jet aircraft in the 1950s, noise from aircraft has been a serious concern for residents of communities exposed to the noise of aircraft over flights. For more than five decades since the emergence of this major advance in air transportation technology, considerable research on the effects of aircraft noise has been conducted to support the development of well-founded government policies on aircraft noise. These policies are needed to balance the public's right to a comfortable and safe living environment (i.e. the public health and welfare) versus the national and local economic dependence on aircraft to transport both products and people, especially in a rapidly growing global economy.

The role of the scientific community in this difficult and complex process is not to make noise policy decisions, but rather to conduct the research needed to accurately describe aviation noise effects and to provide guidance concerning the relationships of the effects to the levels of exposure. Efforts since at least the 1970s have attempted to identify and quantify the effects, correlate these effects with physical metrics of the aircraft noise, and to then use the metrics to predict the likely effects of new or extended runways, new airports and changed operational procedures and changed fleet mixes In general, the public's perception of noise around airports has considered noise to be a more frequent and disturbing effect than air quality and climate effects, although all three require serious consideration and proper management under the rubric of 'environmental protection'.

The efforts of the Noise Panel were directed at assessing which effects are well understood and can be associated with one or more physical metrics that have accepted thresholds of effects, and for which effects and/or metrics further research is needed.

The current situation around airports and future expectations for traffic and noise increases

Over time, noise around airports has been gradually changing from that produced by a relatively small number of loud aircraft over flight events to a larger number of quieter events. The transition period from louder jets to the quieter (high bypass engine) jets led to significant reduction in exposures around most airports that served commercial jet traffic. However, continued increases in passenger numbers and in jet operations means that, rather than diminishing, noise exposure has begun to increase.

Due to a general public sensitivity to aircraft noise and to concern about the effects of these exposures on the population, a large variety of efforts have been implemented to address noise issues at large airports around the world. These noise control and mitigation efforts have been implemented under the guidance of ICAO, national government agencies, airports operators, local authorities and aircraft manufacturers.

The situation of people exposed to noise around airports, as assessed by the most recent studies (ICAO, 2006; EC, 2007) show the following.

- A significant reduction in exposure to aircraft noise has been achieved by the ICAO ban of the more noisy Chapter II aircraft in April 2002, and additional decrease in noise at the source is expected from the present restrictions of the ICAO Chapter III requirements. New discussions are now underway for consideration of additional Chapter IV restrictions, but this possible policy change has not been adopted yet.

- Aircraft traffic is globally increasing by about 5% a year for 2000–2005 (6.11% for 2002–2005), although this estimate varies locally and regionally with the time of day, the individual airport and the geographic region internationally.

- Night traffic is increasing more rapidly than traffic during the day, especially for heavy aircraft and long-range lines, which increases night-time levels of noise, even though night traffic is restricted at some airports and more restrictions on night traffic are being considered for the future. In Europe, between 2002 and 2005, people exposed to 45 dB Lnight have increased by 10% (EC, 2007).

According to the Federal Aviation Administration (FAA, 2008a), US system capacity is projected to increase an average of 4.1% a year. Supported by a growing US economy and falling real yields, system revenue passenger miles (RPMs) are projected to increase by 4.2% a year, with regional carriers (6% a year) growing faster than mainline carriers (4% a year). System passengers are projected to increase an average of 3% a year, with regional carriers growing faster than mainline carriers (3.8% vs. 2.8% a year). By 2025, US commercial air carriers are projected to fly 2.1 trillion available seat miles (ASMs) and transport 1.3 billion enplaned passengers a total of 1.7 trillion passenger miles.

In Europe, a 2003 report prepared for the European Community states that in 2015, "the number of people seriously affected [by aircraft noise] will have increased between 10 and 50% with respect to the current situation" (ANOTEC Consulting, S.L., 2003). And the most recent ICAO/CAEP analysis shows that the global population exposed to above DNL 65 dB will increase by 78% from 2005 to 2025 (ICAO, 2007c. It is therefore reasonable to conclude that exposure to aircraft noise is a large and still growing, problem in many areas of the world. Although this is particularly true of developed countries, increases in international travel and international commerce in a global economy will lead to increasing aircraft noise problems in developing countries.

History of describing and managing exposure to aircraft noise

Efforts by aviation stakeholders to manage exposure to aircraft noise could have followed the ALARA principle (as low as reasonably achievable), as is done in the nuclear power industry. However, a more technical approach was chosen to address aircraft noise by the adoption of a noise metric and development of noise contours around airports.

In the US, the Environmental Protection Agency (EPA) was required by the Noise Control Act of 1972 to conduct a study of the "implications of identifying and achieving levels of cumulative noise exposure around airports." The selection of a measure of cumulative noise exposure was to correlate with human responses regarding hearing loss, sleep and speech interference and annoyance, and the identification of maximum permissible levels was based on the protection of the public health and welfare. The measure of cumulative noise was the day-night average sound level, or day-night level, or DNL. In considering minimizing speech interference both outdoors and indoors, minimizing annoyance (percentage highly annoyed), complaints and community reaction, the study concluded that:

> … to achieve an environment in which no more than 20% of the population are expected to be highly annoyed and no more than 2% actually to complain of noise, the outdoor day-night average sound level should be less than 60 decibels. Higher noise levels must be considered to be annoying to an appreciable part of the population, and consequently to interfere directly with their health and welfare.

The Act also required the EPA to publish "information on the levels of environmental noise the attainment and maintenance of which in defined areas under various conditions are requisite to protect the public health and welfare with an adequate margin of safety." This requirement resulted in what is now commonly referred to as 'The Levels Document', which recommended that to provide this protection, the level should not exceed DNL 55. That level was based on applying a 5 dB margin of safety to the recommended threshold of DNL 60 as described in the preceding paragraph.

More recently, in Europe, the European Commission Directive 2002/49/EC (EC, 2002) has recommended the use of LDEN, where Leq for the 4-hour evening period is weighted by 5 dB; the day period (D) remains with no additional decibels, and the night period (N) contains a 10 dB penalty. These metrics, generally depicted as contours of equal exposure around an airport by using sophisticated noise modelling techniques (as described in Chapter 2), are still the predominant way to describe aircraft noise.

Managing the noise exposure of populations can be achieved in four ways: 1) noise reduction at the source, 2) land use planning and management, 3) noise abatement operational procedures, and 4) restrictions on operations. This is the 'balanced approach' of ICAO described in Chapter 2. Although significant reductions in numbers of people exposed have been achieved in the past two decades, increasing operations and local control of land use may reduce these improvements. Generally, airports have no control over land use decisions, and development as well as house buying decisions are either uninformed about the effects of aircraft noise exposure, or are motivated by forces beyond the control or influence of airports. Nevertheless, many airports work with local communities in attempts to provide information about aircraft noise and its effects. Additionally, proposed changes at airports are often subjected to a fairly rigorous noise (and environmental impact) analysis process, conducted in public forums.

Current state of knowledge

Understanding the effects of aircraft noise on communities

For the past half century, various researchers and agencies have sought to quantify the effects of aircraft noise on people and communities. In general, a consistent course of scientific investigation has been followed. This course may be thought of as having what might be called three basic steps of a scientific process.

1 Identify the effect of interest:

- Community annoyance
- Sleep disturbance
- Cardiovascular and other non-auditory physiological effects
- School learning and academic achievement in children
- Speech/communication interference
- Mental health
- Effects of noise on adult work performance
- Effects of noise on residential behaviour
- Complaints or community actions (as a response to stress caused by one or several of the effects stated above).

2 Design and conduct an experiment, usually one of the following forms.

- A statistically based exposure-response relationship, either through surveys eliciting self-reports of effects, or through epidemiological studies that include objective measures of responses (e.g. blood pressure readings)
- Laboratory experiments to reveal basic physiological responses (awakening, task interference, speech interference).

3 Analyse the results, compare with other similar research results, determine validity/ability to generalize results, and publish.

The Noise Panel discussed the results of these efforts and focused their attention on exposure-response effects of aircraft noise agreed to have significant numbers of studies that yielded fairly consistent results. Table 4.1 summarizes the current state of knowledge as identified by the Noise Panel, and may generally be considered as supported by consensus. This table includes reference to recent results from epidemiological studies showing the effects of aircraft noise on arterial hypertension.

The Noise Panel found quick consensus on the noise effects that have had substantial exposure-response exploration, and these are given in the first column of Table 4.1; the final column indicates the consensus for readiness for use in quantifying effects and for ICAO states developing policy. In cases where exposure-response data exist, the panel's assessment that there is 'sufficient' level of certainty for use implies that methods exist for computing response (effects) given an exposure.

The panel had a lengthy discussion on what is called the 'computational cut-off' (column 5). The values in this column represent the consensus level below which there will be almost certainly no adverse effect, and risk of any effect is *de minimis* in relation to urban/suburban settings for civil airports. This qualification was felt necessary to avoid the perception that these computational limits would apply in rural or natural areas and to airports with few or no jet operations. The panel also wanted to be clear that this cut-off is not intended to suggest a policy decision of levels at which impact occurs.

One complexity not explicitly identified in the table is that there did not appear to be complete consensus on the meaning of 'sufficient' in the last column. Participants may have been considering different data or different interpretations of the data when they agreed the data were sufficient. Hence, to finalize the practical application of the data, some decisions will be necessary to select which data or which interpretations to use. Alternatively, more than one data set or interpretation could be used to quantify the effects of policy alternatives and the results compared to determine the sensitivity of the outcome to the specific choice.

Table 4.1 Assessment of metrics and exposure-response curves available for aircraft noise impact analyses

Noise effect	Primary noise metric	Other metrics	Exposure-response curves	Computational cut-off (for major civil airports in urban/suburban settings)	Notes	Level of certainty for use in impact assessment*
Community annoyance	LDN, LDEN	Number of events	Several exposure-response curves exist, but they may need updating to reflect the current situation. Also need information from Asia and developing countries	40–45 dBA LDN or LDEN 55 dBA level for identifying where potentially serious annoyance begins Need to consider separating day and night	Several non-acoustic factors affect annoyance: • Communications with residents • People feeling empowered • Degree of trust in the airport	Sufficient
Sleep disturbance /awakening	At ear LAmax Or SEL + number of events Lnight	n/a	Several curves are available for predicting awakenings	Indoors 33 dBA LAmax (beginning of effect)	Awakening also depends on the time between events and on the time of night of the events	Sufficient
Sleep structure	Leq for sleep period	n/a	Very limited evidence	No evidence	Few studies based on limited data. Further research needed	Limited
Hypertension	Leq (24), Lnight	n/a	Suggestive but data needed from latest study (HYENA: Jarup, 2008)	Hypertension: 55 dBA		Sufficient
CHD: coronary heart disease	Leq (24), Lnight	n/a	Evidence for road traffic but awaiting evidence for aircraft (HYENA: Jarup 2008)	60–65 dBA Leq outdoors Effect of events/ day not known	Air pollution is confounding factor	Limited
Cognitive performance and academic performance of children	LAeq (8)	Research needed on a number of events measure	RANCH: Stansfeld *et al.*, 2005, Clark *et al.*, 2006, Van Kempen *et al.*, 2006 exposure-effect associations for reading	No thresholds, but above 50–55 dBA Leq – refer to WHO	Exposure to aircraft noise at night also contributes to academic performance reduction or impairment	Sufficient
Speech and communication interference	SIL, AI, LAmax (for speech interference), NAT, TA	Spectra			Contributor to annoyance and cognitive performance. Need improved metrics for communication interference	Sufficient

* Through the strength of evidence.
SEL, sound exposure level; SIL, speech interference level; AI, articulation index; NAT, number above threshold; TA, time above threshold.

Other noise related effects not listed in Table 4.1 are the depreciation of house values in areas surrounding airports (see e.g. the discussion provided by Nelson, 2004) and the concept of disability-adjusted life years (DALY). Although these topics were discussed, and the methods (such as hedonic pricing) are rigorous, there was no consensus that the costs of noise or the benefits of noise reduction could be monetized in a way that properly reflects the effects of noise on people.

In order to address questions related to the effects of aircraft noise, specific summaries were provided for each of the most well understood topic areas to establish the current state of knowledge and to guide the workshop discussions. These summaries on separate noise effects were updated after the workshop, and are available on the workshop website.

- Community annoyance
- Non-auditory physiological (cardiovascular) health effects
- Sleep disturbance
- Valuation of the benefits of aircraft noise reduction
- Effects on children's cognition and health.

Additional concepts for understanding effects, adverse effects and impacts

Noise exposure

Noise exposure is a physical phenomenon that can be quantified by noise metrics, such as those given in Table 4.1. It is possible to measure the amount of noise daily experienced by a moving person through the use of a dosimeter, but determining aircraft noise exposure is place specific and accomplished either through detailed modelling or with sophisticated noise monitors. The term 'exposure' itself concerns only the description of sound levels received by community locations, not the 'effects' of such levels.

Noise effects/adverse effects/noise impacts

The human responses to noise exposures are the effects; when the level of the noise exposure increases, the type of response given by a person or a population can vary between an adaptation response for low noise doses, to reparable damage which disappears when noise stops, or irreparable damage after severe exposure (Rylander and Megevand, 1993). Exposure to night-time noise may provoke primary effects during sleep, or possibly secondary effects (after-effects) such as decreased performance. Long-term effects may also be possible.

The concept of 'adverse effects' of noise on health is used here to identify the point at which effects reach a level that corresponds to an increased risk to public health and welfare. The concept of this risk to health and welfare was not fully vetted by the Noise Panel, nor was any consensus approach articulated. Many adverse effect inventories have been done and generally include potential auditory effects (primarily only for occupational environments), emotional responses such as annoyance, cardiovascular system responses such as hypertension and cardiovascular disease processes, immune system responses, and effects on the digestive or neuro-endocrine systems. Exposure-response relationships are usually established between specified levels of noise exposure and various health effects. The simplest presentation consists of an exposure-response curve (referenced here in Table 4.1, fourth column), which is a graphical representation of exposure relationship. These curves can be used to assist in the selection of the 'critical health effects threshold levels' (impacts), which are the lowest noise levels at which important (i.e. 'significant') effects are judged to appear. This notion of the 'importance' of the effect is often discussed in assessments of noise impacts, although it is acknowledged that the choices for these 'threshold levels' is always subjective and arbitrary, and hence must be a policy decision.

Specific health effects have been studied separately in many research studies, and exposure-response functions have been calculated showing noise levels that correspond to various effects such as sleep disturbance, hypertension, annoyance, etc. A global view of specific effects still typically lacks an assessment of the combination of direct and indirect effects: this broader concept provides a description of the total 'health impact' (Franssen *et al.*, 2002). For example, in the Amsterdam case study (Franssen *et al.*, 2002) noise, air pollution, odours and radar are all considered in a health impact study.

As noted in Chapter 2, ICAO's goal is to limit or reduce the impacts of aircraft noise. The word 'impact' is not used only for noise, but applies to all three topics: 1) noise, 2) local air quality, and 3) climate change. For noise, specifically, the number of people exposed to a specified level of noise is the simplest way to describe aircraft noise impacts. This use of exposure can be a useful concept, but it is inadequate to understand, predict, manage and mitigate the actual 'effects' of aircraft noise on communities. Strictly speaking, if we intend to compute the number of people affected we should be using the exposure-probability. The distinction between 'exposure', 'effects', 'adverse effects' and 'impacts' is crucial for the aircraft noise arena.

Identifying exposure levels at which impact occurs

Considerable scientific data have been published on the consequences of excessive noise exposure, especially those described in Table 4.1. Traditionally, authoritative reviews of the noise effects literature predominantly emphasize community annoyance, sleep disturbance, and non-auditory physiological health effects (primarily cardiovascular effects), and some provide recommendations for target noise exposure criteria (i.e. guidelines) for the avoidance of those effects, such as those recommended in the WHO's 'Guidelines for Community Noise' (WHO, 2000). It is important that up-to-date exposure-response relationships be available to decision makers to provide the required scientific foundation for choosing response relationships and computing the affected numbers across the whole population. Affected people are a part of the exposed population: there is no full causality between exposure and effects, only a risk, a benchmark noise exposure criterion. Because most adverse effects do not commence at a clear point in any exposure-response relationship, suggestions by the scientific community for levels that are chosen to 'fully protect' people from the most severe adverse effects of exposure are generally provided only as noise guidelines, rather than as noise policy regulations or standards, with the guidelines being used as a 'best effort' context and the latter being used to describe legally identified levels at which 'impact' occurs. It is also important to remember that the choice of a noise exposure guideline is ideally based on the consensus of the international scientific community expressed through committees at WHO, ISO, ICBEN, FICAN and others, and their understanding of the available data relating exposures to responses. Well considered and up-to-date exposure-response relationships provide the most useful data, and the Noise Panel has identified in Table 4.1 the effects that have sufficient certainty for use in identifying policy thresholds of impact.

It is important to recognize that recommendations or guidelines such as those provided by the WHO are for ideal exposure levels. There are many situations, however, where there is little realistic possibility of achieving these benchmarks. It is important to recognize the difference between ideal noise exposure goals, which are designed to protect the public health with an adequate margin of safety and noise exposure goals, which are technically feasible and affordable. In developing national and international determinations of 'impact', a balance is needed between the recommended 'ideal' noise exposure guidelines and goals, such as those provided by the WHO (WHO, 2000), and the practical and financial realities of achieving these goals.

Uncertainties in knowledge

Many uncertainties often appear in the scientific literature on environmental noise, including uncertainty in both the reported noise exposures and the individual or community responses to these exposures. Of course, at both the individual and community levels, variability is not the same thing as uncertainty, but they are often closely related to each other. Large variability may be a result of measurement difficulties – for example, people's noise exposures are difficult to determine – or a result of inevitable differences – people react differently to identical noises. In the former, variability coincides with uncertainty, while in the latter, variability is a fact of life. Variability, for whatever reason, however, does not mean that a curve fit to the data is uncertain. Simply by acquiring large numbers of data points, the uncertainty of a curve fit can be quite small, indicating high confidence in the average of the data. This certainty, however, may say nothing about the curve's use in predicting how a given community or given person will react to the noise exposure, especially when the variability (scatter) of the data is large. Uncertainty in predictive ability should not be confused with the uncertainty associated with a curve fit to the data.

At a minimum, the large variability observed in the most commonly accepted meta-analyses, such as those for community annoyance and sleep disturbance, leads to a large uncertainty in the accuracy of the exposure-response relationships when used as predictive tools. Statistical measures (such as the variance, the standard deviation and the standard error of a correlation coefficient) describe the amount of variance accounted for by a prediction curve. They are technically indicators of the variability of the data, but may also be indicative of the amount of uncertainty in a data set.

Several factors can contribute to the uncertainty of the data on human responses to noise. One reason that there is considerable uncertainty about the actual individual exposures of subjects in most community response field studies is because noise measurements (or computed exposures) are typically made outdoors, even though the participants are often inside and moving around their homes. Community annoyance field studies are most prone to this source of uncertainty. Not only is there considerable uncertainty introduced because of individual home differences in the outdoor-indoor transfer functions due to difference in home construction techniques, insulation capabilities, but also because of lifestyle differences, which determine whether the study participants live with their windows open or closed. There are also differences between studies concerning the microphone position and the different sides of a home, which can yield different measured sound levels. This lack of consistency in the measurement techniques can be a major source of uncertainty about exposure.

Probably the largest source of uncertainty in describing individual study participant exposures involves the mobility of the participants throughout the home during the measurement period. It is fairly obvious to state that, as people move throughout their homes, their individual exposures will vary considerably – leading to considerable uncertainty about their exposures. Also, often participants who work some distance from the home and are not even there during the period of exposure are included in community response studies of annual exposures.

The US Air Force meta-analysis (Finegold *et al.*, 1994) of the existing published community annoyance data showed considerable variability of responses within and across studies, as shown in Figure 4.1. Figure 4.2 shows the variability and, hence, the associated uncertainty in the same database as a predictor of annoyance at the critical 65 dB A DNL exposure point.

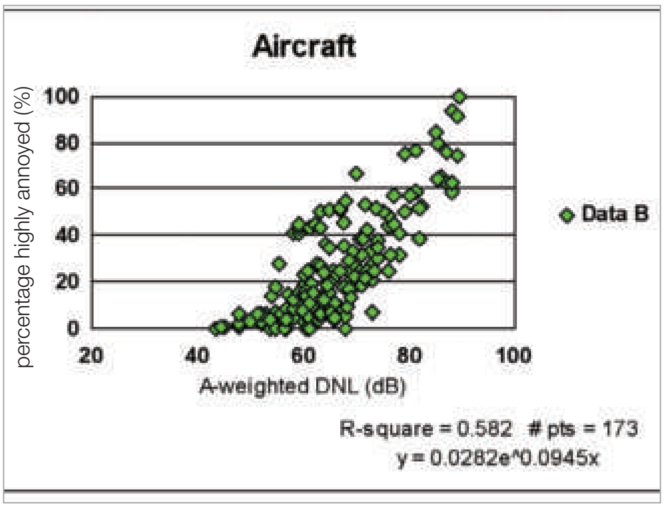

Figure 4.1 Data scatter for community annoyance in response to aircraft noise exposure (Finegold *et al.,* 1994).

There are several reasons why such variability is observed. One reason is that when a specific source of noise, like aircraft noise, is studied, exposure to other sources of noise is not taken into account.

A second factor consists of the large difference in the auditory performance in humans, represented by the hearing threshold, which can differ across individuals by as much as 20 dB. To an unknown extent, this variability shows up in the standard deviation of human responses to noise across study participants. This variability in hearing acuity is well known and accepted by the scientific community, but it makes the adoption of guidelines for noise control difficult.

Another source of variability within and between studies is the existence of both individual and community level tolerance for various types of noise exposure, and thus the acceptability of various noise exposures. For example, it has been known for a long time that community responses to noise, such as exposure to aircraft noise, are highly correlated with various socio-economic factors. Without going into detail on this topic, it should suffice to say that this community level bias is a major source of the variability observed between various field studies. This makes it difficult to develop a single exposure-response curve that applies to all communities because of this source of uncertainty in predicting how a community will respond to aircraft noise.

Despite these obvious sources of variability and uncertainty, the Noise Panel considered that a sufficient level of knowledge exists to develop and promote exposure-response relationships relating community responses to aircraft noise, particularly for community annoyance, sleep disturbance, hypertension, cognitive performance and speech interference.

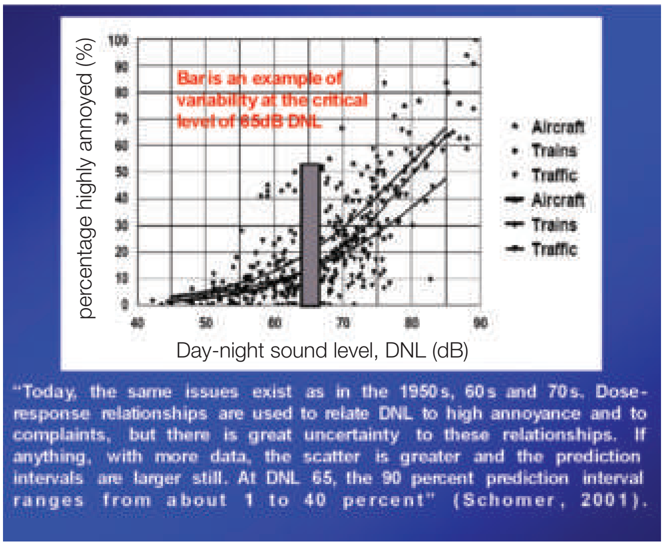

Figure 4.2 Community annoyance data variability at 65 dB (A) DNL (Schomer, 2001).

Findings

The Noise Panel found that there are currently well documented exposure-response relationships, with varying levels of international scientific consensus, for each of the effects listed in Table 4.1, which are ready for immediate application in the overall aircraft noise impact assessment process, except for sleep structure and coronary heart disease (CHD). Table 4.1 gives the consensus on readiness ('sufficient' is ready, 'limited' is not). It does not indicate, however, which data and what interpretation of the data is 'sufficient' for immediate application. Differences of opinions clearly existed within the panel for interpretation of community annoyance data and sleep disturbance data. Hypertension data were discussed, but interpretation and which data should be used was not addressed.

Concern was raised at the workshop about the applicability of the commonly accepted, predominantly Western exposure-response relationships to all countries and all geographic areas of the world. A presentation by a noise expert from Japan showed that additional research is needed, particularly in Asia but elsewhere as well, to examine cultural differences in expectations concerning the acceptability of aircraft noise, such as cultural differences in community annoyance due to these exposures.

The Noise Panel found that because air traffic has evolved from fewer operations with individually loud aircraft to more frequent operations with quieter aircraft, updated exposure-response curves are needed to better reflect current and projected air traffic operations. There was no indication that lack of such updating due to the time and effort required should prevent use of the presently available information.

The CAEP process of assessing aircraft noise impacts is currently based on only the number of people exposed to significant noise as measured by day-night average sound level (DNL). The Noise Panel found that there is no compelling reason to abandon the use of DNL or LDEN (in Europe).

A large majority of the Noise Panel found a clear consensus on definitions of health or welfare effects according to the WHO definition, but consensus was less clear on whether these effects should be separately defined or combined.

The Noise Panel found that cost-effectiveness analyses and cost-benefit analyses are potentially valuable tools for use in assessing the effects of aircraft noise. However, many Noise Panel members' lack of either familiarity or experience with the metrics and techniques meant consensus could not be reached on which analytical techniques are the most valuable ones to be used. The Noise Panel generally found that additional monetary impacts beyond only the traditional effects of housing prices would be useful, including the monetary impacts of health and education effects.

The Noise Panel experts generally found that economic assessment of noise effects is currently quite challenging and no broad consensus exists concerning how this should be done.

Economists presented the state-of-the-practice in noise effect valuation, based on housing value loss and contingent valuation surveys. However, many among the Noise Panel participants expressed their concern that such economic impact models fail to capture the full extent of noise effects, such as the value of cardiovascular effects and the effects of sleep disturbance on worker productivity and worker accidents. Some panellists noted that QALY and DALY (quality-adjusted life years or disability-adjusted life years) analyses were also applicable to noise and had been used to compare noise and air quality impacts in airport analyses. However, other panellists felt that these methodologies were not yet widely agreed upon for use in aircraft noise impact assessments. Ultimately, on the one hand, most of the panellists noted that they did not have economic expertise, making it difficult to draw solid conclusions on this topic. On the other hand, monetization of health effects, education and training, and of the effects on house pricing appears to be a possible common metric to assess the impacts of airport noise, air pollution and possibly climate change.

Recommendations

- The Noise Panel recommends that the approach of quantifying only the number of people exposed to various levels of noise should be expanded to focus more specifically on the various health effects and other effects of exposure to aircraft noise. Specifically, the effects listed in Table 4.1 should be included in assessments of aircraft noise effects and in making decisions about when impacts occur. Such an expansion of effects analysed would provide valuable information for effects that cannot be easily monetized, such as annoyance and sleep disturbance.

- The Noise Panel recommends that the metrics of DNL and LDEN continue to be used, but that informative supplemental metrics be defined and made available for states' use, as deemed appropriate. Supplemental metrics can serve either as the only way to identify certain effects, such as the relationship between night-time noise events and sleep disturbance, or as informative to decision makers and the public. (There was not complete agreement that CAEP has a role in making recommendations about how to communicate with communities.) Supplemental metrics deemed useful by panel members include sound exposure level (SEL), LAmax and number of events (see Table 4.1. Other possible metrics include: number above threshold (NAT) at night, and time above a threshold level (TA). The NAT (or simply the number of events) was suggested for contexts other than night-time, such as for understanding annoyance in general or speech interference. As indicated in Table 4.1, although community annoyance has historically been the predominant noise effect of interest and is commonly described using either DNL or LDEN (in Europe), additional specific noise effects sometimes require their own noise metric, although there is some commonality of metrics across some specific noise effects.

- The Noise Panel recommends the use of noise exposure values lower than the traditional 65 dB DNL (or equivalent) used by many national/federal aviation agencies for identifying potential effects. The panel recommends that CAEP suggest to states that levels of DNL or LDEN (or equivalent) less than 65 dB be used when producing noise maps and managing/mitigating community annoyance.

- Like the Air Quality Panel, the Noise Panel noted that assessing aircraft noise impacts will require a review of the appropriate scope of CAEP's expertise and recommended that CAEP consider how to incorporate this expertise by making use of existing resources and organizations such as the WHO.

- The Noise Panel recommends that ICAO CAEP continue to increase their liaison and coordination activities with international professional societies and organizations involved in aircraft noise issues.

Chapter 5 Aviation impacts on climate

Background

The potential impact of aircraft emissions on the current and projected climate of our planet is one of the more important environmental issues facing the aviation industry. The chemical species released during the fuel combustion process in aircraft engines include carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO and NO_2 or NO_x collectively) and sulphur oxides (SO_x) along with small amounts of soot carbon (C_{soot}), hydrocarbons (HC) and carbon monoxide (CO). Once released at cruise altitudes within the upper troposphere and lower stratosphere (UT/LS), these species interact with the background atmosphere and undergo complex processes, resulting in potential climate impacts and related damages and effects on welfare. Figure 5.1 shows a schematic of how emissions from aviation proceed towards resulting climate impacts and damages. As one moves down the diagram, there is increasing policy relevance, but there is also increasing uncertainty.

The specific ways that aircraft emissions can alter the radiative budget of the Earth and contribute to human-induced climate change are as follows.

- Aircraft engines emit CO_2 and water vapour, important greenhouse gases that directly affect the climate through their absorption and re-emission of infrared radiation.
- Aircraft emitted NO_x enhances atmospheric ozone concentrations through chemical interactions, while HO_x, produced from water vapour emissions into the stratosphere, reduces ozone. Aircraft-produced sulphate and contrail ice particles may also affect ozone via heterogeneous chemical reactions. Ozone affects the radiative balance of the climate system through both its short wave and infrared (greenhouse effect) absorption.
- NO_x emissions from subsonic aircraft reduce the atmospheric abundance of CH_4, another important greenhouse gas; increases in NO_x and ozone both enhance the concentrations of tropospheric hydroxyl radicals (OH), the primary reactant for the destruction of methane.
- Aircraft form liquid particles containing sulphate and organics in their near-field plumes, and emit soot particles. Emissions of sulphur dioxide increase the liquid aerosol mass in aging plumes. Those particles interact among themselves and with ambient aerosol entrained into the plume, forming a complex mixture of particles with different concentrations and chemical composition. These aerosols can be radiatively active themselves, either by scattering (sulphates) or absorbing (soot) solar radiation, or can indirectly affect climate by acting as ice nuclei and altering natural cloudiness.
- Under the right meteorological conditions, processes in exhaust plumes involving water vapour (and aerosols) lead to formation of persistent contrails. Persistent contrails undergo spreading, increase upper tropospheric cirrus cloudiness, and modify the upper tropospheric moisture budget. Both of these effects exert significant spatially inhomogeneous radiative impacts on climate.

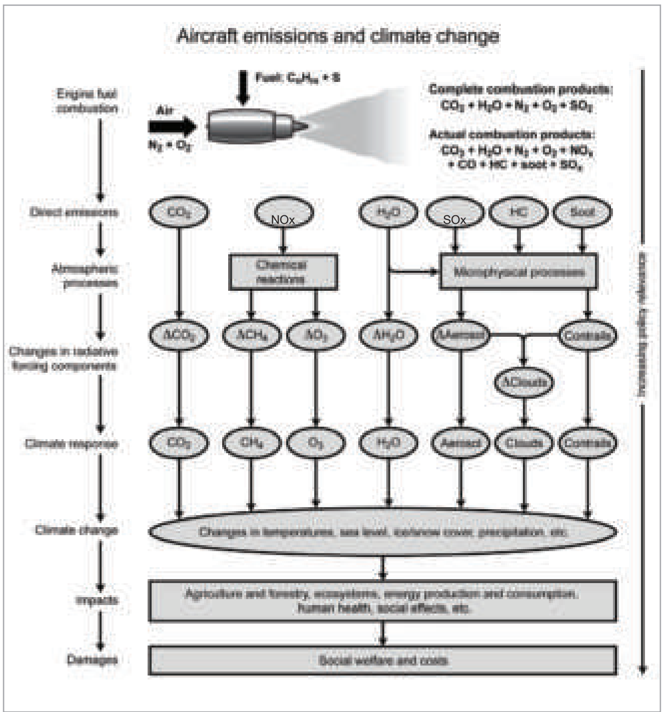

Figure 5.1 Aircraft emissions and their resulting potential impacts on climate change and welfare loss (Fahey: modified from Wuebbles *et al.,* 2007).

Although current fuel use from aviation is only a few per cent of all combustion sources of carbon dioxide (CO_2), one of the most important radiatively active gases affecting climate, the expectation is that this percentage will increase in the future. On a multi-decadal time-scale, aircraft emissions could become an increasingly important contributor to climate change because of the projected increase in passenger demand and associated flights, and of the likely decrease in other emission sources as the world moves away from fossil fuels towards renewable energy sources. Although the long atmospheric lifetime of CO_2 implies little dependence on where CO_2 emissions occur, the effects on climate from the other gases and particles emitted by aviation primarily occur at cruise altitudes in the upper troposphere and lowermost stratosphere. For example, aircraft nitrogen oxides released at these altitudes generally have a larger climate impact than those emitted at the surface, although a small fraction of the much larger surface emissions from energy and transportation sources also reach the upper troposphere.

In 1999, a major international coordinated effort to assess the impacts of aviation on the global atmosphere was sponsored by the UN's Intergovernmental Panel on Climate Change (IPCC, 1999). Since then, a number of studies have been performed that have provided new information on atmospheric impacts from aviation (e.g. Sausen *et al.*, 2005). No comprehensive international attempt has been made to fully update the assessment of the science and the associated uncertainties. However, a workshop on the 'Impacts of Aviation on Climate

Change' was held in Boston during 7–9 June 2006, where thirty-five international experts evaluated current understanding and uncertainties associated with the effects of aviation emissions on climate. The workshop was jointly sponsored by the FAA and NASA under the auspices of the Environmental Working Group of the Joint Planning and Development Office of the Next Generation Air Transportation System (NextGen) and PARTNER (Partnership for AiR Transportation Noise and Emissions Reduction; a Centre of Excellence sponsored by FAA, NASA and Transport Canada).

The experts participating in both the 2006 workshop and the CAEP Impacts Workshop agreed with IPCC (1999) that the three most important ways that aviation affects climate are 1) direct emissions of greenhouse gases including CO_2 and water vapour, 2) emissions of nitrogen oxides that influence ozone, methane and other greenhouse gases, and 3) persistent contrails along with the increase in cirrus clouds from spreading contrails and the potential changes in cloudiness from the effects of particles emitted from aircraft.

The four sets of questions provided to the Climate Panel (and shown in Appendix C) were addressed and thoroughly discussed. These discussions served as the basis for the summary below.

State of knowledge

Aviation emissions and climate effects

Aviation CO_2 emissions depend on the number and type of aircraft operations; the types and efficiency of the aircraft engines; the fuel used; the length of flight; the power setting; the time spent at each stage of flight; and, to a lesser degree, the altitude at which exhaust gases are emitted. The recently released IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) note that carbon dioxide emission factors are based on the fuel type and carbon content, and that because the quality of jet fuel is well defined, computing CO_2 emissions from aviation is relatively straightforward. The IPCC noted that robust and reliable methodologies are available to calculate aviation fuel burnt and emissions throughout the full trajectory of each flight segment using aircraft and engine-specific aerodynamic performance information. ICAO is pursuing efforts to continuously enhance these approaches and workshop participants commended the current efforts by ICAO to continue to advance methodologies for computing aviation emission inventories, but the Climate Panel suggests enhanced consultation with the science community could benefit these efforts. Nonetheless, it is important to recognize that, as far as climate impact is concerned, carbon dioxide emissions from aircraft are not different from other human-related sources of CO_2. The long atmospheric lifetime of CO_2 guarantees that the climate impact of CO_2 emissions does not depend on whether the emissions occur at the surface or at cruise altitudes. There was consensus among participants that despite any uncertainties in emissions inventories, CO_2-related aviation impacts are well understood given the present state of knowledge, and that improving fuel efficiency is a good goal for mitigating aviation climate impacts.

Carbon dioxide emissions and resulting effects on climate are, nonetheless, reasonably well understood compared to other emissions. The uncertainties associated with the contributions to climate change from other aviation emissions continue to be large despite significant improvements in understanding since the 1999 IPCC assessment.

The climate effects from current aircraft emissions are only a small fraction of the total effects of human activities on climate (e.g. emissions of carbon dioxide from aviation are about 2% of the total emissions of CO_2 from fossil fuel burning and changes in land use). As a result, it is very difficult to use a climate model to directly evaluate the climate effects resulting from aviation. The concept of radiative forcing (RF) has been widely used as a metric of climate change to measure the relative efficacy of climate change mechanisms. The RF of the surface-troposphere system due to the perturbation of an agent (say, a change in greenhouse gas concentrations or a change in the solar constant), is defined by IPCC as the change in net (down minus up) irradiance (solar plus long wave; in W m^{-2}) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed (this definition of RF is also called stratospherically adjusted RF or just RF in this document) at the unperturbed values. The globally averaged RF concept provides a first order estimate of the relative climate effects from different forcing agents without the need to actually conduct time consuming and computationally expensive climate model simulations. However, this concept has significant limitations for evaluating effects with highly different lifetimes (e.g. contrails, changes in ozone, methane or CO_2) and, except for CO_2, their resulting spatially inhomogeneous perturbations to the climate system. Thus, without improvements in the concept to account for these effects, radiative forcing alone is not adequate to predict the global mean climate response to aviation emissions.

An update of the IPCC (1999) globally averaged RF from aviation for the "current" time period (relative to no aircraft) has been presented by Sausen *et al.* (2005) for the year 2000. Specifically, similar to the IPCC approach, the forcing from CO_2 was calculated from the cumulative change in concentration of CO_2 from historical operation of the aircraft fleet. The other forcings were calculated from the steady state change in concentrations of O_3, CH_4 and H_2O vapour due to 1992 emissions. The forcing from sulphate, soot, line-shaped (or linear) contrails and contrail- or soot-induced cirrus (together denoted as 'cirrus') also correspond to steady responses. Figure 5.2 summarizes their results as well as the findings from IPCC (1999) for the year 2000 based on linearly scaled results from 1992 to 2050. In view of the large error bars of IPCC (1999), the RF from CO_2, H_2O and the direct effect of sulphate aerosols have not changed significantly, apart from the increase in air traffic from 1992 to 2000. The O_3 and CH_4 effects changed due to more recent analyses from European Chemical Transport Models. The other major changes are related to clouds. First, the new value for the direct global RF from (linear) contrails is 10 mW m^{-2}, roughly a factor of 3 smaller than IPCC (1999). The lower value is an average of results from Marquart *et al.* (2003) and Myhre and Stordal

(2001), which were scaled (by fuel burn) to the year 2000 to yield 6 mW m-2 and 15 mW m-2, respectively. Second, a new upper bound of 80 mW m-2 was estimated for 2000 for the increased cloudiness due to spreading contrails. As indicated in the bottom part of Figure 5.2, the overall conclusion from these analyses is that significant uncertainties still remain in quantifying the impacts of aviation emissions on climate. Except for CO_2, the understanding of the climate effects from other aviation emissions range from fair to poor. Note that the RF for soot in Figure 5.2 is the direct effect of atmospheric soot concentrations and does not include the indirect effect of aviation soot on clouds.

It is also important to consider the relative time-scales associated with the effects on climate (in terms of RF) from all of these various emissions. After emission, effects of the NO_x emissions from aircraft on ozone will last for weeks to months (perhaps somewhat longer for stratospheric emissions), while effects on methane, because of its long atmospheric lifetime (~12 yrs), last for years. Effects from emissions of particles and from contrail formation should last a much shorter time, generally not more than days to a few weeks. On the other hand, emitted CO_2 will affect climate for centuries or longer. About half of emitted CO_2 is taken up rapidly by vegetation and the surface ocean waters within a few decades. After about 100 years, about one-third remains in the atmosphere. Because the ultimate removal from the atmosphere depends on the rate of transfer to the deep ocean, about 20% of the original CO_2 emissions remain in the atmosphere after about 1000 years.

NO_x emissions

The estimates of the impact of NO_x on ozone and methane are based on model simulations. Although observed large-scale atmospheric NO_x enhancements caused by aviation can be simulated by present day models, there is little observational evidence for ozone and methane changes due to the difficulty of distinguishing the perturbation signal from the natural variability, especially at mid-latitudes where most aviation emissions occur. However, with more dedicated effort, identification of aviation NO_x impact on ozone might be possible from observations at least under special circumstances (such as in a stagnant anticyclone).

The climate panellists recognize that atmospheric models of atmospheric chemistry and physics used to assess the effects of NO_x emissions on ozone and methane have been greatly improved since the 1999 IPCC assessment; this was also noted in the conclusion of the 2006 impacts workshop held in Boston (JPDO/PARTNER, 2006; Wuebbles *et al.*, 2007). For example, the representations of atmospheric transport processes in the UT/LS region have been improved (Law *et al.*, 2006).

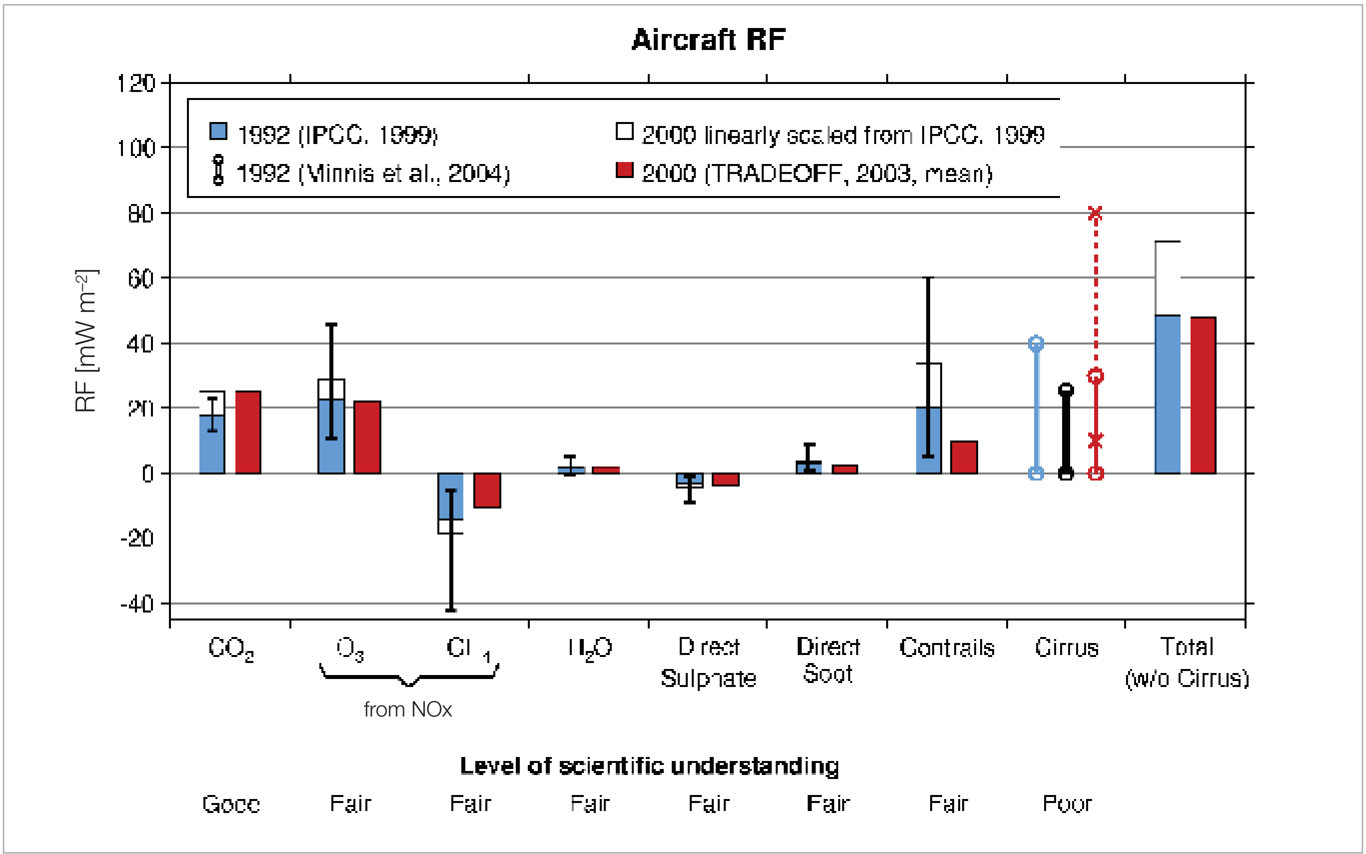

Figure 5.2 Global radiative forcing (RF) (mW m-2) from aviation estimated for the years 1992 and 2000, based on IPCC (1999) and TRADEOFF results. The whiskers denote the 2/3 confidence intervals of the IPCC (1999) values. The lines with the circles at the end display different estimates for the possible range of RF from aviation-induced cirrus clouds. In addition the dashed line with the crosses at the end denotes an estimate of the range for RF from aviation-induced cirrus. The total does not include the contribution from cirrus clouds (Sausen *et al.*, 2005). Note that there are concerns about RF as a metric for climate change; for example, some RFs (e.g. those from contrails, induced cirrus clouds, and ozone from NO_x emissions) are spatially inhomogeneous and seasonally varying, and may not lead to the same temperature change per unit forcing.

However, a detailed intercomparison among these models as well as comparison with observed data is needed to fully assess the present quality of models. The NO_x-methane feedback is difficult to verify because of the long process chain from aviation NO_x emissions to methane destruction, which involves very different parts of the troposphere (from mid-latitudes to tropical regions). The comparison with observations should concentrate on observations that are sensitive to NO_x sources and sinks in the free atmosphere (including upward transport of surface emissions, lightning, aircraft emissions, downward transport from stratospheric sources, and heterogeneous processes on cirrus and aerosol particles, and washout processes). The comparisons should be used to identify shortcomings in each model's capability to represent transport and small-scale processes (including chemistry and aerosols). Improvements should concentrate on better representation of the effects of NO_x emissions on both ozone and methane changes. One well-known model problem is the representation of the scale transition from local engine emissions to the grid scale of global models. This requires special treatment of the initial dispersion period or very high grid resolution. An area that received little attention is heterogeneous chemistry, especially involving contrail and cirrus ice condensate. Few models have detailed heterogeneous chemistry schemes suitable for the UT/LS region and possible plume-scale effects have not yet been properly parameterized in large-scale models.

The radiative effects of CH_4 and O_3 changes arising from NO_x emissions are of opposite sign, as shown in Figure 5.2. The extent to which these effects 'cancel' is particularly uncertain and difficult to fully evaluate. Despite the improvements made to models, uncertainties remain and further studies are needed.

However, the globally averaged radiative forcing values from current models are within the bounds given by Sausen *et al.* (2005). The largest difference in model estimates is found for the estimated negative methane impact, which is now a factor of 2 lower. The different response times of ozone and methane lead to different spatial and temporal behaviour; it should be recognized that the global distribution of the impact is highly different with ozone being regional and methane more global. This gives an impact from aircraft NO_x that is positive in the northern hemisphere and negative in the southern hemisphere, even if ozone and methane radiative forcing could cancel globally.

Some of the key uncertainties affecting the determination of NO_x emissions effects on ozone and methane include the following.

- There remain considerable differences between models in the relative importance of wet and dry deposition for removal of total reactive nitrogen, NO_y.

- There is still at least a factor of 2–3 uncertainty in the total NO_x production by lightning. The uncertainties in the geographical distribution are even larger. It has recently been found that lightning production depends on wind shear (Huntrieser *et al.*, 2007), which is not taken into account in current models.

- The few measurements made at cruise altitudes indicate that NO_x emissions factors used in current emissions inventories could underestimate $EINO_x$ by about 12% on average. This 12% deviation is within the uncertainties of the methods used to predict NO_x emissions and of the measurements, but further opportunities should be taken to further validate these NO_x prediction methods.

- Uncertainties remain as to how NO_x emissions affect the reactive hydrogen budget resulting in changes in OH and CH_4.

- Parameterizations of plume processes in the budget affecting hydrogen oxides and resulting change in OH and CH_4.

- Parameterizations of plume processes in large-scale models are associated with large uncertainties. Plume processing might reduce the impact on ozone by up to about 30% locally.

The effect of aircraft emissions on atmospheric ozone concentration is a function of the altitude at which the emissions are injected. The importance of ozone production cycles from the NO_x emissions through the oxidation of methane and hydrocarbons become less effective with altitude, while the catalytic ozone loss cycles become more efficient. Radiative forcing from ozone changes generally increases with height in the UT/LS region. Any uncertainties in how well we understand the atmospheric chemical and physical processes in the UT/LS affect our ability to understand the magnitude of the aviation effects on ozone and methane. A recent workshop reviewed the knowledge on transport and chemistry in the extra tropical UT/LS, highlighting the need for further studies in this research area (Law *et al.*, 2006).

Contrail, contrail-cirrus and indirect effects

Under the right meteorological condition, aircraft can increase high clouds *directly* by producing persistent line-shaped contrails in ice-supersaturated air and by the spreading of contrail formation to cover larger areas. The principal condition is that the air be ice-supersaturated, which means that the air temperature along the flight track is lower than required to form and maintain ice clouds and that such clouds have not formed. After aging in the atmosphere, contrails may lose their line shape and can no longer be distinguished from cirrus (contrail-cirrus). Clusters of contrails and contrail-cirrus are frequently observed on regional scales within regions of high air traffic. Contrail-cirrus is found even in regions without significant air traffic, because they can be advected over large distances. There are also indications that aircraft can affect high clouds *indirectly* through the emission of soot particles that act as heterogeneous ice nuclei without contrail-cirrus being involved. Aviation soot particles, being the product of incomplete burning of aviation fuel, are expected to increase the number of atmospheric black carbon (BC) aerosols above background amounts formed from surface sources of fossil fuel and biomass burning. In the absence of aircraft emissions, a cirrus cloud might not have formed or the resulting cirrus might have different optical properties. Note that the indirect effect is included in Figure 5.1, but not addressed explicitly in Figure 5.2, although it is part of the 'cirrus' bar.

The formation of linear contrails is obvious and visible. In current model estimates, linear contrail coverage is limited to source areas and optical properties do not always comply with observations. Further, most model studies are not independent because they employ a very similar methodology or rely on identical data sources which are uncertain. Hence, computed linear contrail radiative forcings are very uncertain. The downward scaling of persistent linear contrail RF since the IPCC 1999 report is therefore questionable.

So far, available remote sensing studies, *in situ* measurements and modelling approaches have treated linear contrails. Because of the difficulty in distinguishing contrail-cirrus from natural cirrus, observations do not yet provide data on contrail-cirrus. In addition, contrail-cirrus have not yet been modelled, as no framework exists that would enable the treatment of the entire life cycle of contrails. Therefore, a significant portion of the overall effect of persistent contrails has not been analysed in current assessments. Given recent progress in this area, it appears possible in the near future to estimate a bound on the total effect of linear contrails and contrail-cirrus as a class of ice clouds.

Contrary to contrails, the occurrence of the soot-induced cirrus effect remains yet to be unequivocally proven. One key issue of the aviation soot impact is the ice nucleation efficiency, which is not known. Available laboratory studies are inconclusive and field data are not yet available. The potential soot impact on cirrus has recently been analysed along with an identification of key uncertainties (Kärcher *et al.*, 2007). Recent ground-based measurements have provided some data concerning the size distribution, structure and chemical composition of exhaust soot, and the impact of fuel sulphur on particle hygroscopicity, but not on ice nucleation behaviour in cirrus conditions.

Metrics for aviation impacts

As mentioned above, aviation emits a variety of gases and aerosols, with varying chemical and physical characteristics, which can impact climate either directly or indirectly. Various methods and metrics exist for the purpose of placing these emissions on a common scale with respect to their climate effects, for example, RF, Global Warming Potentials (GWPs), Global Temperature Potentials (GTPs) and temperature change from various simplified climate models. RF as applied in Figure 5.2 provides a metric for examining effects of past emissions, but separate emissions-based metrics are also needed to address other questions, for example, to assess projections of the climate effects from emissions into the future or to compare relative climate effects of different gases. Metrics might be used by industry and policymakers, for example, when considering potential interdependencies and trade-offs among changes in emissions resulting from technological or operational changes, or for comparing with the climate impacts from other transport activities. It is important to consider metrics that capture overall impacts of aviation, thereby allowing assessments of interdependencies and direct comparison with other modes or transport or anthropogenic activity.

Considerations in developing metrics include choosing an appropriate structure for the metric (which may depend on the design of any climate policy it is intended to serve), quantifying the input values (due to underlying uncertainties) and taking into account value judgements in the choice of parameters within these metrics (e.g. the evaluation of long-term impacts versus short-term impacts). Such value judgements go beyond natural sciences. In the choice of impact parameter there is also a trade-off between relevance and uncertainty. Care should be taken that choices related to metrics are based on broad consensus, and that the associated metrics are not misinterpreted or used in the wrong context.

There are large difficulties in developing metrics for aviation because many of the emissions or their effects are short-lived and influence climate directly and indirectly via complex chemical and physical processes. For some emissions, the values of the metrics depend on where the emissions are emitted into the atmosphere (unlike the gases included in the Kyoto Protocol) – both the regional distribution, and for aircraft, the distribution as a function of altitude. The time history of emissions (e.g. adoption of scenarios) is important for determining the climate impact, and therefore for the selection of metrics.

The most used metric traditionally has been RF as used in Figure 5.2. This metric provides a historical integrated perspective on climate, but is not emissions based and has a number of limitations. RF as a backward-looking metric is not relevant to policymaking, as it does not provide information on the future impacts of current aviation activity. Present RF is affected by emissions in the *past*, and it may be argued that RF and RFI should not be used to assess the impact of *present* emissions on future climate, unless future emission increases are similar to past increases. In the case of CO_2, these emissions will continue to cause a forcing for many decades into the future independent of future emissions. By contrast, for the short-lived emissions, the forcing due to these prior emissions will disappear rapidly if emission decreases. The RFI does not take this into account as it essentially captures the maximum effect of the short-lived emissions, but fails to account for the persistence of CO_2 and thus underplays its climate impact (Forster *et al.*, 2006). RFI is no emission metric and the application of the RFI appears inconsistent with the use of GWPs within the Kyoto Protocol; its suggested use seems to have been restricted to a single sector (i.e. aviation) and its use could result in inappropriate measures being taken.

Because of the large difference in time-scales of the emissions effects on climate, the Climate Panel felt it is inappropriate to develop policy using a simple multiplier on the radiative forcing of CO_2 from aviation in order to account for the climate effects of other emissions. The panellists felt that the present policy focus should be on CO_2, pending further research on and evaluation of metrics to address other emissions.

In general, the specific metric needed is likely to depend on the specific question being asked or the specific climate protection goals. Several different metrics will be necessary depending on the questions to be addressed. Some of the existing metrics discussed at the workshop included various versions for the concepts of integrated radiative forcing or GWPs, GTPs and the very simple modelling tools based on Linearized

Temperature Response functions. The GWP concept is used to relate emissions from surface sources within the Kyoto Agreement. None of these metrics have been adequately tested and evaluated by the science community to fully understand their advantages and disadvantages for determining the climate effects of aviation emissions. A short-term goal should be to make significant improvements in the representativeness and adequacy of existing metrics for aviation climate impact studies and clarify the purposes of these and newly proposed metrics (i.e. clarify the questions being asked).

Assumptions made regarding time-scales and the use of scenarios or pulses in determining metrics need to be explicitly stated. For example, the GWP and GTP metrics represent two fundamentally different ways of comparing emissions. While GWP integrates the RF along the time path up to the chosen time horizon and accords equal weight to all points in time, the GTP focuses on *one* particular point in time and gives the temperature effect at that time. For short-lived gases, this difference in metric design has a large effect on the metric values since the climate systems is insensitive to the short-lived radiative forcings after approximately a decade. Thus, the choice of metric is dependent on the perspective adopted in climate policies.

There was an overall concern about the use of damage functions in quantifying the socio-economic impacts of aviation-induced climate change. While there is a wide body of literature on damage assessment including the IPCC Working Group 2 reports (IPCC, 2007b), there is no agreement on any single benchmark study in the area. With regard to aviation, there are concerns about aggregating the spatially and temporally diverse impacts into a damages estimate. It is important to enumerate all the potential impacts on the society and environment resulting from aviation-induced climate change. The panel did agree that it may be possible to estimate the health impacts related to climate change for comparison with health impacts due to air quality and noise effects.

The Climate Panel felt that the globally averaged radiative forcing or resulting global temperature response concepts are currently the best means to assess the climate response to aviation activity. However, existing concepts are not suited for regional forcings estimates, or determining resulting regional impacts. Because of the large difference in time-scales of the emissions effects on climate, the panellists felt it is inappropriate to develop policy using a simple multiplier such as RFI on the instantaneous radiative forcing of carbon dioxide from aviation in order to account for the climate effects of other emissions and effects. Limited analysis may be possible of the resulting impacts on human health and ecosystems, but large uncertainties remain. Although there are published analyses of potential climate damages in the literature, these analyses have not fully accounted for the nonlinear nature of the impacts nor have they adequately accounted for climate impact thresholds. As a result, there is no agreed approach for damages in the IPCC assessments. Hence, the majority of panellists (albeit with some disagreement) felt it is not appropriate at this time to realistically include monetization of resulting damages.

Findings and recommendations

The Climate Panel offers the following key findings and recommendations.

Findings

Assessing the physical impacts of aviation and aviation's climate contribution requires a comprehensive approach that includes all emissions and effects. The CAEP process of assessing the physical *impacts* of aviation greenhouse gases (GHGs) is currently limited to creating aviation emission inventories, which is only the first step. The Climate Panel noted that while this is an important component of the process, it is not an assessment of *impacts, per se*.

It was shown during the workshop that CAEP will need to move beyond simply considering emissions and emissions inventories in order to quantify climate impacts. Figure 5.1 shows a schematic of how information on emissions from aviation influences calculations of climate impacts and damages and the necessary steps involved. Moving down the diagram, there is increasing policy relevance, but there is also increasing uncertainty. The Climate Panel believes that current scientific understanding can, at best, justify analyses of climate response in terms of globally averaged radiative forcing or the resultant global temperature response for aviation. The utility of the radiative forcing metric is limited by only being a proxy for global temperature response. Calculating a global temperature change assumes one knows the climate sensitivity factor (which defines the relationship between radiative forcing and temperature) for the forcing terms, which is not the case for all the terms in Figure 5.2. While it is recognized that understanding of regional impact could be of value in policy considerations, it is also recognized that the scientific understanding of regional impacts are currently highly uncertain. Panellists noted that only limited analysis of the resultant impacts on human health and ecosystems is possible from globally averaged climate indicators.

The Climate Panel noted that carbon dioxide (CO_2) emissions from aviation are not different from other human-related sources of CO_2; their climate impact is independent of where the CO_2 is released into the atmosphere. CO_2 emissions and resulting effects on climate are reasonably well understood, although as mentioned earlier, there do remain some issues with aviation emissions of CO_2 that need to be resolved. Nonetheless, there is a reasonable basis for policy action to mitigate this impact.

The Climate Panel noted that the uncertainties associated with the contributions to climate change from aviation emissions other than CO_2 continue to be large despite significant improvements in understanding since the 1999 IPCC assessment. Climate panellists regarded the possible effects of contrails and soot emissions on cirrus to be particularly uncertain. It is difficult to put bounds at this time on the soot effects. Nonetheless, panellists indicated progress has been made in understanding the effects of contrail-cirrus, and that new observations are needed to enhance understanding of these issues.

The Climate Panel discussed results from recent studies of the globally averaged radiative forcing from aircraft-emitted NO_x through its ozone and methane perturbations. Panellists had no reason to argue about the uncertainty bounds given by Sausen *et al.* (2005). The largest uncertainty (×2) is found for the estimated methane impact. The panel concluded that effects of NO_x emissions on ozone and resulting feedbacks on methane are still uncertain, but, in the near term, significant improvements could be made through carefully designed intercomparisons and evaluation of the atmospheric models used to study these effects. Also, comparisons with the NO_x-sensitive observations are crucial in this respect. Concentrated efforts are needed to remove identified shortcomings.

Climate panellists noted that the evaluation and ranking of the climate impacts and associated economic and health impacts change for different aviation emissions dependent upon the chosen time-scale. For example, carbon dioxide has an atmospheric adjustment time of more than 100 years, while the other emissions and effects have an impact for much shorter periods of time (contrails and cirrus – hours to days; particles – months or less; ozone – less than 1 year; methane – ~12 years).

The Climate Panel noted that various methods and metrics have been developed for the purpose of placing the impacts from different emission effects on a common scale (e.g. globally averaged RF). However, the use of many of these metrics is limited at this time because they have not been sufficiently evaluated for aviation studies. RF has traditionally been applied as a metric for a chosen year calculated from emissions over a specific time period when the history of emissions is known or based on observed (or estimated) concentrations; however, as discussed earlier, RF has its own limitations. RF can also be used in a forward looking perspective (e.g. either integrated RF due to emissions in 1 year over a chosen time horizon (as in IPCC AR4, chapter 2; IPCC, 2007a) or as a function of time for an assumed emission scenario). However, in the latter case, the relative impacts of the different forcing agents will depend on the adopted emission scenario and the assumptions that this scenario builds on. Currently, there is no single definitive metric that combines all aviation climate-related effects on an equivalent emission basis. The choice of metric depends on how the question is formulated (including such issues as emission period, evaluation year and impact parameter).

The Climate Panel noted that climate impacts resulting from a given change in temperature occur at different time-scales, leading to the need to consider a trajectory of impacts that will occur over different time-scales. Panellists noted that current aviation emissions of CO_2 will have impacts on the climate system for over 100 years (in large part because of the thermal inertia of the ocean-atmosphere coupled system).

The Climate Panel noted that there are large difficulties in analysing the climate response of aviation and, thus, in developing metrics for the response because many of the emissions and effects are short-lived and influence climate both directly and indirectly via complex chemical and physical processes. Panellists noted that there are other difficulties in developing metrics for climate change, including the choice of an appropriate structure for the metric (which may depend on the design of any climate policy it is intended to serve), the quantification of input values (due to underlying uncertainties) and the need for value judgements in the choice of parameters within these metrics (e.g. the evaluation of long-term impacts versus short-term impacts). Such value judgements go beyond natural sciences. In the choice of impact parameter there is also a trade-off between relevance and uncertainty.

There was consensus among panellists that the use of the radiative forcing index (RFI) (mentioned in the Intergovernmental Panel on Climate Change Aviation Assessment, 1999 and as has been proposed in some policy discussions) as a multiplier on CO_2 emissions to aggregate the impacts of short- and long-lived aviation emissions is not appropriate to cover the possible range of impacts. The panellists noted that the specific metrics needed depend on the specific question being asked, or on the specific climate protection goals. The panellists felt that it is important to consider multiple metrics that capture marginal impacts of aviation, as this enables direct comparison with other modes of transport or anthropogenic activity. A short-term goal should be to make significant improvements in the representativeness of existing and new metrics for aviation climate impact studies. The panellists also noted that assumptions made regarding time-scales and the use of scenarios or pulses in determining metrics need to be explicitly stated and the purposes of the metrics clearly clarified (i.e. the questions being asked). Additional research is needed. There needs to be a specific effort put into developing and testing climate metrics for use in aviation studies; such an effort should be driven by the specific questions policymakers need to have addressed.

The panellists expressed an overall concern about the use of damage functions in quantifying the socio-economic impacts of aviation-induced climate change. While there is a large body of literature on damage assessment, such as the IPCC Working Group 2 (WG2) report, there is no agreement on any single benchmark study in the area. Panellists noted that there are concerns about aggregating spatially and temporally diverse impacts into only one damage estimate. The panellists concluded that it is important to enumerate all the potential impacts on the society and environment resulting from aviation-induced climate change. They also noted that it may be possible to estimate the health impacts related to climate change for comparison with health impacts arising from air quality and noise effects, but there are many other impacts beyond health impacts from climate. It is important that the science operates within firm boundaries, but it should have interaction with economic evaluations. The panellists ultimately noted that the economic expertise of those present was limited to just one panel member and that CAEP would benefit from additional climate-related economic expertise on the subject.

The Climate Panel noted that nonlinear behaviour of and thresholds in climate impacts will make it very difficult to develop meaningful economic approaches to cost-benefit analysis of impacts. In addition, some impacts are difficult to quantify economically (e.g. deaths or changes in ecosystems associated with climate change). Panellists felt that existing economic approaches in the literature that attempt to account for climate impacts are likely to be inadequate in this regard. The panellists felt that these approaches have not adequately accounted for these nonlinearities and do not account for thresholds at all. The mix of gases and particles with different time-scales and spatial effects make it difficult to monetize the climate effect from aviation. Again, the panellists ultimately noted that the economic expertise of the panellists was limited to just one panel member and that CAEP would benefit from additional climate-related economic expertise.

Recommendations

- The Climate Panel recommended that if CAEP is to consider impacts, it will need to move beyond emissions inventories towards an emphasis on climate impacts, as reflected in Figure 5.1.

- Uncertainties remain in the calculation of some of aviation's radiative forcing impacts, particularly those from NO_x-induced ozone and methane perturbations, and additional cloudiness from contrails/aviation-induced cirrus. The Climate Panel recommended carefully designed model comparison exercises in order to reduce uncertainties, and further basic science investigation of some effects.

- The Climate Panel recommended that more effort should be put into the development of appropriate metrics that can be used to evaluate a range of policies: such metric development should be driven by the policy questions and a range of metrics developed and used to evaluate potential policy options.

- The Climate Panel noted that it was difficult to adequately assess climate impacts from aviation in a 3-day meeting and recommended that CAEP consider a process to achieve international scientific consensus on the approaches used to analyse the science input into aviation policy considerations.

- The Climate Panel recommended that an updated international consensus analysis of aviation impacts be undertaken, and that this could be achieved with an IPCC or IPCC-like assessment, and that such an updated assessment would be very helpful to CAEP, or by some similar process as suggested by the Air Quality and Noise Panels, whereby ongoing science input with international consensus could be provided to CAEP.

Chapter 6 Interdependencies

Background

As noted in Chapter 2, CAEP has adopted three environmental goals for aviation involving noise, air quality emissions, and global emissions (climate) impacts. In moving forward with measures to further quantify these impacts, establish goals and identify solutions to reach these goals, it will be important for CAEP to consider priorities among them, to transition to a more comprehensive assessment approach, and to consider a broader set of options to reduce environmental impacts. Aviation benefits, and adverse environmental effects, result from a complex system of interdependent technologies, operations, policies and market conditions. However, environmental policy to mitigate impacts has generally considered these impacts in a limited context. For example, analyses have tended to consider only noise, only local air quality (limited to emissions inventories), and only climate change (also limited to emissions inventories). It is widely recognized that actions in one domain may produce unintended negative consequences in another without full assessment.

CAEP's work is guided by four terms of reference: 1) technological feasibility, 2) economic reasonableness, 3) environmental benefit, and 4) consideration of interdependencies. There are recognized trade-offs among environmental parameters. On a simple first order level, CO_2 emissions are directly related to fuel consumption, NO_x emissions are directly related to combustion temperature and noise is inversely related to exhaust velocity. Fuel consumption may be reduced by increasing combustion temperature, but this will increase NO_x emissions. Noise may be reduced by schemes to reduce exhaust velocity, but this will increase weight, which in turn will increase fuel burn and CO_2. Increased pressure ratio will generally reduce fuel burn (CO_2) and noise, but increase NO_x. Schemes to reduce emissions may cause sound resonation at low engine powers. Operational options also lead to complex trades. Changing one aspect of aircraft operations, for example, reducing throttle setting during take-off, leads to a variety of environmental effects as documented in ICAO/CAEP (2007a). Fuel burn (CO_2) increases, but NO_x and noise decrease. While SO_x increases as a result of increased fuel burn, total PM decreases because of the decrease in secondary PM via reactions with NO_x, which has decreased. And there are economic effects associated with each of these effects. There are of course instances when all impacts are positive. Continuous descent arrival (CDA) procedures lead to reductions in fuel burn, emissions and noise. Reducing the overall weight of an aircraft through new lightweight materials such as composites reduces all environmental impacts. But, there are often trade-offs among various parameters.

Even evaluating the value of reducing a single environmental parameter is difficult. At its 6th Meeting (February 2004), CAEP considered various options for NO_x stringency. Of these, the least expensive was \$30,000/tonne-NO_x. While this does put a monetary value on a unit mass of NO_x, it cannot tell us if there is a net benefit to society and how that particular benefit compares against the cost and alternative options. It also does not tell us the impact of any additional fuel burn and noise that may be associated with the NO_x reduction technologies. While interdependencies and trade-offs are widely recognized, the challenge is applying appropriate metrics. It is difficult to discern the value of a pound of CO_2 versus a pound of NO_x versus a person exposed to significant noise without translating these impacts into some type of a common basis.

At its 7th Meeting (February 2007), CAEP acknowledged the growing complexity associated with assessing noise and emissions effects of aviation, especially when considering impacts and their influence on benefits-costs. CAEP further acknowledged the need to get a better understanding of these impacts and the benefits of environmental mitigation based on establishing the value of such reductions in addressing the stated problem and endorsed the consideration of a transition to a more comprehensive approach to assessing actions by CAEP/8. CAEP/7 also noted that to fully assess interdependencies and analyses of the human health and welfare impacts, CAEP would need to do three things. First, it would need to employ tools that were capable of looking not only at one aviation environmental parameter in isolation, but also at the effect that changing one aviation-related environmental parameter has on other aviation environmental parameters. Second, CAEP would need to frame the impacts of these parameters in common terms, so that it can understand the implications of the interdependencies and make policy decisions taking those implications into account. Lastly, CAEP should establish the benefit of environmental mitigation as part of a comprehensive assessment. Putting the various environmental impacts in common terms is perhaps the greatest challenge, as well as the most uncertain.

CAEP's role is to inform policy with technical input supported by robust analyses. An important perspective on scientific versus policy uncertainty is shown in Figure 6.1. While scientific uncertainty associated with estimating different metrics increases when moving from inventories, through physical changes and health and welfare impacts, to comparing costs and benefits, the relevance to decision making increases. Thus, it is critical to advise CAEP on potential approaches to comparing various environmental impacts using existing knowledge, as well as steps it may take to enhance such a capability in the future.

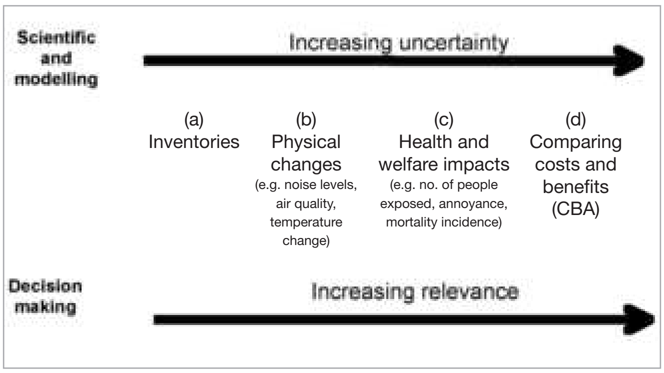

Figure 6.1 Scientific versus policymaking perspectives on uncertainties.

State of knowledge

To inform ICAO, CAEP conducts analyses of various policy options (certification stringency and market-based measures), including economic considerations. The current approach to policy analyses is cost-effectiveness analyses (CEA).[3] The technological feasibility of various stringency options is determined by WG1 (noise) and WG3 (emissions). The Forecast and Economic Analysis Support Group (FESG) works with the working groups to estimate manufacturer and operator compliance costs. A fleet forecast used in modelling to calculate the benefits of reduction in the number of people exposed to noise. The analysis is a single-parameter model for noise or emissions (although CAEP is applying some new models that compute various parameters in an integrated manner). CEA is relatively simple to apply and is an accepted approach within CAEP. CEA does provide a ranking of policy options and it can include limited consideration of interdependencies (e.g. fuel penalty). However, CEA benefits are calculated on an inventory basis (e.g. reduction in global emissions and number of people exposed to significant noise). The concept of number of people exposed has been used on a limited basis within CEA for noise impacts but has not been applied to estimate emission impacts. Also, there is a lack of common metrics that impedes assessment of interdependencies. Ultimately, the lack of impacts information impedes well-informed policy prioritization.

An alternative approach to CEA is cost-benefit analysis (CBA),[4] which is the approach recommended by many states. CBA may entail monetization of benefits, which would provide a common metric for comparison of costs and benefits within and between policy options. However, the range of methodologies required to estimate the physical and health impacts of aviation is formidable and there are significant uncertainties in assessing impacts. Attempting to monetize impacts is very difficult. It is highly sensitive to policy choices such as discount rate and time frames. Workshop attendees also raised ethical concerns, for example, valuing life across different global regions, choosing between quality of life and quantity of life. Despite these limitations, however, CBA has been widely used in various disciplines to inform policymaking decisions. However, CBA has not been yet applied within CAEP.

As an example of an initiative from CAEP member states, The US Federal Aviation Administration, in collaboration with Transport Canada, is working with an international team of researchers to develop a comprehensive suite of software tools that will allow for a better assessment of the environmental effects of aviation. The main goal of the effort is to develop a new capability to assess the interdependencies among aviation-related noise and emissions effects, and to provide more comprehensive cost analyses of aviation environmental impacts. Other member states also contribute a wide variety of modelling tools that will inform the decision-making process and augment the US-Canada initiative.

Figure 6.2 shows a simplified schematic of the US-Canada tool suite. The three main functional components of the tool suite are: the Environmental Design Space (EDS), which is used to estimate aircraft performance trade-offs for different technology assumptions and policy scenarios; the Aviation Environmental Design Tool (AEDT), which takes as input detailed fleet descriptions and flight schedules, and produces estimates of noise and emissions inventories at global, regional and local levels; and the Aviation Environmental Portfolio Management Tool (APMT). APMT serves as the framework within which policy analyses are conducted and provides additional functional capabilities. APMT functional capabilities include an economic model of the aviation industry that takes as inputs different policy and market scenarios, and existing and potential new aircraft types (the latter from EDS). It then simulates the behaviours of airlines, manufacturers and consumers, producing a detailed fleet and schedule of flights for each scenario year for input to AEDT. APMT also takes the outputs from AEDT and performs comprehensive environmental impact analyses for global climate change, air quality and community noise. These environmental impacts are quantified using a broad range of physical and monetary metrics (including, but not limited to, monetized estimates of human health and welfare and impacts, thereby enabling both cost-effectiveness and cost-benefit analyses). While the CEA component of the tool suite is based on well-established CAEP approaches, the physical impacts approach and assumptions of APMT must be reviewed by CAEP prior to considering monetization. The APMT physical impacts and subsequent monetization approaches have been reviewed by independent experts and published in the scientific, peer reviewed literature and submitted to CAEP for consideration (e.g. Marais *et al.*, 2008, ICAO/CAEP 2007b). These reviews noted that although there are numerous uncertainties, the approaches adopted by APMT relied on best available state-of-the-art methodologies, and uncertainties and areas requiring further refinement were well documented.

Important improvements in impacts and benefits analyses include a more complete identification of significant parameters; a more comprehensive understanding of impacts related to all significant parameters; development of common

[3] Cost-effectiveness analysis (CEA) is used to determine the outcome or impact of alternative regulatory choices. It is useful for answering the question: "Given several options for addressing an environmental problem through regulation – each with similar benefits, which choice has the lowest costs?" Typically, the benefits are defined using some surrogate for the ultimate environmental effect (e.g. kg NO_x vs. the value of adverse health effects). "Cost-effectiveness analysis does not necessarily reveal what level of control is reasonable, nor can it be used to directly compare situations with different benefit streams." (Guidelines for Preparing Economic Analyses. United States Environmental Protection Agency, p. 178.)

[4] Cost-benefit analysis (CBA) seeks to determine the extent to which a policy option will produce a net benefit to society. It is typically complemented with distributional analyses to determine which segments of society bear the costs and benefits. By estimating the net present value of benefits less costs relative to a well-defined baseline scenario, CBA can be used to estimate the degree to which a policy scenario improves economic efficiency. CBA requires that benefits and costs be expressed in the same units (typically monetary). It is the recommended basis in North America and Europe for assessing policy alternatives.

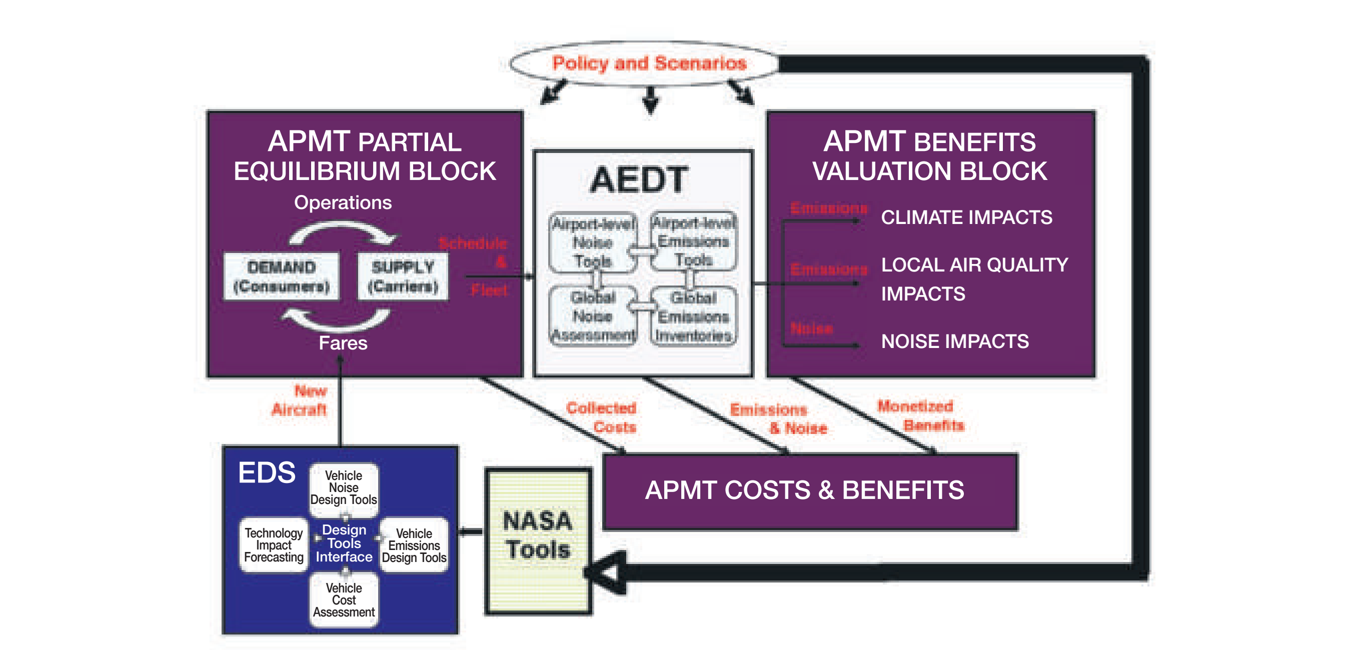

Figure 6.2 Schema of the components of the US-Canada tool suite.

metrics across all parameters; and better assessment of interdependencies. Ultimately, these improvements will result in better information to direct policy.

More recently, the Institute for Aviation and the Environment, University of Cambridge, Cambridge, United Kingdom has initiated a modelling suite of tools – the Aviation Integrated Modelling (AIM) project, which is developing a policy assessment capability to enable comprehensive analyses of aviation, environment and economic interactions at local and global levels.[5] The AIM architecture is shown in Figure 6.3.

The AIM project has the goal of developing a policy assessment tool for aviation, environment and economic interactions at local and global levels, now and far into the future. More details are found in Reynolds *et al.* (2007). The AIM suite of models has not been introduced to CAEP for consideration.

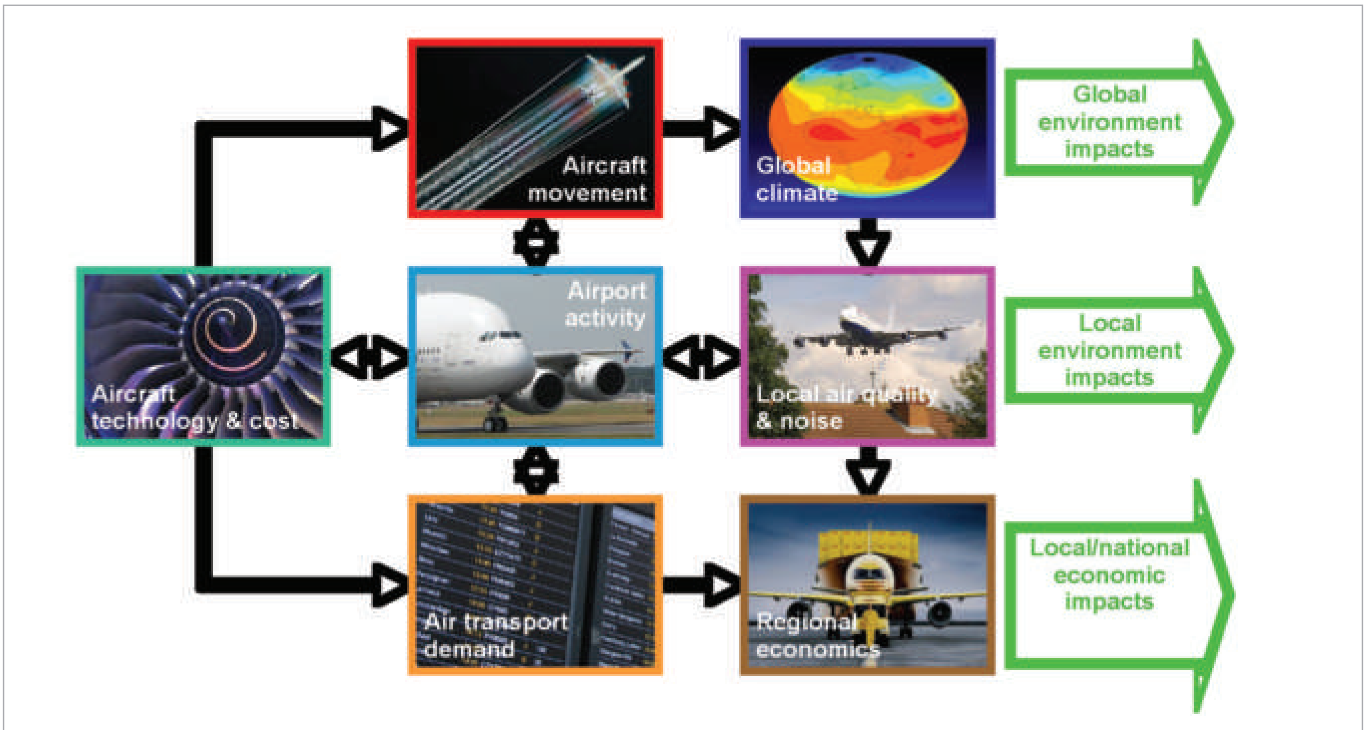

Figure 6.3 Aviation Integrated Modelling (AIM) architecture.

[5] http://www.arct.cam.ac.uk/aim/index.html.

Findings

The interdependencies breakout groups noted that intrinsic physical interrelationships exist between noise, air quality and climate. Interdependencies are important and trade-offs are being made (e.g. modern aircraft design and mitigation strategies).

Panellists noted that cost-effectiveness analyses (CEA) were not appropriate for assessing interdependencies between noise, air quality and climate impacts and that cost-benefit analyses (CBA) could in principle enable such comparisons. However, they also noted that CBA modelling and metrics exist for noise, air quality and climate individually to various levels of maturity (but less so for climate), and CBA approaches are also being pursued by a number of research groups to address interdependencies (e.g. APMT and AIM, as noted above). However, there are no agreed CBA approaches to compare interdependencies. Interdependencies are being addressed, however, at least within a qualitative framework (e.g. CAEP does evaluate potential impact on fuel burn and noise resulting from increased NO_x stringency).

For health and welfare effects, the panellists noted that air quality impacts are regularly monetized as part of policy and environmental impact analysis activities. For noise impacts, both hedonic and contingent valuation methods have been widely applied in Europe, North America and Australia; however, there is no consensus on the extent to which these monetary estimates capture some health and non-market impacts. The panellists acknowledged that monetization is regularly used by economists for assessing climate policies (see e.g. various IPCC reports), but there are some differences in the approaches used by different economists. The panellists noted that there are ranges of damage estimates in the literature; however, these ranges may still be appropriate to inform decisions.

Panellists did note the availability of potential metrics to assess health and welfare impacts. Four methods were noted to assess the health impacts of emissions: exposure, intake fraction, number of people affected, aggregated impact measures (DALYs – disability-adjusted life years, QALYs – quality-adjusted life years, and costs). For climate change, a number of physical impact parameters (e.g. integrated RF, global temperature rise, rate of temperature change, regional temperature rise, sea level rise) over the range of time-scales are available. For noise, the number of events as well as dB is important. Housing depreciation, sleep awakenings, etc. are important considerations for metrics. Panellists recognized that different assessments may produce different rank orders but multiple metrics will potentially better inform the decision process.

Panellists noted the importance of uncertainties and their distinction from preferences. Uncertainties are objective, while preferences are how one may weigh different elements in the decision-making process. Some factors fall between these two categories.

Panellists noted that CAEP needs a framework to examine interdependencies for comparison of various policy options as well as local decisions (some of which have global implications). The framework must be comprehensive and must include what is known today while being adaptable to future advancements in knowledge in each discipline of air quality, noise and climate; and it should facilitate communication among disciplines. The framework needs to consider multiple scenarios (e.g. NO_x stringency over different time-scales and different growth scenarios) within each policy option.

The panellists noted the importance of a transparent, policy analysis framework that assesses noise, air quality and climate as well as their integration, integrates the latest relevant knowledge from the physical and social sciences, and is open to various stakeholders (e.g. researchers, decision makers and parties affected by those decisions).

Finally, within the interdependencies discussions panellists noted that presently CAEP lacks the scientific expertise in many of the impact areas discussed during the workshop.

Recommendations

- The panellists recommend that CAEP use multiple metrics (e.g. health outcomes, quality of life, monetization) to address interdependencies among various environmental impacts. Different assessments may produce different rank orders but multiple metrics inform the decision process. CAEP should not seek single or multiple processes or metrics to replace the decision maker; additional data just serve to inform policy decisions. The scientific process needs to be adhered to throughout and any value judgements that are made by policymakers when interpreting and applying scientific input made should be explicitly stated.

- Panellists recommended that CAEP assess climate and other impacts by adding a range of physical metrics to the traditional cost-benefit analysis approach for air quality (and to whatever extent is feasible noise), thereby moving towards a more comprehensive environmental impact analysis which may be more effective for evaluating these complex trade-offs. CAEP, as a first step, could assess the order of magnitude of monetary effects to help focus on important issues. Although there are wide ranges of damage estimates in the literature, these ranges may still be appropriate to inform decisions. The panellists recommended CAEP ultimately seek further advice from a broader range of economists.

- Panellists recommended that CAEP make use of multiple impact metrics to better inform the decision process. CAEP should consider making use of the four methods noted to assess the health impacts of emissions: 1) exposure, 2) intake fraction, 3) number of people affected, and 4) aggregated impact measures (DALYs – disability-adjusted life years, QALYs – quality-adjusted life years, and costs). For climate change, CAEP should consider a number of physical impact parameters (e.g. integrated RF, global temperature rise, rate of temperature change, regional temperature rise, sea level rise) over a broad range of time-scales. For noise, the number of events as well as dB should be considered as well as housing depreciation, sleep awakenings, etc.

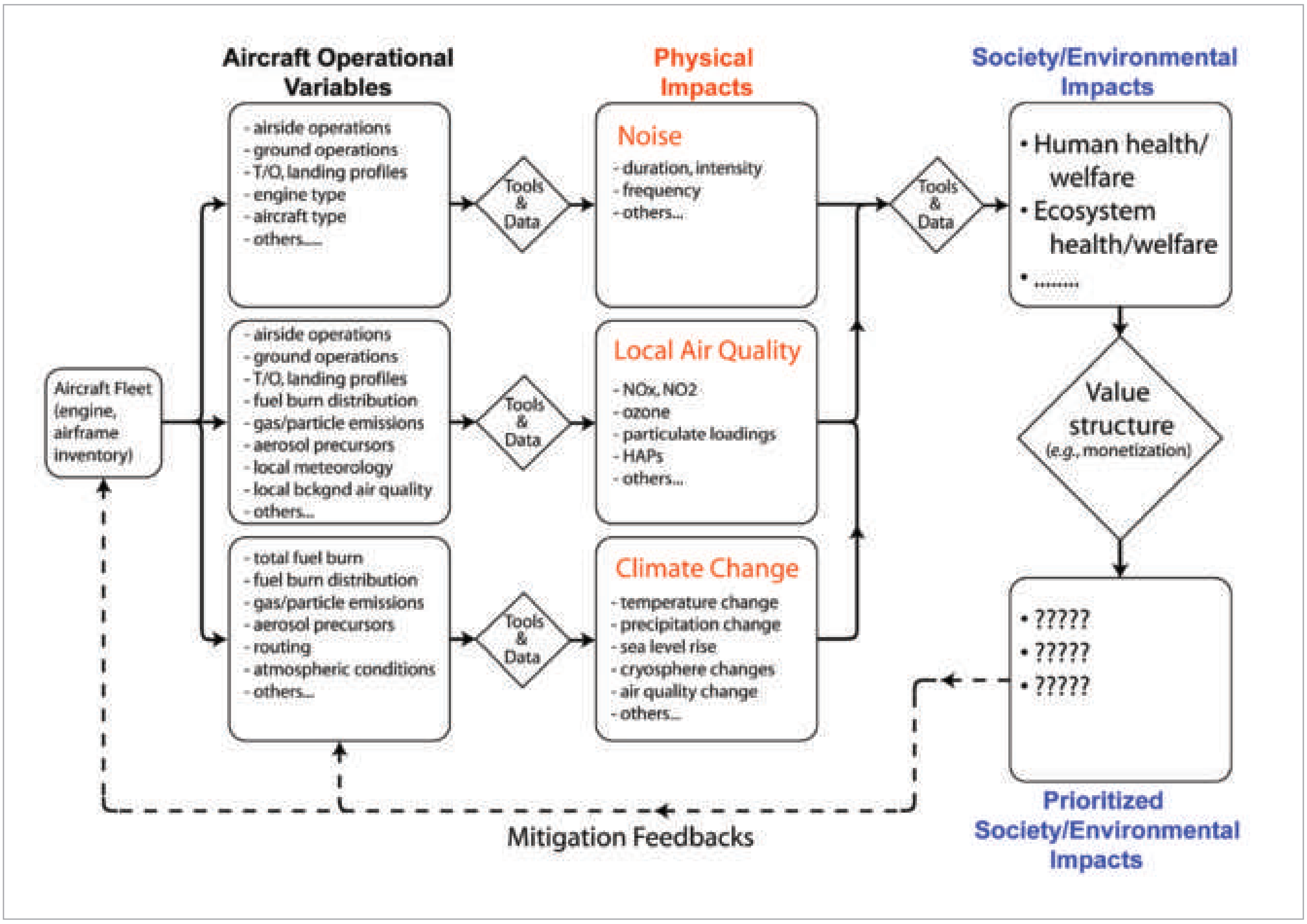

Figure 6.4 Potential framework for assessing aviation environmental impacts.

- The panellists noted that assessments should quantify uncertainties when possible and provide qualitative description when quantification is not possible. Also, uncertainties and preferences should be clearly distinguished.
- The panellists recommended that CAEP consider adopting a conceptual framework for addressing interdependencies as shown in Figure 6.4. Notably, the figure created by the panellists very much follows the elements contained in Figures 6.2 (APMT) and 6.3 (AIM).
- The panellists suggested that CAEP move towards a transparent policy analysis framework that assesses noise, air quality and climate impacts as well as their interrelationships, continuously integrates the latest relevant knowledge from the physical and social sciences, and is open to all stakeholders.
- Finally, within the interdependencies discussions panellists recommended that CAEP consider augmenting its expertise in evaluating impacts. CAEP should consider exploring successful frameworks for seeking ongoing scientific advice and should seek help from the scientific community by providing input to the scientific community on specific CAEP targets of interest and related questions.

Chapter 7 Summary and overarching recommendations

Background

During the 7th Meeting of CAEP in Montreal (February 2007), it was agreed that a scientific workshop would be organized to advise CAEP on how the existing state of scientific knowledge and practical approaches on noise, air quality and climate impacts of aviation may be used to inform policy decisions. Additionally, the workshop would also critically examine the key issues towards comprehensive evaluation of environmental impacts of aviation. Conclusions from such a workshop were envisaged to facilitate CAEP's future development of cost-benefit or other analyses approaches for assessing the environmental health and welfare impacts of aviation environmental policy and would, in due course, lead to refining associated interdependencies and trade-offs analyses taking environmental impacts into account.

The Workshop on 'Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts' was held in Montreal, 29–31 October 2007. This report provides a summary of findings and recommendations by participants of the workshop to inform CAEP. The report seeks to advise CAEP on how existing scientific knowledge may be used to inform policymakers, and near-term (next 1–2 years) steps that can be taken to improve this knowledge.

The workshop was possibly unique in that it brought together international experts from the noise, air quality and climate science communities to address the state of knowledge and uncertainties. Moreover, the workshop certainly was unique in that these communities interacted in a final session to consider interdependencies.

The format of the workshop was typical in that it relied upon the enthusiastic engagement of a relatively small number of individuals, each considered experts in their field, to present, discuss and conclude on relevant issues. To this end, the workshop was considered by all to be a success. The interdependencies session, in which the three communities were mixed, was also very productive and was considered an important first step by all the participants.

The underlying theme of the workshop was practical and output-oriented, which may be précised as keeping the assessment ("what we know") and uncertainty evaluation ("what we don't know/know well enough") in balance with the final question, characterized as "what can we do now, and in the near term?" (see Appendix C). To this end, the skilful and knowledgeable handling of the session co-chairs is gratefully acknowledged by the organizers.

Below, an overall summary is presented that addresses the above questions. This final summary is, by necessity, not as detailed as the session summaries provided in Chapters 3 to 6 and is not intended to replace them, since the individual chapter summaries contain many critical details that should not be neglected in taking forward the process of enabling environmental protection and the reduction of aviation impacts on health, welfare and ecosystems. Nonetheless, the emphasis here is placed upon the larger picture of enabling future progress.

Air quality

Degradation of air quality may directly impact upon human health. Moreover, it can also affect crop productivity and ecosystem response. In reality, aviation impacts on air quality are no different to those from other sources, as no pollutant has as yet been identified as being unique to the sector. The emphasis is naturally focused on airports as a source and the LTO cycle in particular; there has been some discussion and limited research on non-LTO impacts on air quality, but these are still in their infancy and were not discussed at the workshop.

Currently, the *raison d'être* for air quality assessment of aviation sources is one of regulatory compliance, risk assessment and planning consent. One of the clear messages from the workshop was that while the development of detailed emissions inventories for airports is critical (which implies all sources, aircraft and non-aircraft), such inventories are not enough in and of themselves for air quality impacts assessment. Dispersion modelling must be employed in order to determine the source-receptor relationships for direct/indirect (or primary/secondary) air pollutants that will be unique for every airport studied. These relationships depend upon the source strengths their spatial distribution, prevailing meteorological conditions and the pollutants involved, as different scales of influence are involved, depending upon the pollutant and its chemistry-microphysical-atmospheric transport interactions.

Much progress has been made on emission characterization and for many years, the ICAO LTO Certification process has facilitated high quality characterization of aircraft NO_x emissions. However, the situation is not so satisfactory on the issue of particle emissions, about which many health impacts are currently concerned. Characterization of particle emissions is technically and scientifically demanding, since particles may be found in the volatile and non-volatile fractions (the sum of these components is often referred to as particulate matter or PM). Indeed, such a characterization may be too simplistic as some species such as the so-called hazardous air pollutants (e.g. polycyclic aromatic hydrocarbons or PAHs) may be semi-volatile. The instrumental problems and challenges of measuring particles, their composition and phase should not be underestimated and requires continued efforts to refine. Essentially, more measurements are needed at a variety of distances from aircraft engine sources.

The aviation source is unique with respect to its plume dynamics and this represents a significant uncertainty in the characterization of initial dispersion. Some efforts have been made to elucidate this, notably in the US and the UK with LIDAR measurements for near surface plumes in combination with other gas and particle-phase measurements. Ultimately, it will be necessary to be able to model the plume under static and dynamic conditions (aircraft roll and take-off/landing) including vortex interaction, and develop parameterizations that can be incorporated into larger scale models. Such modelling is predicated on high quality measurements being available for parameterization and verification.

A variety of dispersion modelling techniques exists that are suited to a range of different pollutants. Currently, these can be divided into 'local' dispersion models that either treat pollutant dispersion as passive tracers or those that are subject to simplified chemical conversion (e.g. PM and $NO_x/NO/NO_2$ system), and 'urban/regional' models that are typically used for the examination of pollutants that are involved in photochemical reactions where the spatial scale of impact is greater (e.g. the formation of ground-level O_3). The reason for such model development and usage is essentially source apportionment. This implies that high quality inventories of emissions for both the airport and non-airport locality are necessary, up to a regional scale, depending on the pollutant being studied. Also, some panellists noted that to the extent that cruise emissions may impact air quality, the length scales get larger and may require consideration beyond regional effects.

In developing the above modelling system for such source apportionment studies, it is also necessary to emphasize the importance of high quality dedicated measurements. Simple comparisons of models and their outputs are inadequate. Panellists also noted the ongoing efforts of CAEP to compare various models used for regulatory purposes. Although these efforts are laudable, panellists noted that intercomparing models is not adequate for validation; comparison with experimental data is critical. Many measurements are currently being made in airports and their environs: however, these are often made for reasons of regulatory compliance and may not be adequate for the purpose of model development and validation. The workshop noted that dedicated measurement campaigns with more technically sophisticated instrumentation would be needed and encouraged states to support such campaigns.

In addition to the above technical and scientific issues, input from other communities is required to fully address air quality impacts; specifically those expert in epidemiology and health risk analysis, etc., as well as applying these impacts to cost-benefit analysis (CBA). The workshop noted that such expertise is mature and exists outside of CAEP. Only by involving such expertise can a comprehensive approach to air quality impacts analysis for airports be developed. What can CAEP do? In the first instance, it is important to recognize that air quality is much more than quantification of emissions. Evidently, the range of expertise required is beyond that currently incorporated into CAEP and its working groups. However, such incorporation of expertise is not necessarily advocated by the workshop co-chairs, nor is it necessarily the most efficient way of progressing. CAEP already has a substantial work program, and expanding to include this expertise would entail substantial investment and possibly unnecessary duplication of the efforts of others. CAEP may wish to look towards seeking input organizations with expertise in air quality impacts analysis such as the World Health Organization (WHO), since such expertise is clearly beyond its current abilities but certainly within its scope of interest.

Noise

The CAEP process of assessing aircraft noise *impacts* is primarily based on the number of people exposed to significant noise as measured by day-night sound level or DNL, which is not an assessment of impacts *per se*. This approach of quantifying people exposed should be modified to focus more specifically on the health effects or outcomes of aircraft noise exposure. For noise, the most appropriate definition of health is that of the World Health Organization (WHO), which indicates that health is "a state of complete physical, mental, and social wellbeing and not merely the absence of disease, or infirmity."

Workshop discussions focused on the primary effects of noise exposure, summarizing the current state of knowledge as noted in Chapter 4. There are currently well documented exposure-response relationships for each of these effects, which can be applied presently by CAEP to the overall aircraft noise assessment process, except for sleep structure and coronary heart disease (CHD). Also, because air traffic has evolved from fewer operations with loud aircraft to more frequent operations with quieter aircraft, an update to exposure-response curves is needed to better reflect current and projected air traffic operations.

The applicability of and ability to generalize existing noise effects research data and related exposure-response relationships and thresholds to all countries is questionable. This issue could be addressed directly in future internationally coordinated noise research programs to identify similarities and differences in human responses to aircraft noise across cultures and geographic regions.

Cost-effectiveness analyses (CEA) and CBA are potentially valuable tools for use in assessing the impacts of aircraft noise. However, the Noise Panel discussions noted that primary emphasis for aircraft noise impact assessment should be on expanding exposure analyses. Noise panellists generally felt that economical assessment of noise impacts is challenging. Economists presented the state-of-the-practice in noise impact valuation, based on housing value loss or contingent valuation surveys. But many among the Noise Panel expressed their concern that such economic impact models fail to capture the full extent of noise effects, such as the value of cardiovascular effects and the effects of sleep disturbance on worker productivity and worker accidents. Some panellists noted that DALY (disability-adjusted life years) and QALY (quality-adjusted life years) analyses, which are very well developed for air quality impacts, were also applicable to noise and had been used to compare noise and air quality impacts in airport analyses. However, other panellists felt that these methodologies were not yet widely agreed upon for noise impacts. Ultimately, panellists noted that most of them did not have economic expertise and that CAEP should seek further advice.

As noted in the air quality summary above, fully assessing aircraft noise impacts will require a review of the appropriate scope of CAEP's expertise. However, as stated previously the workshop co-chairs feel that seeking to incorporate this expertise within CAEP is likely not the most effective way to make progress. Rather, CAEP should seek to leverage expertise in other coordinating bodies and research organizations, and hold targeted workshops to seek input as appropriate.

Climate

Quantification and assessment of the climate impacts of aviation (and for that matter, any other source) possibly represents the greatest challenge but arguably the most pressing need, given the long time-scales of response.

Similarly to air quality issues, quantification of emissions alone is a first step, but in isolation is of limited use in assessing climate impacts and related metrics. A range of modelling techniques and concepts is necessary in order to assess the climate impacts. Most of these techniques and concepts are routinely applied to estimate the climate impacts of emissions from other sources. In fact, aviation climate impacts are consistently included in the reports of the IPCC.

Workshop climate panellists readily agreed that inventories were not sufficient to quantify impacts; however, the panellists could not readily agree on a single best approach to defining climate impacts. An 'impact chain', such as that presented in Figure 5.1 can be qualitatively developed; however, when attempting to quantify impacts within the framework for assessing impacts shown in Figure 6.1, the challenges are significant. Most of the expertise of the workshop was restricted to defining certain key indicators of aviation impacts such as global mean or regional radiative forcing or temperature response. Such modelling of 'physical' impacts is complex and requires considerable scientific and intellectual resources to undertake this to a consensual level. The following steps from regional and global indicator geophysical responses through to resource/ecosystem/energy/health/societal responses and subsequent social welfare and costs responses represents a considerable challenge for society as a whole and is certainly not restricted to the debate over one sector's impacts on climate.

Considerable scientific progress has been made since the effort galvanized for the Intergovernmental Panel on Climate Change's 'Special Report on Aviation and the Global Atmosphere', published in 1999. This should be viewed not solely as those efforts focusing on aviation impacts, but rather the whole background state of knowledge as embodied in the publications of the IPCC's Assessment Reports.

The clear message from the workshop was that in terms of climate, aviation's emissions impacts are "more than those from just CO_2", and this was a message that had not changed since the IPCC (1999) report. The quantification of this has changed in terms of magnitude relative to emissions (current), but non-CO_2 impacts are still considered to be significant in terms of global mean radiative forcing. Nonetheless, some particular challenges for aviation climate impact assessment remain, notably those of quantifying and attributing changes in cloudiness (linear persistent contrails and contrail-cirrus) to aviation and its impact on radiative forcing and temperature response. Understanding of other effects, such as the balance between O_3 production and ambient CH_4 destruction from aviation NO_x emissions, climate impacts due to soot particles and aerosols, and the different scales of radiative forcing and temperature response remain a challenge but are solvable in the near future through dedicated design simulations and analyses.

The time-scales of response was a theme that was often referred to. Emissions of CO_2 will have a radiative impact over a time-scale of a century or more, while those from non-CO_2 effects will be shorter. However, this is not the full picture since other metrics such as global mean temperature response or sea level rise have much longer time-scales, *even for non-CO_2 effects*, because of the thermal inertia of the coupled atmosphere-ocean climate system.

Because of the complex chemical and physical responses induced by aviation on climate and their different time-scales, there has been considerable interest in developing metrics. Such metrics should be distinguished by their purpose and usage, such that relatively straightforward quantitative metrics of current response (e.g. radiative forcing) may be of limited use as policy metrics addressing different impacts. Metrics appropriate to the policy being formulated will need to be developed. This is not to say that this subject is too immature to be utilized, for example, consideration of Global Warming Potential (GWP), Absolute Global Warming Potential (AGWP) and Global Temperature Change Potential (GTP) is increasingly finding its way into the scientific literature. Such relatively simple formulations have the advantage of relative simplicity and transparency: what requires ongoing consideration are the inputs from more complex models and the application of such metrics to particular questions posed.

Considerable difficulties are involved in assessing the socio-economic responses to changes in the climate system. Although there is a large body of literature on damage assessment, the panellists noted there was no scientific consensus on the best approach or the values/metrics involved. Appropriate approaches are also dependent on the question being asked, and it is difficult to provide generic advice to CAEP that would cover a range of potential questions. Applying a number of approaches is helpful, but each has drawbacks. Aggregating complex responses that vary in time and space with global mean metrics was a particular cause for concern, along with inherent nonlinearities and potential thresholds of non-reversible damage. The Climate Panel noted that there was not good representation of such impact assessment expertise available (with the notable exception of one international expert on this subject), but there was consensus across the panel that monetary evaluation of climate impacts, even though it is routinely applied, may well be beyond what the majority of panellists felt comfortable with and would find credible, given the complexities and uncertainties of input assumptions. Understanding that policymakers may nevertheless wish to examine such data, it is critical to always show a range of different metrics, with quantified uncertainties to try to prevent inappropriate use. It is also critical to compute impacts for a range of time horizons and leave how different results are weighed up to the policymaker.

What can CAEP do? Clearly, quantification of emissions is only a first step in the climate impact evaluation process. Moreover, the expertise for climate impact evaluation largely lies outside of CAEP and similarly to air quality impacts, incorporation of such expertise is not necessarily the best direction of efforts and resources, since much of the assessment process is common to all climate impacts, not the aviation sector alone. The panellists felt that it was important for CAEP to take cognizance of wider scientific endeavours on assessing climate impacts and be more proactive in its interaction with wider domains for international consensus approaches. It was suggested that an updated IPCC or IPCC-like assessment would be useful (while taking cognizance of current European and US efforts to provide assessments). The resources involved in such an exercise, however, should not be underestimated.

Interdependencies

The workshop concluded that intrinsic physical interrelationships exist between noise, air quality and climate. Interdependencies are important and trade-offs are routinely made (e.g. modern aircraft design and mitigation strategies). There was strong consensus that cost-effectiveness analyses (CEA) were not appropriate for assessing interdependencies between noise, air quality and climate impacts. The workshop agreed that cost-benefit analyses (CBA) could in principle enable such comparisons. However, while CBA modelling and metrics exist in principle for noise, air quality and climate individually to various levels of maturity (but less so for climate), there are no agreed credible approaches to compare interdependencies. A number of states are pursuing efforts to develop such approaches and we can look forward to new findings and experiences that can inform future efforts.

Ultimately, it is clear that there is not one simple, single answer. Multiple metrics are important (e.g. health outcomes, quality of life, to some degree monetization) to address interdependencies. How questions are posed and different approaches to assessments may produce different rank orders but multiple metrics inform the decision process. No single or multiple process or metric can replace the decision maker; additional data will just serve to inform policy decisions more fully.

For health and welfare effects, there is widespread consensus thanks largely to the efforts of the World Health Organization on approaches to monetized air quality impacts; however, a consensus does not exist among the noise community, although techniques are available. Monetization has been done for climate, but there is not a single widely accepted approach. CAEP may wish to assess climate and other non-quantifiable impacts in terms of an added (non-quantified) cost/benefit to a CBA between air quality and noise.

Again, what can CAEP do? What is clear is that CAEP needs a framework to examine interdependencies for comparison of various policy options as well as local decisions (some of which have global implications). The workshop offered such a conceptual framework (Figure 6.1). We do not have all the answers today, but that does not mean that CAEP should not take steps to progress towards such a framework. The framework must be comprehensive and must include what is known today while being adaptable to future advancements in knowledge in each discipline. The framework should facilitate communication among disciplines, as this is critical to make progress. And ultimately, the framework needs to consider multiple scenarios (e.g. NO_x stringency regarding different time-scales and different growth scenarios) within each policy option.

Finally, the workshop concluded that any assessments should always quantify uncertainties when possible and provide qualitative description when quantification is not possible. Also, uncertainties and preferences should be distinguished. Uncertainties are objective, while preferences are how you want to weigh the elements in your decision. Some factors fall between these two categories and scientists and policymakers should work together to understand these differences and take steps to continuously improve the decision-making process…

Next steps

The 2007 CAEP Impacts Workshop highlighted the vast body of expertise that is potentially available to ICAO's endeavours on aviation environmental protection. As to how this expertise may be harnessed is not a trivial question, nor one that can necessarily be answered here. The workshop was a critical but welcome first step in addressing the technical issues that surround aviation's impacts on air quality, noise and climate.

The purpose of the workshop has been fulfilled in that in the view of the organizers, the objectives of the workshop have been achieved and are made available to CAEP and the wider public. However, we emphasize that the workshop is not an end in itself. CAEP must now discuss how it wishes to take forward the work of its strategic environmental objectives, having been provided with such advice from technical specialists over the range of scientific disciplines involved.

CAEP states its environmental goals in terms of mitigation of noise and emission *impacts*. However, these impacts have not been characterized and estimated beyond inventories and people exposed to 'significant' noise. CAEP should seek to move towards truly defining impacts in order to provide meaningful guidance and direction on defining environmental needs, goals and targets to achieve those goals.

The workshop suggested that CAEP move towards a transparent, policy analysis framework that: 1) assesses noise, air quality and climate as well as their integration, 2) integrates the latest relevant knowledge from the physical and social sciences, and 3) is open to various stakeholders (e.g. researchers, decision makers and parties affected by those decisions). However, doing so will take time and careful consideration, and will probably require substantial investment.

What is clear to the workshop organizers is that effective future efforts cannot be undertaken in isolation, nor at an UN Agency level alone. The range of stakeholders involved necessitates wider coordination, not least of all accounting for the efforts of the individual scientists and scientific organizations who so freely and generously gave of their time to make the workshop a success.

The workshop chairs suggest that CAEP form a small virtual group of individuals representing the relevant science communities to develop proposals for future possibilities that will facilitate improved scientific understanding that ultimately facilitates policy-relevant advice to be provided to ICAO and member states with regard to environmental protection. The intent behind a virtual group is that such an approach will increase the likelihood of engaging top scientists. The virtual group should also include participation of stakeholders (that is CAEP members and observers) to ensure that the focus remains on policy-relevant science.

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Appendix A: Workshop participants

Air Quality Panel

Alex Nguyen	US
Anuj Bhargava	US
David Carruthers	UK
David Carslaw	UK
David Kittelson	US
David Simpson	Norway
Erik Lebret	Netherlands
Haluk Ozkaynak	US
Ian Waitz	US
Kevin Brand	Canada
Mike Bennett	UK
Paul Madden	UK
Peter Wiesen	Germany
Phil Whitefield	US
Rex Britter	UK
Rich Golaszewski	US
Rick Miake-Lye	US
Robin Ormerod	Australia
Roger Wayson	US
Sarav Arunachalam	US
Serge Lamy	Canada
Sue Greco	US
Vlad Isakov	US
John Kinsey	US

Noise Panel

Barbara Griefahn	Germany
Ben Sharp	US
Bob Solaimani	
David Southgate	Australia
Dieter Schwela	UK/Germany
Dominic Collin	France
Ichiro Yamada	Japan
Irene van Kamp	Netherlands
Danny Houthuijs	Netherlands
Jacques Lambert	France
John Bradley	Canada
Jon Nelson	US
Alain Joselzon	Airbus
Ken Plotkin	US
Neil Standen	Canada
Nick Miller	US
Patricia Davies	US
Raquel Girvin	US
Roger Worth	
Shirley Thompson	US
Stephen Bly	Canada
Stephen Stansfeld	UK
Tetsuya Kaneko	Japan
Truls Gjestland	Norway
Michiko So Finegold	US
Mary Haines	Australia/UK

Climate Panel

Andrew Gettelman	US
Andy Dessler	US
Bernd Kärcher	Germany
Bill Randel	US
Brian O'Neill	US
Dave Fahey	US
Jack McConnell	Canada
Jan Fuglestvedt	Norway
Jose Rodriguez	US
Joyce Penner	US
Karen Rosenlof	US
Malcolm Ko	US
Mark Jacobson	US
Michael Prather	US
Olga Popovicheva	Russia
Pat Minnis	US
Peter van Velthoven	Netherlands
Piers Forster	UK
Robert Sausen	Germany
Steve Baughcum	US
Ulrich Schumann	Germany

Interdependencies Panel Assignment

Panel 1
(Don Wuebbles/Michel Vallet)

Alex Nguyen	LAQ
Rex Britter	LAQ
Paul Madden	LAQ
Phil Whitefield	LAQ
Mike Bennet	LAQ
Robin Ormerod	LAQ
Haluk Ozkaynak	LAQ
Sue Greco	LAQ
Jon Nelson	Noise
Barbara Griefahn	Noise
Dominic Collin	Noise
Ichiro Yamada	Noise
Patricia Davies	Noise
Ben Sharp	Noise
Shirley Thompson	Noise
Mary Haines	Noise
Brian O'Neil	Climate
Andy Dessler	Climate
Pat Minnis	Climate
Joyce Penner	Climate
Jack McConnel	Climate
Karen Rosenlof	Climate
Dave Fahey	Climate

Panel 2
(Michael Pilling/Ivar Isaksen)

David Carruthers	LAQ
Vlad Isakov	LAQ
Anuj Bhargava	LAQ
David Kittelson	LAQ
David Simpson	LAQ
Rick Miake-Lye	LAQ
Erik Lebret	LAQ
Ian Waitz	LAQ
Raquel Girvin	Noise
David Southgate	Noise
Neil Standen	Noise
Truls Gjestland	Noise
Nick Miller	Noise
Irene van Kamp	Noise
John Bradley	Noise
Jan Fuglestvedt	Climate
Andrew Gettleman	Climate
Bernd Karcher	Climate
Steve Baughcum	Climate
Malcolm Ko	Climate
Mark Jacobson	Climate
Peter Van Velthoven	Climate

Panel 3
(Jack Spengler/Larry Finegold)

Roger Wayson	LAQ
Peter Wiesen	LAQ
David Carslaw	LAQ
Sarav Arunachalam	LAQ
John Kinsey	LAQ
Kevin Brand	LAQ
Rich Golaszewski	LAQ
Alain Jozelzon	Noise
Michiko So Finegold	Noise
Dieter Schwela	Noise
Ken Plotkin	Noise
Jacques Lambert	Noise
Stephen Bly	Noise
Stephen Stansfeld	Noise
Tetsuya Kaneko	Noise
Piers Forster	Climate
Bill Randel	Climate
Ulrich Schumann	Climate
Michael Prather	Climate
Jose Rodriguez	Climate
Olga Popovicheva	Climate

Workshop Stakeholders

Observers	Affiliation
Jane Hupe	ICAO
Blandine Ferrier	ICAO
Willen Franken	EU
Maryalice Locke	US
David Jansen	IATA
Betty Hawkins	IATA
Myrka Manzo	IATA
Chris Markou	IATA
Paul Ladden	ICCAIA
Anuj Bhargava	ICCAIA
Steve Baughcum	ICCAIA
Alain Jozelman	ICCAIA
Dominique Collin	ICCAIA
Renzo Fernandez	Embraer
Johan Johnsson	Bombardier
Floretina Viscotchi	Bombardier
Ebad Jahangir	P&W
Steve Brown	IBAC
Eli Cotti	IBAC
Xavier Oh	ACI

Appendix B: Workshop agenda

CAEP Impacts Science Workshop Planning Committee Agenda

29 October–1 November 2007
ICAO Headquarters Montreal, Canada

Sunday, 28 October 2007

7.00pm–9.00pm	Chairs/planning committee meeting in Marriott Lounge

Monday, 29 October 2007

8.00am–9.00am	Chairs/planning committee meeting
9.00am–10.00am	Plenary Session: Introduce the workshop and goals
10.00am–10.30am	*Break*
10.30am–12.00pm	Plenary Session: Panel co-chairs topic background briefings
12.00pm–1.00pm	*Lunch*
1.00pm–3.00pm	Breakout groups on Noise, Air Quality, Climate – address questions – Part 1
3.00pm–3.30pm	*Break*
3.30pm–5.30pm	Breakout groups on Noise, Air Quality, Climate – Part 1 continued

Tuesday, 30 October 2007

8.00am–9.00am	Chairs/planning committee meeting
9.00am–10.30am	Plenary Session: Feedback from breakout groups; synthesize input; questions from observers; agree on goals for next steps
10.30am–11.00am	*Break*
11.00am–12.00pm	Breakout groups on Noise, Air Quality, Climate – address questions – Part 2
12.00pm–1.00pm	*Lunch*
1.00pm–3.00pm	Breakout groups on Noise, Air Quality, Climate – Part 2 continued
3.00 pm–3.30pm	*Break*
3.30pm–4.30pm	Feedback from groups, synthesize input, questions from observers
4.30pm–5.30pm	Plenary: Introduce charge to address interdependencies; include background briefings, assignments for next steps

Wednesday, 31 October 2007

8.00am–9.00am	Chairs/planning committee meeting
9.00am–10.00am	Group breakouts (3) – reconstituted groups addressing interdependencies
10.00am–10.30am	*Break*
10.30am–12.00pm	Group breakouts continued
12.00pm–1.00pm	*Lunch*
1.00pm–2.30pm	Group breakouts (3) continued – may include some original groups coming back together as deemed necessary by panel chairs
2.30pm–3.00pm	*Break*
3:00pm–4.00 pm	Plenary: Feedback from groups; questions from observers
4.00pm–5.00pm	Synthesize results/questions from observers, next steps to report preparation, closing remarks
5.30pm–6.30pm	Planning team, panel chairs and recorders discuss drafting report

Thursday, 1 November 2007

8.00am–4.00pm	Planning team, panel chairs and recorders meet to draft report

Appendix C: Workshop questions

Air Quality Impacts Panel

Emissions

- What pollutants are currently well characterized for airport operations and which are not?
- Considering possible future changes with fuels, engines, controls and equipment, what needs to be done to ensure an adequate emissions inventory?

Measurements

- What important studies have been conducted assessing localized air pollution impacts of airports? How have these studies informed us about magnitude, geographic extent and risk of airport activities on public health?
- Can these studies be scaled to other airports and/or are additional field studies or routine monitoring necessary? (What basic questions need to be addressed in future studies?)

Modelling

- Is there agreement on the adequacy of existing models for regional air quality? What are their emissions inventory and meteorology requirements and can these be appropriately represented in the models?
- What models are recommended for local impact assessment? How do we define the spatial and temporal resolution of emissions for these models (air- and groundside)?
- What are the main uncertainties in local and regional air quality models? How can they be minimized and assessed?

Health risk assessment

- What is the relative importance of each emissions type, in particular NO_x, CO, HC and PM?
- Are the current guidelines for NAAQS, cancer and non-cancer risk assessment appropriate for application to assessing the local and regional public health impacts of airports?
- What are the data/information requirements to express quantitatively estimates of human health impacts?
- How might impacts assessments provide guidance to land use development patterns around airports?
- How do we compare with impact from other sectors (over time and space)?

Noise Impacts Panel

1 On which welfare attributes (e.g. public health, learning, housing values, etc.) does aviation noise have a negative impact?

- Have quantitative relationships been established between noise metrics and noise impacts? What noise metric(s) is (are) used, how is aviation noise impact quantified, and how is the relationship between the two measures defined?
- What are the pros and cons of using these noise metric-impact relationships to evaluate noise policy?
  - How much uncertainty lies in each noise metric-impact relationship? How well is each noise impact currently measured? Are there better ways to quantify the noise impact?
  - How generalizable is each noise metric-impact relationship?
  - How well does the public understand/accept each noise metric-impact relationship?
  - Which noise metric-impact relationships require further study?
- Are there alternative ways to model the noise metric-impact relationships?
- Have thresholds of 'significant impact' been established, and how good are they?

2 What other noise impacts should be considered that we currently cannot quantify?

- Why are these potential impacts worth studying, and in what context might they be used? Would they replace or complement the noise impacts considered today?

3 What other noise metrics should be considered, which we currently do not use to quantify noise damage?

- Why might these metrics be important? Would these metrics replace or complement currently used metrics?
- What other potential noise metric-impact relationships should be studied?
  - Should non-acoustic or psycho-acoustic factors be included in noise metric-impact relationships? If so, how should they be modelled?

4 Based on our answers to Questions 1–3 above, which noise metric-impact relationships can/should be used for noise policy evaluation (cost-benefit analysis) today?

- Are there specific applications for which some noise metric-impact relationships are better suited than others (e.g. local vs. global, short-term vs. long-term)?
- How realistic is the economical assessment of noise impacts?
  - Can the costs and/or benefits be realistically quantified, such as through the impact of noise on property value?
  - Can this approach be reinforced by monetization of noise on health?
- Is the economical impact by monetization a method to assess the global impact of air traffic? If not, what alternatives do we have?
- Which alternative noise metric-impact relationships might have the greatest potential for improving noise policy evaluation?

Climate Impacts Panel

1 What are the current understanding and uncertainties associated with atmospheric composition changes and climate impacts due to aviation:

- from an increase in CO_2?
- from ozone and methane changes due to NO_z emissions?
- from contrails and effects on cirrus cloudiness?
- from changes in water vapour?

What are the spatial and temporal variations in non-CO_2 climate impacts?
What level of time-space resolution is sufficient for model simulations and measurements to best address the above issues?
Are there relevant observations (types, time and space resolution) to support our estimates of aviation impact?

2 What are the metric(s) that can best capture impacts on different space and time-scales?

- What are the appropriate impact parameters?
- Usefulness and limitations of the global averaged radiative forcing concept?
- Utility of pulse vs. continuous emission perturbations scenarios and simulation to estimate climate impacts?
  - GWP-weighted emissions
  - Radiative forcing/integrated radiative forcing/temperature response from pulse emission
  - Radiative forcing/integrated radiative forcing/temperature response from actual emission scenarios.
- Scales of time integration for CO_2 and non-CO_2 climate impacts and changing magnitudes of non-CO_2 impacts in relation to CO_2 impacts?
- What are the best approach to come up with common metrics with air quality and noise?
- How do we compare with impacts from other sectors (over time and space)?
  - Using emission inventory
  - Using actual impact simulations.

3 How will the climate impacts depend on changes in emissions and operations? Trade-off options

- What is the impact of changes in routings?
- What is the impact of changes in fuel use (technology, routings)?
- What are the impacts of future emission changes (scenarios) and how can we limit the uncertainties?
- Are emissions from future supersonic transport (business jets) a likely scenario to include?

4 What are the best approaches for climate impact analysis (for policy)?

- How well can we monetize impacts of aviation on climate?
- How will selection of discount rates and aviation scenarios affect the outcomes of impact analyses?
- How can we include the effect of climate change and associated uncertainties in the impact studies?
- What level of time-space resolution is sufficient for model simulations and measurements to best address the impacts as defined by a metric? Are those requirements sufficiently different from those for understanding the science?
- Are there relevant observations (types, time and space resolution) to support our estimates of aviation impact as defined by a metric? Are those requirements sufficiently different from those for understanding the science?

Interdependencies groups

- What are the key aviation-specific interdependent environmental impacts?
- Common metrics:
  - What are the key issues for trade-offs and interdependencies among and within these aviation-related environmental impacts?
  - What are the metric options to interrelate environmental impacts among all three groups?
- What are the best options for analyses quantifying aviation interrelated environmental impacts?
- How best can we practically apply the present state of knowledge and modelling and data analysis ability to quantify the impacts (recognizing uncertainties)?

Appendix D: List of presentations

Noise

de Hollander, G. *et al.*, Environmental Disease Burden: Evaluating the Health Impact of Environmental Exposures

Finegold, L. and Vallet, M., Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts Workshop: Evaluating the Impacts of Aircraft Noise

Griefahn, B. and Basner, M., Aircraft Noise Effects

Lambert, J., Valuation of the Benefits of Aircraft Noise Reduction

Stansfeld, S., Aircraft Noise and Cognitive Performance in Children

Air quality

Arunachalam, S., Investigation of Air Quality Impacts of Aviation Using CMAQ

Bennett, M., Is an Aircraft a Chimney Lying on its Side?

Brand, K.P., Air Quality Impacts

Carruthers, D., Air Quality Modelling at London Heathrow Airport: Model Intercomparison and Assessment with ADMS-Airport

Carslaw, D., Some Insights from Measurements at Heathrow

Greco, S., State of Knowledge: Mobile Source Fine Particulate Matter ($PM_{2.5}$) Emissions-to-Exposure Relationships

Kinsey, J., Overview of Future Aviation Fuels and Engine Technologies

Lebret, E. and Houthuijs, D., Health Impact Assessment Schiphol Amsterdam Airport: Local Air Pollution Issues

Özkaynak, H., Overview of Research at EPA on Applications of Air Pollution Exposure Models

Spengler, J. and Pilling, M., Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts Workshop: Evaluating Aviation Local Air Quality Impacts

Whitefield, P. *et al.*, A Review of Campaigns to Quantify the PM Emissions from Commercial Aircraft Engines

Climate change

Fuglesvedt, J., Metrics for Comparing the Impact of Emissions from Transport on Climate

Kärcher, B., Critical Role of Contrails and Contrail-cirrus

Wuebbles, D. and Isaksen, I.S.A., Assessing Current Scientific Knowledge, Uncertainties and Gaps in Quantifying Climate Change, Noise and Air Quality Aviation Impacts Workshop: Evaluating the Impacts of Aviation on Climate

Interdependencies

Fahey, D., Assessment of Aviation Impacts on the Environment and Society – A Schematic Flow Diagram

Jensen, D. And Mann, M., CAEP Economic Analysis

Appendix E: Glossary

ADMS – Atmospheric Dispersion Modelling System

AEDT – Aviation Environmental Design Tool

AERMOD – The Environmental Protection Agency's regulatory air dispersion model, models point, area and volume sources

Aerosols – Airborne suspension of small particles

AGWP – Absolute Global Warming Potential

AI – Articulation index

AirClim – Regional assessment of aviation impacts has recently been addressed using the AirClim model

ANSI – American National Standards Institute

Anthropogenic – Caused or produced by humans.

AOGCMs – Atmosphere-ocean general circulation models

APMT – Aviation Environmental Portfolio Management Tool

AQ – Air quality

ASM – Available seat miles

ASTM – American Society for Testing and Materials

ATC – Air Traffic Control

BC – Black carbon; graphitic carbon, sometimes referred to as elemental or free carbon

CAEP – Committee on Aviation and Environmental Protection

CAFE – EU Clean Air for Europe

CBA – Cost-benefit analysis

CCMs – Climate-Chemistry Models

CDA – Continuous descent arrival

CEA – Cost-effectiveness analysis

CHD – Coronary heart disease

CHIMERE – European air quality modelling system

Cirrus – High, thin clouds composed of mainly ice particles

Climate Model – A numerical representation of the climate system. Climate models are of two basic types: 1) static, in which atmospheric motions are neglected or are represented with a simple parameterization scheme such as diffusion; and 2) dynamic, in which atmospheric motions are explicitly represented with equations. The latter category includes general circulation models (GCMs)

CMAQ – Congestion Mitigation and Air Quality Improvement Program

CO – Carbon monoxide

CO_2 – Carbon dioxide

Coagulation – Collision between two (or more) particles resulting in one larger particle

Contrail – Condensation trail (i.e. white line-cloud often visible behind aircraft)

CRFs – Concentration response functions

C_{soot} – Soot carbon

CTMs – Chemical Transport Models

CV – Contingent valuation

DA – Policy analysis requires assessing which segments of the economy or parts of society receive the benefits and which segments bear the costs; broadly termed distributional analysis (DA)

DALY – Disability-adjusted life year

DENL – The average of LAeq over the day with an adjustment to allow for the additional annoyance during the defined evening and night periods. The day period is 12 h and normally from 0600 to 1800; the evening 4 h is normally from 1800 to 2200 with an adjustment of +5 dB, and the night 8 h uses an adjustment of +10 dB. This derived descriptor is to be used in the implementation of the new European Commission (EC) Directive on Environmental Noise (EC END 2002/49). The length of each period is given in hours, but the clock times can be changed to suit the lifestyle of the country

DNL – Day-night (average sound) level. The average of LAeq over the day with an adjustment of 10 dB to allow for the additional disturbances during the defined night period. DNL has been commonly used in the United States since 1974. While some countries will continue to use LDN and others will use LDEN, a method for comparison between LDN and LDEN is provided in Miedema and Oudshoorn (2001). According to these authors, for specific types of noise, the agreement is: aircraft DENL = DNL + 0.6, road traffic DENL = DNL + 0.2, and railway DENL = DNL

ECAC – European Civil Aviation Conference

EDMS – Emissions and Dispersion Modelling System

EDS – Environmental Design Space

Effective Perceived Noise Level (EPNL) – ICAO uses this as the basic metric for the aircraft Noise Certification Process. Described in EPNdB units, which is a single evaluation of the subjective aspects of aeroplane noise on human beings. PNdB is the unit used to measure the instantaneous PNL, while EPNdB is used to describe the movement of an aircraft, according to ICAO Annex 16

EIA – Environmental Impact Assessment

EIAP – Environmental Impact Assessment Process

EMEP – Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe

ENIA – Environmental Noise Impact Assessment

EPA – US Environmental Protection Agency

EPACT – Energy Policy Act of 2005

EPNL – Effective perceived noise level (see note above)

Equivalent Energy Level (LAeq) – The level for a continuous, steady sound (in dBA) that has the same energy as a time-varying sound over the same time period. LAeq is the basis for a number of derived descriptors discussed below

Feedback – When one variable in a system triggers changes in a second variable that in turn ultimately affects the original; a positive feedback intensifies the effect, and a negative one reduces the effect

FESG – Forecasting and Economic Support Group

FICAN – US Federal Interagency Committee on Aviation Noise

Freezing – The process of phase transition from liquid to solid state

GCM – General circulation model

GHG – Aviation greenhouse gases (see note below)

Greenhouse gas (GHG) – A gas that absorbs radiation at specific wavelengths within the spectrum of radiation (infrared) emitted by the Earth's surface and by clouds. The gas in turn emits infrared radiation from a level where the temperature is colder than the surface. The net effect is a local trapping of part of the absorbed energy and a tendency to warm the planetary surface. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere

GTP – Global Temperature Change Potential

GWP – Global Warming Potential

HAPs – Hazardous Air Pollutants

HC – Unburned hydrocarbons

HIA – Health Impact Assessment

HP – Hedonic property pricing

HYENA – Hypertension and exposure to noise near airports

IATA – International Air Transport Association

ICAO – International Civil Aviation Organization

ICBEN – International Commission on Biological Effects of Noise

ICCAIA – International Coordinating Council of Aerospace Industries Associations

I-INCE – International Institute of Noise Control Engineering

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization for Standardization

JCAB – Civil Aviation Bureau of the Ministry of Transport of Japan

Jet – The continuous strong stream of exhaust gases leaving the engine exit

LAQ – Local air quality

LAmax – The LAmax noise level is the maximum A-weighted noise level measured over a given measurement period

LAeq – See Equivalent Energy Level

LDEN – See DNL

Leq – See Equivalent Energy Level

Lnight – Equivalent Energy Level for night hours

LFN – Low Frequency Noise

LHR – London Heathrow Airport

LIDAR – Light Detection and Ranging Data

LinClim – Another simplified climate module that assesses global radiative forcing and temperature impacts of aviation CO_2, O_3, CH_4, sulphate, soot and contrails effects

LTO – Reference landing and take-off cycle below 915 metres altitude (3000 feet)

LWP – Level weighted population

MAGENTA – Model for Assessing Global Exposure to the Noise of Transport Aircraft

Maximum Noise Level (LAmax) – The maximum noise level during a given time period. Often used as a criterion in conjunction with LAeq or LA10 to limit the highest noise levels

Mitigation – An anthropogenic intervention to reduce the effects of emissions or enhance the sinks of greenhouse gases

NAAQS – National Ambient Air Quality Standards

NAT – Number above threshold

NCM – Noise contour module

NDI – Noise depreciation index; the estimated percentage change in housing values for each decibel increase in noise

NDSI – Noise Depreciation Sensitivity Index

NextGen – Next Generation Air Transportation System

NO_x – Emissions of oxides of nitrogen; oxides of nitrogen, defined as the sum of the amounts of nitric oxide (NO) and nitrogen dioxide (NO_2) with mass calculated as if the NO were in the form of NO_2

Nucleation – Phase change of a substance to a more condensed state initiated at a certain loci within a less condensed state

Number Above Threshold (NAT) – The number of events above a threshold noise level, which can be easily transformed easily into Time Above (TA) by summation of the length of time of all events above a fixed threshold level

O_3 – Ozone; a gas that is formed naturally in the stratosphere by the action of ultraviolet radiation on oxygen molecules. A molecule of ozone is made up of three atoms of oxygen

Optical Depth or Optical Thickness – The parameter of a transparent layer of gases or particles defined as the logarithm of the ratio between incident and transmitted radiative flux

PAHs – Semi-volatile organic compounds (polycyclic aromatic hydrocarbons (PAHs), nitro-PAHs)

PARTNER – Partnership for AiR Transportation Noise and Emissions Reduction; a Centre of Excellence sponsored by FAA, NASA and Transport Canada

Peak Noise Level (LCpeak) – Peak C-weighted sound pressure level, typically used for an impulse or explosive sound. This environmental noise descriptor is based on C-weighting rather than an A-weighting frequency filter

Perceived Noise Level (PNL) – The level of a sound that is considered to be equally noisy between two exposures. It is calculated from the one-third octave band spectra

Percentile Value (LA*n*) – The level exceeded for a percentage of a prescribed time period. The most commonly used percentile values are LA10, the level exceeded for 10% of the time period and thus representative of higher noise levels, and LA90, the level exceeded for 90% of a time period and usually considered representative of the background noise level

Plume – The region behind an aircraft containing the engine exhaust

PM – Particulate matter

$PM_{2.5}$ – Particle mass less than 2.5 micrometres aerodynamic diameter

Pressure Ratio – The ratio of the mean total pressure exiting the compressor to the mean total pressure of the inlet when the engine is developing take-off thrust in ISA sea level static conditions

QALY – Quality-adjusted life year

Radiative Forcing (RF) – A change in average net radiation (in $W\ m^{-2}$) at the top of the troposphere resulting from a change in either solar or infrared radiation due to a change in atmospheric greenhouse gases concentrations or some other perturbation in the radiative balance relative to the pre-industrial period (1750)

RAINS – Regional Air Pollution Information and Simulation

RANCH – Road Traffic and Aircraft Noise and Children's Cognition and Health project

RF – Radiative forcing

RFI – Radiative Forcing Index

RPM – Revenue passenger miles

SHEDS – Stochastic Human Exposure and Dose Simulation model

SIL – Speech interference level

Soot – Carbon-containing particles produced as a result of incomplete combustion processes

Sound Exposure Level (SEL) – The noise level for a sound over a defined time period, nominally 1 second, that would have the same total energy as the noise from a single event such as a helicopter flyover or a train pass-by

SO_x – Sulphur oxides

Stakeholders – Person or entity holding grants, concessions, or any other type of value which would be affected by a particular action or policy

Stratosphere – The stably stratified atmosphere above the troposphere and below the mesosphere, at about 10–50 km altitude, containing the main ozone layer

TA – Time above (a threshold)

TRADEOFF – TRADEOFF was a European Commission Fifth Framework Project model-based project investigating the atmospheric impact of aviation

Tropopause – The boundary between the troposphere and the stratosphere, usually characterized by an abrupt change in lapse rate (vertical temperature gradient)

Troposphere – The layer of the atmosphere between the Earth's surface and the tropopause below the stratosphere (i.e. the lowest 10–18 km of the atmosphere) where weather processes occur

UT/LS – Upper troposphere and lower stratosphere

VOCs – Volatile organic compounds

Wake – The turbulent region behind a body or aircraft

WECPNL – This is the abbreviation of Weighted Equivalent Continuous Perceived Noise Level

WHO – World Health Organization

WTP/WTA – Willingness to pay/willingness to accept