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The Uncertainties of Ground-Level Emission Estimates at Airports, from an Operational and Interdisciplinary-to-Transdisciplinary Standpoint

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Abstract: Air quality issues are of remarkable interest due to the relevant number of people affected; in the case of ground-level aviation emissions many inventories exist but several degrees of uncertainty, mostly related to the intrinsic variability of aircraft operations and environmental factors, can be highlighted. Via an interdisciplinary-to-transdisciplinary approach accounting for various disciplines, such as Atmospheric Physics, Earth Sciences and Aeronautical procedures, this research paper provides a new insight on the above mentioned uncertainties and calls for more attention be focused on airport air quality measurements and evaluations.

Keywords: airport air quality; environment; human health; emission estimates; airports; aircraft operations; ground handling

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Introduction

Air quality-related issues are at times *en pair* with the major issue of climate change, which has effectively become a core aspect of politics, policies, society, and economics. Though climate altering agents such as carbon dioxide (CO_2) and methane (CH_4) are distinct from *sensu stricto* pollutants hazardous for humans, both topics are now of concern. Moreso, climate-altering agents such as CO_2 and CH_4 do pose a safety hazard the moment the increase in temperatures also affects safety in contexts such as workplaces and cities, potentially resulting in more annual deaths attributable to heat waves. Airplanes are generally regarded as relevant sources of emissions, though they only account for about 3.1% of anthropogenic fossil fuel combustion CO_2 emissions on a global scale, according to an estimate on 2019 traffic by the International Energy Agency (IEA), released in 2022[1]. Aviation-related CO_2 emissions are of popular concern mostly due to the high emission-to-passenger ratio compared to other means of transportation, such as railway systems, as well as the perception of air travel of some sort of "luxury" service, especially when it comes to short routes. In the era of social media, it's not uncommon to see VIPs and other popular figures being criticized for the frequency by which they rely on air transportation instead of its "greener" alternatives.

For many reasons, airports are generally subject to monitoring campaigns meant to assess the extent of emissions, especially on a ground-level basis. The International Civil Aviation Organization (ICAO) has in fact issued the Airport Air Quality Manual[2], a key official document meant to address the issue and provide details on how such monitoring efforts are performed. This manual will be referenced many times in this research paper as AAQM.

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[1] International Energy Agency (IEA) (2022). *Aviation*.

[2] International Civil Aviation Organization (ICAO) (2020). Doc 9889, *Airport Air Quality Manual*. ICAO, Montreal.

As evidenced by the AAQM document, air quality concerns are integrated into a much wider context of rising pressure on the world of aviation due to its environmental impact. The pressure includes, but is not limited to, issues such as aviation noise and the need to reduce aviation-related emissions via the introduction of Sustainable Aviation Fuel (SAF), as well as the effective banning of short air routes which can be replaced by trains and comparable transportation services. Such bans are already in effect in several countries, and even more countries are expected to join them soon; however, the bureaucratic measures of influencing the free market via bans have met their intrinsic contradictions during the Covid-19 pandemic, when airlines were forced to operate nearly empty flights because doing so would have ensured the legal preservations of slots. This example, though referred to a rather unique scenario, still highlights very well the odds of dealing with bureaucracy when it comes to the aviation market. Yet still, with the *datum* and premise of environmental concerns and comparable issues, aviation is a key tool for the economy and its efficiency is particularly remarkable in long-haul routes, where even the best alternatives would require travel times one or two orders of magnitude greater than those ensured by commercial aircraft, if not more. Aviation is therefore meant to stay, improve and adapt, and its persistence goes with a reasonable tradeoff between its conspicuous advantages and its drawbacks, with air pollution being one of them[3].

Airports tend to vary a lot in terms of age: some have been built very recently, others will be built in the future, and a significant fraction of them are pretty much historical as they have been serving their respective cities for nearly a century, ever since the early days of commercial aviation. This clearly indicates that urbanization increase in developing and developed countries may imply a geographic "annexation" of airports into urban and suburban areas as they grow, and ICAO itself reports that the airports themselves may also drive such urbanization processes around them. In addition to this, as air traffic has been on a nearly constant rise for decades, the exposure of urban areas to ground-level emissions related to aviation, as well as noise, has also increased. Notable urban areas, hereby not mentioned for the sake of conciseness, have experienced – and are still experiencing – active protests (in the form of sit-ins, petitions, political pressures, *etc*.) against their local airports that oftentimes result into growing social pressure towards a different management of the airports themselves, or even their closure in favor of airports located elsewhere. The geographic proximity of growing urban areas around airports is a driving factor of major restrictions, such as enforced airport closure times, specific maneuvers that need to be performed upon take-off, *etc*. In purely aeronautical terms, among the keys to noise abatement are the early retraction of flaps, steeper climb profiles and reduce thrust take-offs, though obviously they cannot be employed at all times, and do not nullify noises completely.

As a strategic infrastructural system, an airport shows multiple sources of emissions, ranging from the aircraft themselves to Ground Service Equipment (GSE), vehicular traffic and airport terminal building-related emissions. According to the AAQM, regulations on these sources may vary considerably depending on the country or state, thus adding more degrees of variability in a market that is perhaps among the most homogeneous ever (aircraft essentially operate in the exact same ways all over the world). That said, there are international standards on aircraft emissions, and new lines of aircraft such as the Boeing B737 MAX series and Airbus A320 family NEO variants set the fundamentals of their market on lower fuel consumption and, as direct consequence, lower emissions per passenger carried. The focus on low consumption is such that it has gained priority over reducing travel times – in the case of the MAX series, Bowed Rotor Motoring (BRM) lengthens the engine startup sequence by several minutes, and consequently results into longer travel times as well as higher chances of delays. However, this is deemed a necessary tradeoff as the reduced fuel consumption (and costs) are more valuable than mere minutes of travel time being gained.

Speaking or air quality and emission concerns as seen across the globe, it's worth noting that regulations not only may vary in terms of actual thresholds, but also show an intrinsic variability in terms of which compounds are more likely to be subject to said regulations, and the restrictions that

[3] Grobler, C.; Wolfe, P.J.; Dasadhikari, K.; Dedoussi, I.C.; Allroggen, F.; Speth, R.L.; Eastham, S.D.; Agarwal, A.; Staples, M.D.; Sabnis, J.; Barrett, S.R.H. (2018). *Marginal climate and air quality costs of aviation emissions*. Environmental Research Letters 14, 114031.

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come with them: in the case of nitrogen oxides in the atmosphere, which are one of the products of aviation-related emissions, there are two different takes reported between the United States of America and the European Union. US regulations are apparently focused on NO_x releases and their effects on increased tropospheric ozone (O_3) levels, while in Europe countries seem more likely to focus their regulations on NO_2. In the fields of Atmospheric Physics and Chemistry, in fact, several proximity indicators of sources (broad estimates on the distance between detection points and emission areas) are based on NO_x/NO_2 and O_3 ratios, as well as correction methods such as those suggested by Steinbacher et al. (2007)[4].

The World Health Organization (WHO) also has its own take on the issue, in the form of actual guidelines released globally. Speaking of NO_2, the hourly guideline for this compound is 200 $\mu g/m^3$ (micrograms per cubic meter), while regional guidelines are in the 75-400 $\mu g/m^3$ range, as highlighted by the AAQM. WHO guidelines also address particulate matter equal or smaller than 10 microns, the so called "PM10" category of particulates: the WHO has set a guideline value of 50 $\mu g/m^3$ while regulators across the world operate in the 50-150 $\mu g/m^3$ range. Surprisingly, the AAQM highlights one regulation gap in global guidelines, which is one of the key aspects of this research paper: in the case of O_3, the WHO reportedly has no hourly or daily guideline, though it set an 8-hour guideline of 100 $\mu g/m^3$ while regulators across the world are in the 100-160 $\mu g/m^3$ range. This is indeed a remarkable example of a major entity in the context of health policies and health hazards not providing a reasonable hourly value around which local regulators can build their own restrictions and guidelines.

With respect to the main engine emission standards issued by ICAO, which are also highlighted in the AAQM, they're applied for certification at various scales from the national to multi-national level and aimed at turbofan/turbojet engines capable of more than 26.7 kN (kilonewton) of thrust, but even according to the AAQM itself they're not applied to turboprops, turboshafts, piston engines, or Auxiliary Power Units (APU) installed on aircraft. What's remarkable about the standards mentioned above is that they set the fundament for the broader assessments of air quality: in fact, these standards are based on the uninstalled engine performance as measured against a LTO (landing and take-off) cycle up to a threshold of 3000 ft AGL (feet Above Ground Level), equivalent to 915 meters AGL. The ICAO standards are indeed based on uninstalled engine performance measured against an idealized landing and take-off (LTO) cycle up to 915 m (3 000 ft) above ground level (AGL). It is also recognized by ICAO itself than even though these values are widely used, notable variations driven by environmental- and operational-specific situations do occur, and regulators and encouraged to work on more accurate assessments. The fact that even ICAO itself would provide a generic recommendation on how to go beyond standardized values, and the fact that national regulators may then issue various thresholds despite aviation being a market known for operating pretty much the same way across the globe, is itself another evidence pointing in the direction of subtle gaps in this field (though, from a legal standpoint, national regulations are legitimately recognized by both international and national laws and this paper doesn't question their legal validity).

After these remarks, an enormous gap in assessments addressing these thresholds could be assumed, but it's not actually the case: by its very nature as an international market, aviation does have many regulations deemed applicable on a global basis, such as the standards developed in the context of the Committee on Aviation Environmental Protection (CAEP) which were later implemented by the ICAO Council. Following the first regulation on emissions issued by ICAO in 1981, relevant updates have been released over the years: CAEP/2, in 1993; CAEP/4, in 1999; CAEP/6, in 2005; CAEP/8, in 2011. It's worth noting that the release of new CAEP issues has accelerated over time, perhaps as result of more pressure – of both social and political nature – on environmental issues. As stated before, the global reference is a LTO cycle up to 915 meters, equal to 3000 feet (from now on, 915m/3000ft) in altitude above the ground level of the runway. The engine standards focus

[4] Steinbacher, M.; Zellweger, C.; Schwarzenbach, B.; Bugmann, S.; Buchmann, B.; Ordóñez, C.; Prevot, A.S.H.; Hueglin, C. (2007). *Nitrogen oxide measurements at rural sites in Switzerland: Bias of conventional measurement techniques*. Journal of Geophysical Research 112(D11): 307.

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on CO (carbon monoxide), HC (hydrocarbons) and the already mentioned NO_x as compounds of concern; this will be better described in the second section of the paper. CO is known as a byproduct of combustion in a number of anthropic activities, and the same principle is applied to hydrocarbons, though many of them vary a lot in terms of nature and characteristics.

Of particular importance are regulatory restrictions that became more and more strict over time. In the case of NO_x, it is reported that between 1981 and recent years, emission standards were constrained by approximately 50% (regulations introduced, for instance, by the CAEP of 1993, 1996, 1999, 2005, and 2011 gradually increased these restrictions, and nothing has gone in the opposite direction). These restrictions – which took place step by step, accounting for the time and tests required to certify newly produced engines – were also largely driven by technological breakthroughs allowing fewer NO_x outputs, though the actual interaction of released compounds in the atmosphere and other pollutants or agents of climate change poses several side-challenged which will be addressed later in the paper.

Aircraft aside, vehicles operating at airports, such as the GSE mentioned before as well as many other vehicles serving a variety of purposes, are also now subject to a number of restrictions based on the category they fall into. The two broader families used for this very purpose group vehicles by "duty" (heavy or light, also called off-road and on-road, respectively). It is reported that certain GSE are classified as "non-road mobile machinery", depending on whether their use involves roads or not. In addition to vehicles that are specifically developed and built for aircraft assistance, a variety of regular vehicles such as fire trucks also operate in the environment of an airport and are subject to standard regulations on emissions applied on a nation-wide scale.

Overall, aviation operates in an international scenario where procedures applicable on a global scale in terms of pure air traffic management oftentimes combine with heterogeneous regulations on emissions, which evolve in a dynamic context and are subject to changes over time. However, the issue of air quality (which doesn't necessarily match that of pure emissions) underlines a number of major uncertainties this paper is set to address in the next section.

Evaluation

The AAQM provides a full list of categories by which airport emissions are grouped, each representing a specific operational scenario as well as a number of subcategories. The categories are: 1a) aircraft main engine; 1b) Auxiliary Power Unit (APU); 2a) Ground Support Equipment (GSE); 2b) Airside air traffic of vehicles such as cargo loaders; 2c) Aircraft refueling, in the form of evaporation through fuel tanks/vents, trucks, and pipeline systems; 2d) De-icing and anti-icing substances during the winter season, in particular during snowstorms; 3a) Sources related to the main airport infrastructures, such as cooling and heating plants; 3b) Emergency power generators, such as those ensuring that runway lights can operate even in the case of power shortages; 3c) Activities and facilities related to the maintenance of aircraft, such as engine test beds, and washing; 3d) Activities focused on the maintenance of airport facilities and equipment; 3e) The storage, handling and distribution of fuel; 3f) Construction activities connected to the development of an airport; 3g) Activities related to fire training with various types of fuel; 3h) Surface de-icing, this time applied to the infrastructure, with a focus on access roads; 4a) Vehicle traffic linked to the airport as a whole, accounting for curbsides, drive-ups, parking lots, *etc*. Though it is believed by the author that any estimate on these emission categories is grossly challenged by uncertainties, this paper will address the issues related to specific disciplines and their fields.

In the simplest scenario, a given airport has one runway (intended as an actual linear infrastructure) which in turn has two bearings, identified by QFU (Magnetic bearing of the runway in use). The bearing identifies the orientation of the runway, RWY from now on, with respect to the magnetic north pole, divided by a factor of 10 (*e.g.*, 30 for 300 °N); the two headings have a 180° difference from each other. Other, more articulated scenarios with parallel runways having the same orientation would introduce the identifiers L and R (Left and Right, respectively) to differentiate them, but these examples are now ignored for the sake of conciseness. Airport runways are not built at random, as they are the result of studies on local wind circulation meant to ensure the safety of air traffic on the principle by which both take-offs and landings need to be performed against the wind: this leads to a very important assumption by which the local influence of emissions is distinct from contributions to the global output. In fact, local emissions (intended as those affecting the airport workforce and nearby suburbs) should take in consideration wind speed and direction, while 100% of the emission output does however add up to total atmospheric pollution levels. Moreso, this should at least indicate that emission outputs related to take-off and landing maneuvers are concentrated on an axis that is coincident with the runway in use, plus a buffer zone accounting for high pollutant concentration levels, which would then be reduced as the distance from the axis increases: it doesn't seem the case, however, of the main state of the art on the literature of the field, as classifications are performed on a per radius basis that – for example – attributes the label of "near-airport" range category to everything located in a 10-kilometer radius from the airport itself, a range deemed of particular attention in terms of health hazards, as reported by both Carslaw et al. (2006)[5] and Carslaw & Beevers (2013)[6]. In fact, many annual deaths caused by a number of diseases linked to air pollution are attributable to people either living or spending working hours within this radius.

The point is that wind circulation, broadly characterized by the key parameters of wind speed (WS) and wind direction (WD), does influence the transport of pollutants on local to large scales. Models such as NOAA's (National Oceanic and Atmospheric Administration) HYSPLIT[7] (Hybrid Single-Particle Lagrangian Integrated Trajectory) allow to backtrack – or even make short-term future predictions – based on these wind parameters and are frequently used to monitor the distribution of pollutants that follow major events, such as large wildfires. The introduction of WS and WD (plus their intrinsic variability over time, linked to synoptic atmospheric circulation), even if fully integrated with air traffic below 915m/3000ft, does pose new challenges in the correct estimation of local pollutants caused by aircraft: one rather uncommon exception, though worth a mention due to its implications, is the Circle-To-Land procedure by which an aircraft would approach a given airport for landing, then perform a short turn (normally a left turn, according to the Rules of the Air), reach the other side of the aerodrome and land on the opposite RWY. Such a landing pattern completely invalidates any local scale pollution distribution model, as the sources of emission throughout the entire maneuver (hereby intended as points in space, the engine exhausts) follow a completely different path, and at different altitudes/orientations, each with different WS/WD parameters (especially the former, which is notoriously dependent on altitude). Moreso, at the time of writing there's no tangible evidence that such landing procedures are tracked and a recorded in a nation-wide or international database, open to researchers and their institutions, up to a point that could be used to provide reasonable pollution estimates on a local scale. Even the emission estimate on an absolute scale, in this case, is challenged by different flight times (a Circle-To-Land maneuver and a standard landing are likely to be performed with different timing and fuel consumption settings). As said before, the Circle-To-Land scenario may be regarded as a rare circumstance, but it's worth noting that training procedures performed by military airplanes of various air forces operating at commercial airports follow a similar pattern several times in a row during each training session and the exercises themselves frequently involve large airplanes with remarkable emission outputs. These odds may be considered an example of "Missing information" as intended by the AAQM: inventories not fully integrated with air traffic control, local civil aviation authority records and precise meteorological stations would systematically fail to account for these non-standard maneuvers.

In addition to the challenges posed by local pollution and emission estimates, even the accounting of released compounds itself is challenged by intrinsic degrees of uncertainties: at the

[5] Carslaw, D.C.; Beevers, S.D.; Ropkins, K.; Bell, M.C. (2006). *Detecting and quantifying aircraft and other on-airport contributions to ambient nitrogen oxides in the vicinity of a large international airport*. Atmospheric Environment 40, issue 28, pgs. 5424-5434.

[6] Carslaw, D.C. & Beevers, S.D. (2013). *Characterising and understanding emission sources using bivariate polar plots and k-means clustering*. Environmental Modelling & Software 40, pgs. 325-329.

[7] Stein, A.F.; Draxler, R.R; Rolph, G.D.; Stunder, B.J.B.; Cohen, M.D.; Ngan, F. (2015). *NOAA's HYSPLIT atmospheric transport and dispersion modeling system*. Bulletin of the American Meteorological Society 96, pgs. 2059-2077.

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time of writing, in fact, there are no comprehensive and detailed data on specific methane releases by aircraft that could be used to provide adequate assessments. Methane (CH_4), though not a pollutant *per se*, is a potent GHG (greenhouse gas) due to its global warming potential (GWP) exceeding that of CO_2 by nearly two orders of magnitude over the time period of two decades and is nearly 30 times higher over the course of a century[8]; despite this, methane levels in the atmosphere are about 200 times lower than those of CO_2, thus making carbon dioxide the biggest threat to climate (this compound also tends to persist in the atmosphere for longer periods of time, potentially one millennium, so that's why it's currently the focus of social, political and economic debates). Unlike carbon dioxide however, methane has showed degrees of variability (both in terms of global growth rates and carbon isotope fractionation, the latter being a characteristic that will be described later on in this section) which have a now confirmed influence on social sciences such as Sociology and Psychology, as evidenced by an earlier study[9] analyzing the side-effects of a complex compound when it comes to climate change communication and its numerous implications for present day society.

Prior to the analysis of engine emissions, in this context is deemed relevant to make a number of references to the Covid-19 pandemic and the consequent collapse of commercial aviation that followed, in particular with respect to the complexity of atmospheric chemistry it allowed to highlight. Globally, the disruption of aircraft operations resulted in notable atmospheric NO_x reductions which are well documented, and totally compromised long term predictions on worldwide air traffic growth, such as the environmental trends to 2050 by Fleming & de Lepinay (2019)[10] issued just one year prior to the pandemic. It's worth noting that research on the effects of aviation on climate change showed spatial variations depending on where operations occur, so the net effects may change locally; several uncertainties in estimations have been highlighted too[11]. Air traffic reductions related to the Covid-19 outbreak are perhaps the most documented reduction of human activities during that period, as others would be subject to gross uncertainties; therefore, airports may be considered a good environmental indicator for the major lockdowns that took place all over the world. Recent models created by Lee et al. (2021)[12] reported baseline values for methane radiative forcing sensitivity to aviation NO_x emissions, a result that was converted by Stevenson et al. (2022)[13] to a sensitivity of methane to a pulse change in aviation NO_x emissions of 1.12 ppb (parts per billion) (CH_4)/Tg(NO_2)yr^{-1}. These estimates indicate a tangible influence of NO_x emissions

[8] Myhre, G.; Shindell, D.; Bréon, F.M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.F.; Lee, D.; Mendoza, B.; Nakajima, T.; Robock, A.; Stephens, G.; Takemura, T.; Zhan, H. (2013). *Anthropogenic and Natural Radiative Forcing*. In: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York.

[9] D'Amico, F. (2023). *The "methane problem" as an ongoing challenge to climate change communication and understanding. When data estimate uncertainties become a social uncertainty*. Rivista internazionale di sociologia giuridica e diritti umani vol. 6, pgs. 81-96.

[10] Fleming, G. & de Lepinay, I. (2019). *Environmental Trends in Aviation to 2050*. In: ICAO Environmental Report, 2019 Destination Green the Next Chapter. International Civil Aviation Organization. ICAO, Montreal.

[11] Holmes, C.D.; Tang, Q.; Prather, M.J. (2011). *Uncertainties in climate assessment for the case of aviation NO*. Proceedings of the National Academy of Sciences 108 (27), pgs. 10997-11002.

[12] Lee, D.S.; Fahey, D.W.; Skowron, A.; Allen, M.R.; Burkhardt, U.; Chen, Q.; Doherty, S.J.; Freeman, S.; Forster, P.M.; Fuglestvedt, J.; Gettelman, A.; DeLeón, R.R.; Lim, L.L.; Lund, M.T.; Millar, R.J.; Owen, B.; Penner, J.E.; Pitari, G.; Prather, M.J.; Sausen, R.; Wilcox, L.J. (2021). *The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018*. Atmospheric Environment 244, 117834.

[13] Stevenson, D.S.; Derwent, R.G.; Wild, O.; Collins, W.J. (2022). *COVID-19 lockdown emission reductions have the potential to explain over half of the coincident increase in global atmospheric methane*. Atmospheric Chemistry and Physics 22, 14243–14252.

dropping to CH_4 levels, in accordance with past research from over a decade before. The broad effects of NO_x are such that recent research proposed a reduction of these emissions as more favorable compared to a slight increase in CO_2 emissions, a result that is hereby showed to demonstrate how the driving mechanisms of climate change and atmospheric pollution oftentimes rely on an intricate set of interactions between compounds, and the release (or increase) of certain emissions should not be regarded as an independent parameter. The climate altering balance tradeoff proposed by this research could eventually spark new advances in the development of sustainable fuels.

Speaking of methane, aircraft engines are confirmed to release certain quantities of this compound during idle, taxi, take-off, approach, and cruise phases, and its role in climate change is considerable, as remarked by Lee et al. (2009)[14] and other research teams. In general, with all released compounds considered, the climate change potential of aircraft is also related to side effects such as contrails, as reported by Burkhardt et al. (2010)[15] and others. Research on such impact has been performed in areas where domestic traffic is very heavy, such as the United States of America. Research on the local impact of air traffic on the environment is generally focused on LTO cycles, in accordance with the AAQM, while research on broader effects of air traffic also considers cruise phases[16]. In Europe, the currently available databases issued by regulators such as EASA[17] on air transportation safety and environmental impact use "HC" as a generic parameter for released hydrocarbons that includes, but is not limited to, methane. The parameters used by EASA provide information on the grams (g) of HC released per kilogram (kg) of fuel during different phases based on an Emission Index (EI), and they do so on a per-engine basis; for instance, a HC EI Idle (g/kg) of 4.6 for the CFM56-5B7/P engine, which is now out of production, indicates an emission of 4.6 grams of hydrocarbons per kilogram of fuel consumed when the engine is set to idle, a condition typical of the engine startup sequence, which normally lasts several minutes and precedes the taxi procedure, as well as holdings on ground due to nearby aircraft movements. Directives on airport air quality do specify "NMHC" (Non-methane Hydrocarbons) as released pollutants, but they're not quantified in EASA reports on engine outputs, thus making methane impossible to factor out by subtracting NHMC from HC data.

That said, before addressing into the detail the odds of several emission estimate uncertainties with respect to engine outputs, it's worth explaining what the main AAQM (and, consequently, ICAO) directives on engine emissions are based on in terms of computations. As per the referenced document, these emissions depend on three key parameters, which are Time-In-Mode (TIM), the Emission Index (EI) already mentioned before, and fuel flow through the main engine. Extra parameters include fleet sizes and types, as well as the number of operated aircraft movements, which both propagate the low-end values to higher scales, depending on traffic intensity. TIM is essentially the time period in minutes that satisfies the specific conditions by which the engines are operating at a given setting. The EI, as stated before, provides a value representing the mass of pollutant that is released per unit mass of fuel burned, classified by compound or category of compounds (NO_x, CO, and HC – note again how hydrocarbons are grouped into one category). A multiplication between the mode-specific EI and TIM-specific fuel flow results into the estimation of units of grams of pollutant per LTO. Consequently, modal emissions for a given aircraft *plus* engine combination are equal to TIM multiplicated by the amount of fuel used at a given power level, which is then multiplied by the EI (also at the related level), and the number of engines on the aircraft, which is generally equal to two. Inventories based on these methodology approaches are grouped by levels

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[14] Lee, D.S.; Fahey, D.; Forster, P.M.; Newton, P.J.; Wit, R.C.N.; Lim, L.L.; Owen, B.; Sausen, R. (2009). *Aviation and global climate change in the 21st century*. Atmospheric Environment 43, pgs. 3520–3537.

[15] Burkhardt, U.; Kärcher, B.; Schumann, U. (2010). *Global Modelling of the contrail and contrail cirrus climate impact*. Bulletin of the American Meteorological Society 91, pgs. 479–484.

[16] Yim, S.H.L.; Lee, G.L.; Lee, I.H.; Allroggen, F.; Ashok, A.; Caiazzo, F.; Eastham, S.D.; Malina, R.; Barrett, S.R.H. (2015). *Global, regional and local health impacts of civil aviation emissions*. Environmental Research Letters 10, no. 3, 034001.

[17] European Aviation Safety Agency (EASA) (2023). ICAO Aircraft Engine Emissions Databank (06/2023).

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of detail and range from “simple” to “sophisticated”, with “advanced” being the intermediate tier. “Hybrid” models combining characteristics of more than one approach exist, though the AAQM warns on a *caveat* when it comes to relying on such models.

Speaking of the accuracy of these estimates, a precise calculation of HC values emitted by aircraft movements and related activities would be nearly impossible to achieve: HC values are engine, not aircraft specific, and even in the context of the same commercial operator, aircraft of the same type such as the Airbus A320 may have different engines mounted on them, so the analysis may have to be performed on a per-airplane basis, and precise registrations or tail numbers of aircraft are no longer available in the records after a given amount of time, which is normally two years. Even if they were available, these estimations would not take into account the emissions caused by ground equipment and vehicles which rely on regular fuel whose combustion does release quantities of methane (*e.g.*, Ground Power Unit or GPU, Air Starter Unit or ASU, Air Conditioning Unit or ACU), which themselves are various in nature depending on the aircraft’s technical conditions during transit (*e.g.*, a faulty Auxiliary Power Unit or APU would require the GPU and ASU be employed), airline, cargo loads (*e.g.*, cargo on commercial aircraft requires extra personnel and equipment for unloading/loading), aircraft type (*e.g.*, turboprop planes like the Bombardier Dash Q-400 require the GPU be connected during the first phase of engine start), PRM figures (Passengers with Reduced Mobility who require *ad hoc* equipment and vehicles for disembarkation and boarding), logistics and infrastructure (*e.g.*, remote stands require personnel and passengers be transferred via ground vehicles, instead of walking) and so on. As per the AAQM, these would all qualify as “Missing information” on local emissions: the absence of a precise log on these activities, as well as their integration with meteorological data, would lead to these emissions being ignored by inventories.

In purely operational terms, records do not provide precise information on the duration of engine running periods on ground, as on-block and off-block times may diverge from them depending on airline-specific operating procedures, technical issues, and operational ACARS (Aircraft Communication Addressing and Reporting System) devices. In this study, it is concluded that a precise estimation of emissions from aircraft, ground equipment and vehicles is not possible.

A case could be made that the integration of airports with advanced air quality and emission monitoring instruments, placed at key locations to cover most of the traffic or at least the most notable influence of local traffic, could at least overcome the reported uncertainties via quantitative data. Such monitoring efforts could indeed provide relevant information should certain thresholds be crossed for N hours, but even in this case the uncertainties would be gross: unless the airport is built far away from its respective city, pollution levels would be affected by nearby industrial and urban activities, and even in the case of airports located far from urban/industrial areas, any spike detected at a given moment may not be necessarily connected to air traffic (wildfire and landfill emissions result into notable peaks, just to report two examples)[18]. A possible solution would be an integrated monitoring system accounting for carbon isotopes, relying on the VPDB standard (Vienna Pee Dee Belemnite[19], the shell of a Late Cretaceous belemnite cephalopod) to detect deviations from the 0‰ (*per mille*) value of both CH_4 and CO_2, the so defined δCH_4 and δCO_2 (delta C) parameters. However, not only are these instruments very expensive to implement – even the main atmospheric monitoring stations lack a total coverage of carbon isotope data on the atmosphere, so the extension of said network to airports would be a challenge under several points of view – but any detection at an airport would have to be reanalyzed and validated in order to consider observed δCO_2 and δCH_4 values attributable to natural processes, as well as anthropic processes distinct from aircraft emissions. A possible solution would be the integration of ^{14}C (carbon-14) measurements as an

[18] Akagi, S.K.; Yokelson, R.J.; Wiedinmyer, C.; Alvarado, M.J.; Reid, J.S.; Karl, T.; Crounse, J.D.; Wennberg, P.O. (2011). *Emission factors for open and domestic biomass burning for use in atmospheric models*. Atmospheric Chemistry and Physics 11, issue 9, pgs. 4039–4072..

[19] Craig, H. (1957). *Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide*. Geochimica et Cosmochimica Acta 12, issues 1–2, pgs. 133-149.

indicator of fossil versus present-day sources:[20] due to its radiogenic nature, ^{14}C tends to decay over the course of thousands of years, up to the point where it becomes nearly impossible to detect (this normally occurs after the equivalent of ten half-times, which are equivalent to approximately 57300 years – modern technology fails at detecting ^{14}C past this threshold). Fossil fuels, which are much older than that (their age is in the range of several dozen millions of years, at times hundreds of millions of years) are depleted in ^{14}C; with adequate analysis, it's therefore possible to distinguish CO_2 peaks derived, for instance, from a wildfire affecting modern plants from the CO_2 released by aviation emissions, which relies on fuel totally depleted in ^{14}C. A continuous, integrated analysis accounting for all three main carbon isotope compounds would provide strategic details, except it's not impossible to implement with present-day technologies: standard δCO_2 measurements are still in their implementation phase throughout international networks of atmospheric monitoring, and ^{14}C evaluations require samples be collected and sent to laboratories for precise analyses, thus making a coordinated and instantaneous integration between the two methods all but impossible at this point. In addition to that, the AAQM does not include any mention of carbon isotopes as tools to differentiate emission sources around airports as guidelines for air quality indicators, and the broader academic research is lacking with respect to that, so standards and guidelines may have to be developed first. At the time of writing, in fact, not a single comprehensive study on a notable-scale employment of such standards with respect to ground-level aviation emissions has been reported.

If these extra technologies were to be implemented one day, depending on operating costs, human resources and instrument availability, they could mitigate "Error estimations" as intended by the AAQM when it comes to emission inventories. According to the document, these errors are divided into the subcategories of Measured, Calculated, and Estimated: the efficient integration of advanced atmospheric analyses, combined with meteorological and ATC data, could not only mitigate errors affecting inventories but could also provide insights and tools meant to improve the inventories themselves. For instance, in one hypothetical scenario by which the local CO_2 inventory levels at a given airport operating under regular conditions are systematically underestimated by ≈150ppm compared to observed values, research efforts could then be redirected to the estimation *vs.* observation anomaly and perhaps pinpoint the gap or error leading to that difference. That, in turn, could be used to upgrade the algorithm not only on a local scale, but also globally should the air traffic and environmental settings at that airport be somewhat relatable to other conditions elsewhere.

Restrictions on the accuracy of atmospheric measurements at airports may be overcome by the actual need behind the measurements themselves. In fact, it is recognized that continuous (or sporadic) measurements could be the result of a legal requirement at various levels, asking for an assessment of atmospheric pollution in a given area (this principle is applicable to various contexts other than airports – see core industrial areas, for example). Other reasons leading to more accurate measurements could have "voluntary" baselines as the driving factor behind them, in the form of airport authorities willing to perform more detailed analyses, or public concern over pollution levels in a given area (again, this may be applicable to a number of scenarios unrelated to aviation) that result into the central government funding these measurements. In an ideal scenario, these measurements would be performed globally, with standardized procedures, and their accuracy/frequency could be adjusted depending on the intensity of local air traffic (*e.g.*, busy airports may have to be monitored at a higher rate), as well as precise local meteorological conditions (*e.g.*, weak local circulation may lead to the accumulation of pollutants and, consequently, the need for continuous or more frequent evaluations), as well as the overall urban setting (*e.g.*, distance to, and population density of, urban centers). In addition to these procedures, which need to be discussed on a global scale, regulating factors such as the maximum amount of data gaps (*e.g.*, caused by lack of reports or unrepaired instruments) allowed before a sanction takes place, as well as precise legal requirements on the accuracy of reported data, need to be implemented. An integrated and well-

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[20] Zhang, G.; Liu, J.; Li, J.; Li, P.; Wei, N.; Xu, B. (2021). *Radiocarbon isotope technique as a powerful tool in tracking anthropogenic emissions of carbonaceous air pollutants and greenhouse gases: A review*. Fundamental Research 1, issue 3, pgs. 306-316.

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regulated international network would then be beneficial for all authorities and countries involved, especially in terms of source apportionment (SA), a key tool by which emission sources can be detected. Right now, SA seems poorly developed in the context of atmospheric measurements at airports, for the reasons stated above.

Despite the gaps in source apportionment (SA) methodology, the AAQM however acknowledges the complexity of monitoring aviation-related emissions in geographic contexts where other emission sources are present: it is recognized, in fact, that the airport inventory – intended, by the AAQM, as a local scale source emission estimate – might constitute a "small percentage to the overall area emissions inventory". The same document also reports that railway systems and trains, though considered part of local emission sources due to their infrastructural relevance (sometimes, train stations are perfectly integrated into airports, so the two sources coexist and each one of them has a direct influence on the other), are not covered by the document itself. This, combined with the odds of precise carbon compound analysis in atmosphere mentioned before, significantly contributes to the degrees of uncertainty that form up the core of this research paper.

Conclusions and perspectives

Via an integrated approach accounting for multiple fields of research and expertise, this research paper addressed the issue of airport air quality and the various uncertainties affecting estimates on levels ranging from local to global. In fact, via an *excursus* on global guidelines on the matter as well as their development over the course of the past few decades, where concerns over atmospheric pollutions have grown remarkably, plus the description of atmospheric measurement methods that are as of today not applied – or are applied sporadically – to air quality measurements at airports, the paper highlights the major key aspects of these uncertainties. In fact, environmental factors and local wind circulation are of remarkable interest when it comes to mounting pollution levels. Moreso, several aspects regulating air traffic on ground and at low altitudes, each adding up to the uncertainties of aviation-related emissions, are also mentioned. The erroneous concept by which the concepts of air quality and aviation-related emissions, which are intertwined but not identical, is also addressed. The paper calls for a better integration of multiple disciplines, including – but not limited to – Atmospheric Physics/Chemistry, Aviation and Earth Sciences, as the key towards future estimates on the contribution of aviation to local-to-global pollution and emission levels. Some of the above mentioned integration would require technological breakthroughs in the form of more cost-efficient and common carbon isotope detectors, while other aspects of the integration would require a higher amount of data on the management of aircraft on-ground be collected and collectively computed to optimize estimates. Finally, a coordinated effort on an international scale could share data and provide relevant insights on how to improve models, via a continuous trial and error methodology.

Declaration on AI Use: The author declares that at no point during the development of this paper AI and comparable tools were used. This statement applies to all aspects of this research, ranging from conceptualization to writing.

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