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Review article

Human exposure to ozone in school and office indoor environments

Heidi Salonen[a,b,*,1], Tunga Salthammer[b,c,**,1], Lidia Morawska[b]

[a] Aalto University, Department of Civil Engineering, PO Box 12100, FI-00076 Aalto, Finland
[b] Queensland University of Technology, International Laboratory for Air Quality and Health, 2 George Street, Brisbane Q 4001, Australia
[c] Fraunhofer WKI, Department of Material Analysis and Indoor Chemistry, 38108 Braunschweig, Germany

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ABSTRACT

Background: Although it is recognized that ozone causes acute and chronic health effects and that even trace amounts of ozone are potentially deleterious to human health, information about global and local exposures to ozone in different indoor environments is limited. To synthesize the existing knowledge, this review analyzes the magnitude of and the trends in global and local exposure to ozone in schools and offices and the factors controlling the exposures.
Methods: In conducting the literature review, Web of Science, SCOPUS, Google Scholar, and PubMed were searched using 38 search terms and their combinations to identify manuscripts, reports, and directives published between 1973 and 2018. The search was then extended to the reference lists of relevant articles.
Results: The calculated median concentration of ozone both in school (8.50 μg/m^3) and office (9.04 μg/m^3) settings was well below the WHO guideline value of 100 μg/m^3 as a maximum 8 h mean concentration. However, a large range of average concentrations of ozone was reported, from 0.8–114 μg/m^3 and from 0 to 96.8 μg/m^3 for school and office environments, respectively, indicating situations where the WHO values are exceeded. Outdoor ozone penetrating into the indoor environment is the main source of indoor ozone, with median I/O ratios of 0.21 and 0.29 in school and office environments, respectively. The absence of major indoor ozone sources and ozone sinks, including gas-phase reactions and deposition, are the reasons for lower indoor than outdoor ozone concentrations. However, there are indoor sources of ozone that are of significance in certain indoor environments, including printers, photocopiers, and many other devices and appliances designed for indoor use (e.g., air cleaners), that release ozone either intentionally or unintentionally. Due to significantly elevated outdoor ozone concentrations during summer, summer indoor concentrations are typically elevated. In addition, the age of a building and various housing aspects (carpeting, air conditioning, window fans, and window openings) have been significantly associated with indoor ozone levels.
Conclusions: The existing means for reducing ozone and ozone reaction products in school and office settings are as follows: 1) reduce penetration of outdoor ozone indoors by filtering ozone from the supply air; 2) limit the use of printers, photocopiers, and other devices and appliances that emit ozone indoors; 3) limit gas-phase reactions by limiting the use of materials and products (e.g. cleaning chemicals) the emissions of which react with ozone.

1. Introduction

Ozone is an atmospheric trace gas with high oxidizing potential. Its presence is essential in the stratosphere but is undesirable in the troposphere because it can react easily with many compounds, thus generating oxygenated organic species and particles (Finlayson-Pitts and Pitts Jr., 2000).

Human exposure to ozone is primarily by inhalation, but reactions on skin are also reported (Weschler, 2016). Acute and chronic health effects and the contributions of ozone to morbidity and mortality are summarized in (WHO, 2006). More recent studies have shown that daily exposure to high levels of ozone may cause DNA damage, as previously reported for operators in photocopier centers (Kleinsorge et al., 2011; Manikandan et al., 2010; Mortimer et al., 2002). According to Nazaroff (2013), outdoor ozone is also a pollutant of special concern. Of particular importance is the exposure of children to ozone, as exposure could have lifelong consequences. Moreover, it is widely known that the physiology of children and adults is different. Although

* Correspondence to: H. Salonen, Aalto University, Department of Civil and Structural Engineering, PO Box 12100, FI-00076 Aalto, Finland.
** Correspondence to: T. Salthammer, Fraunhofer WKI, Department of Material Analysis and Indoor Chemistry, 38108 Braunschweig, Germany.
E-mail addresses: heidi.salonen@aalto.fi (H. Salonen), tunga.salthammer@wki.fraunhofer.de (T. Salthammer).
[1] These authors contributed equally to this work.

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children have higher air intake per kg of body weight, their airways are narrower, which makes them potentially more vulnerable to air pollutants (Moya et al., 2004). According to the U.S. Environmental Protection Agency, EPA (2017), long-term exposure to higher concentrations of ozone may be linked to permanent lung damage (e.g., abnormal lung development in children). Further, ozone has been associated with school absenteeism due to respiratory illnesses, medication use, respiratory problems associated with asthma, decreased respiratory functions, and increased hospital admissions for asthma (Demirel et al., 2014; Gilliland et al., 2001; Lee et al., 2004; Lin et al., 2008; McConnell et al., 2002; Penard-Morand et al., 2005; Romieu et al., 1992; Sheffield et al., 2015). It has been estimated that a 10 μg/m^3 increase in 1 h maximum ozone leads to a grand mean of 0.21% increase in mortality, without controlling for other air pollutants (Levy et al., 2005).

In the urban atmosphere ozone is formed by reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) with short atmospheric lifetimes in the presence of sunlight (Seinfield and Pandis, 2016). Outdoor air is the most common source of ozone in indoor air (EC, 2006), and it has been estimated that, depending on the air exchange rate and ozone removal rate, indoor ozone concentrations are 30%–70% of outdoor levels (Weschler and Shields, 1999) when specific indoor sources (e.g., air purifiers, laser printers, photocopiers) are not present (Nicolas et al., 2007). Fig. 1 provides an overview of the key factors and processes affecting indoor ozone concentrations.

In general, it is more challenging to control outdoor ozone than other outdoor air pollutants because it is a secondary pollutant and its formation processes depend not only on the availability of precursors but also on other factors, such as region, season, and time of day (Finlayson-Pitts and Pitts Jr., 2000). In order to protect human health the World Health Organization (WHO) has provided a guideline value of 100 μg/m^3 as the maximum 8 h mean ozone concentration (WHO, 2006). Governmental organizations have issued various of recommendations or standards for outdoor air ozone. In Europe, 120 μg/m^3 (8 h average, allowing 25 exceedances per year) is the reference value, and 240 μg/m^3 (1 h average) is the alert threshold (E.C. Ozone Directive, 2016). In the United States, the National Ambient Air Quality Standard (NAAQS) for ozone is 0.070 ppm (8 h average) (US EPA, 2018). In Australia, the National Air Quality Standard for ozone is 0.08 ppm (4 h average) (Australian Government, 2018). For residential indoor air, Health Canada set an 8 h average of 40 μg/m^3 (Health Canada, 2010). Unlike other air pollutants the concentrations of which have been decreasing, ozone concentrations worldwide are either decreasing much slower, are remaining unchanged, or are even increasing, despite the efforts to control them (Abeleira and Farmer, 2017; Karlsson et al., 2017; Stowell et al., 2017; Wang et al., 2017). The increase could be a baseline or seasonal increase or an increase in the frequency and magnitude of high ozone episodes. This is due to changes in the types and concentrations of precursor compounds that influence the pathways and kinetics of atmospheric chemistry. Fisk (2015) projected that climate change-related increases in ozone—which are due to changes in air movement, cloud cover, humidity, and the emission rates of reactive VOCs and NO_x —will result in substantial adverse health effects. Based on the available evidence, this is to a great extent a consequence of indoor exposures. Fann et al. (2015) analyzed scenarios for the United States and concluded that climate change will support an increase in ambient ozone levels until 2030. Melkonyan and Wagner (2013) provide a similar projection for Germany.

While ozone is a concern in any type of indoor environment, it is of particular significance in schools and offices. The similarity between these environments is firstly in that children spend a good part of the day at school, and a large fraction of the adult population in urbanized countries spend many hours a day in an office environment. Therefore, it is of great importance to ensure that classrooms and offices are safe, healthy environments (Salthammer et al., 2016). Secondly there is a similarity in when these environments are occupied, which is during daytime when the outdoor ozone concentrations are the highest and hence their impact on indoor concentrations, particularly in schools and offices. There are also differences within these two types of environments and between them. For example, office tend to be more often mechanically ventilated than schools, however, there schools, which are mechanically ventilated and offices, which are naturally ventilated. However, to date there has been little focus on indoor ozone in schools and offices, with most published studies concentrating on carbon dioxide, organic compounds, or particles. Therefore, the aim of this work was to assess the magnitude and trends of global and local exposure to ozone in schools and offices and the factors controlling that exposure, based on published literature. Our specific objectives were to: (i) assess the concentrations and exposures occurring indoors; (ii) conclude on the apportionment between outdoor air as a source and indoor source contribution; (iii) review the new ozone generating devices available on the market and the patterns of their usage (e.g., in different countries by different population groups); and (iv) make recommendations about mitigating indoor ozone.

2. Material and methods

A Web of Science, SCOPUS, Google Scholar and PubMed search of

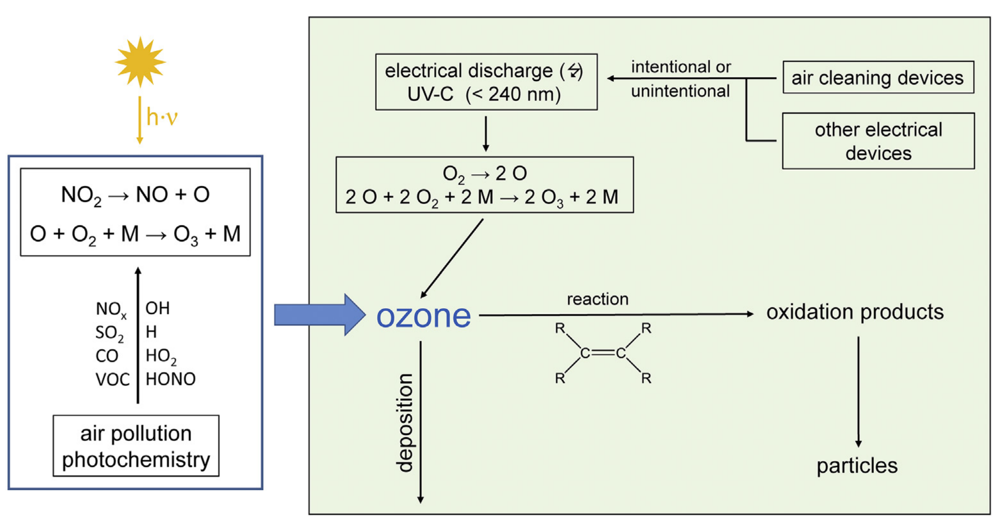

Fig. 1. The key factors affecting indoor ozone concentrations, including ozone infiltration from outdoors, emissions from indoor sources, deposition (e.g., surface removal), and chemical reaction (e.g., with unsaturated hydrocarbons).