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Review

Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review

Mauro Masiol, Roy M. Harrison*

Division of Environmental Health and Risk Management, School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

HIGHLIGHTS

- Aviation is globally growing (+5% y^{-1}) mainly driven by developing countries.
- Airport operations cause an increase in ground-level pollution.
- Chemical and physical properties of the emitted gases and particles are reviewed.
- An overview of other additional sources within airports is provided.
- Future research needs on aircraft emissions are highlighted.

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ABSTRACT

Civil aviation is fast-growing (about +5% every year), mainly driven by the developing economies and globalisation. Its impact on the environment is heavily debated, particularly in relation to climate forcing attributed to emissions at cruising altitudes and the noise and the deterioration of air quality at ground-level due to airport operations. This latter environmental issue is of particular interest to the scientific community and policymakers, especially in relation to the breach of limit and target values for many air pollutants, mainly nitrogen oxides and particulate matter, near the busiest airports and the resulting consequences for public health. Despite the increased attention given to aircraft emissions at ground-level and air pollution in the vicinity of airports, many research gaps remain. Sources relevant to air quality include not only engine exhaust and non-exhaust emissions from aircraft, but also emissions from the units providing power to the aircraft on the ground, the traffic due to the airport ground service, maintenance work, heating facilities, fugitive vapours from refuelling operations, kitchens and restaurants for passengers and operators, intermodal transportation systems, and road traffic for transporting people and goods in and out to the airport. Many of these sources have received inadequate attention, despite their high potential for impact on air quality. This review aims to summarise the state-of-the-art research on aircraft and airport emissions and attempts to synthesise the results of studies that have addressed this issue. It also aims to describe the key characteristics of pollution, the impacts upon global and local air quality and to address the future potential of research by highlighting research needs.

1. Introduction

Among pollution issues, poor air quality attracts a high level of interest within the scientific community and engages public opinion because of the known relationship between exposure to many air pollutants and increased adverse short- and long-term effects on human health (e.g., Schwartz, 1997; Ayres, 1998; Brunekreef and Holgate, 2002; Kampa and Castanas, 2008; Maynard, 2009; Yang and Omaye, 2009; Rückerl et al., 2011). In addition, air pollution can seriously impair visibility (Hyslop, 2009), may damage materials in buildings and cultural heritage (Watt et al., 2009; Screpanti and De Marco, 2009) and has direct and indirect effects upon climate (Ramanathan and Feng, 2009). While air pollution remains a major concern for developing countries (Fenger, 2009; Liaquat et al., 2010) as a result of the rapid growth of population, energy demand and economic growth, developed countries have experienced a significant decline in the concentrations of many air pollutants over the past decade.

* Corresponding author. Current address: Department of Environmental Sciences/Center of Excellence in Environmental Studies, King Abdulaziz University, PO Box 80203, Jeddah 21589, Saudi Arabia.
E-mail address: r.m.harrison@bham.ac.uk (R.M. Harrison).

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List of abbreviations

AAFEX	Alternative Aviation Fuel Experiment
AEs	Airport emissions
APEX	Aircraft Particle Emissions eXperiment
APU	Auxiliary power unit
BC	Black carbon
C^*	Effective saturation concentration
CIs	Chemi-ions
CIMS	Chemical ionisation mass spectrometry
EC	Elemental carbon
EI	Emission index
EXCAVATE	EXperiment to Characterise Aircraft Volatile Aerosol and Trace-species Emissions
F_{00}	Engine thrust expressed as a percentage of maximum rated power
FGEP	Fixed ground electrical power
FSC	Fuel sulphur content
FT	Fischer–Tropsch fuel
GMD	Geometric number mean diameter
GPUs	Ground power units
GRPs	Ground running procedures
GSEs	Ground service equipments
ICAO	International Civil Aviation Organization
LTO	Landing and take-off cycle
OC	Organic carbon
NMHC	Non-methane hydrocarbon
NO_x	Nitrogen oxides ($NO + NO_2$)
NO_y	Reactive odd nitrogen (NO_x and their oxidation products)
OA	Organic aerosol
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate matter
PM_1	Particulate matter (aerodynamic diameter less than 1 μm)
$PM_{2.5}$	Particulate matter (aerodynamic diameter less than 2.5 μm)
PM_{10}	Particulate matter (aerodynamic diameter less than 10 μm)
RF	Radiative forcing
RPK	Revenue passenger kilometres
RTK	Revenue tonne kilometres
SARS	Severe acute respiratory syndrome
SIA	Secondary inorganic aerosol
SN	Smoke number
SOA	Secondary organic aerosol
SVOCs	Semi-volatile organic compounds
TC	Total carbon
TF	Turbofan engine
TIM	Time-in-mode
TJ	Turbojet engine
TP	Turboprop engine
TS	Turboshaft engine
UFP	Ultrafine particles (diameter <100 nm)
UHC	Unburned hydrocarbons
VOCs	Volatile organic compounds
ε	Abundance ratio (($\bullet SO_3 + H_2SO_4$)/total sulphur)
ξ	Partitioning coefficient

Airport emissions (AEs) have received increasing attention in recent years because of the rapid growth of air transport volumes and the expected expansion to meet capacity needs for future years (Amato et al., 2010; Kurniawan and Khardi, 2011; Kinsey et al., 2011). Most studies highlight knowledge gaps (e.g., Webb et al., 2008; Wood et al., 2008a; Lee et al., 2010) which are a matter of concern as the literature indicates that aircraft emissions can significantly affect air quality near airports (Unal et al., 2005; Carslaw et al., 2006; Herndon et al., 2008; Carslaw et al., 2008; Mazaheri et al., 2009; Dodson et al., 2009) and in their surroundings (Farias and ApSimon, 2006; Peace et al., 2006; Hu et al., 2009; Amato et al., 2010; Jung et al., 2011; Hsu et al., 2012). Emission standards for new types of aircraft engines have been implemented since the late 1970s by the International Civil Aviation Organization (ICAO) through the Committee on Aircraft Engine Emissions (CAEE) and the subsequent Committee on Aviation Environmental Protection (CAEP). One of the key actions of the ICAO committees was the provision on engine emissions in Volume II of Annex 16 to the Convention on International Civil Aviation, the so-called "Chicago Convention", which recommended protocols for the measurement of carbon monoxide (CO), nitrogen oxides ($NO + NO_2 = NO_x$), unburned hydrocarbons (UHC) and smoke number (SN) for new engines (ICAO, 2008). Standards were listed on a certification databank (EASA, 2013), which represents a benchmark for engine emissions performance and is used in many regulatory evaluations (ICAO, 2011). This regulation has produced significant improvements in engine and fuel efficiency and technical progress to reduce emissions. However, although these efforts have led to a substantial reduction in direct aircraft emissions over the past two decades, these gains may be offset by the forecast growth of the aviation industry and the resulting increase in airport traffic (ICAO, 2011). Furthermore, the ICAO regulation address only four main generic pollutants and a more detailed chemical and physical characterisation of exhausts is required to quantitatively and qualitatively assess aircraft emissions. An increasing number of studies provide a detailed chemical speciation for many exhaust compounds, including gases and airborne particulate matter (e.g., Anderson et al., 2006; Herndon et al., 2008; Agrawal et al., 2008; Mazaheri et al., 2009; Onasch et al., 2009; Herndon et al., 2009; Kinsey et al., 2011; Mazaheri et al., 2011; Santoni et al., 2011). However, the literature remains very sparse and many questions remain unresolved because of the large differences in measurement strategies, technologies and methods, compounds analysed and environments studied.

Aircraft exhausts are only one of several sources of emission at an airport (ICAO, 2011). Although exhaust plumes from aircraft engines were conventionally considered to account for most of the emissions, other sources are present within modern airports and contribute to air pollution at the local scale. Among these, tyre, brake and asphalt wear and the re-suspension of particles due to the turbulence created by the aircraft movements can account for large fractions of total particulate matter mass (e.g., British Airports Authority, 2006), but their chemical and physical characteristics have been investigated in only a few studies (Bennett and Christie, 2011; Bennett et al., 2011). Moreover, the emissions of the units providing power to the aircraft on the ground have received relatively little consideration despite their potentially high impact on the local air quality (Schäfer et al., 2003; Ratliff et al., 2009; Mazaheri et al., 2011). These units include the auxiliary power units (APUs), which are small on-board gas-turbine engines, and the ground power units (GPUs) provided by airports. In addition, airport ground service equipment (GSEs) further impact the air