MODELLING AIR TRAFFIC IMPACT ON LOCAL AIR QUALITY WITH IESTA AND ADMS-AIRPORT: VALIDATION USING FIELD MEASUREMENTS ON A REGIONAL AIRPORT

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Abstract

The local air quality at the airport scale is simulated with the IESTA / Clean Airport models suite and evaluated against in situ observations. IESTA / Clean Airport is an Onera facility aiming at the evaluation of air traffic environmental impact around an airport, by means of fast high-fidelity physics simulation. Regarding local air quality impact, the ADMS-Airport Gaussian dispersion tool is integrated within the simulation platform.

This paper presents a complete traffic, emissions and dispersion modelling methodology, applied to local air quality measurements and several days worth of operational trajectory recordings on a busy regional airport. The simulation results are validated through comparisons to observed nitrogen oxides (NO_x) concentration.

1 Introduction

The aviation emissions of atmospheric pollutants have a strong impact on environment from the global to the local scale. In 1999, the IPCC report [1] pointed that aviation contribute up to 3.5 % of the anthropogenic radiative forcing due to greenhouse gases emissions at the global scale (e.g. emissions of carbon dioxide CO_2). More recently, Lee et al., 2009 [2] suggested that they expect the traffic to be higher and to potentially increase the radiative forcing in 2050 from a factor 3 or 4 over 2000 levels. On the other hand, Meinshausen et al., 2009 [3] showed that halving carbon dioxide emissions by 2050, compared to 1990, could stabilize global warming.

At the local scale, the aircraft emissions strongly impact the local air quality, mainly due to nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$[1], PM_{10}), unburned hydrocarbons (UHCs), sulfur dioxide (SO_2) and carbon monoxide (CO) pollutants (Lee et al., 2010 [4]). They generate health hazards like premature mortality (Barrett et al., 2010 [5], Stettler et al., 2011 [6]) and contribute to larger scale episodes of photochemical pollution.

At the airport scale, few studies have been conducted to assess the impact of aircraft emissions during landing, take-off and taxiing on air quality (Schürmann et al., 2007 [7], Woody et al., 2011 [8]). Most of them use local atmospheric dispersion models like EDMS (Emissions and Dispersion Modeling System) from the Federal Aviation Administration (FAA), ADMS (Atmospheric Dispersion Modelling System) or LASAT (Lagrangian Simulation and Aerosol Transport) (Unal et al., 2005 [9], Hirtl et al., 2007 [10], Riddle et al., 2004 [11]). In general, these studies use aircraft emissions inventories rates averaged from the whole traffic.

This paper deals with the assessment of an airport contribution to air quality at the local scale

[1] particles on the order of 2.5 μm or less

using modelling tools in confrontation with observations. In fact, the IESTA / Clean Airport set of models integrated with the atmospheric dispersion model ADMS are used for the simulation of a real observed case of local air pollution, characterized by high levels of NO_x concentration. The description of the methodology and models (Section 2) is followed by an analysis of the obtained results and their validation (Section 3).

2 Methodology and tools

Several days of air traffic on a busy regional airport have been documented in fall 2010, particularly for atmospheric characteristics. Meteorological parameters (temperature, humidity, pressure, wind speed and direction) as well as pollutants concentration (NO_x, CO, SO_2, O_3 and PM_{10}) have been measured near the control tower at 2 m of elevation. Concerning the air traffic data, only a list of aircraft state vectors from control radar streams is provided containing the spatio-temporal information of the aircraft and its ICAO type.
All these data allow the simulation of a real day of air traffic with the corresponding atmospheric conditions using the IESTA / Clean Airport platform described hereafter.
In this study, only the results concerning the 10th of September are shown. This day is characterized by a strong traffic at the airport, low winds, anticyclonic conditions and high measured NO_x concentrations.

2.1 The IESTA / Clean Airport simulation framework

The Air Transport Systems Evaluation Infrastructure (IESTA, Onera) application Clean Airport [12] [13] is a set of numerical models dedicated to the design and modelling of innovative air transport systems and their evaluation, in particular for environmental impacts (noise, fuel consumption, emissions and air quality). The IESTA computation chain is able to simulate the air traffic system from the aircraft trajectories, the aircraft state vectors, the engines state (thermodynamic characteristics, thrust, fuel flow, emissions) to the atmospheric dispersion through the integration of several local dispersion codes.
More precisely, the IESTA Aircraft Module can closely follow a 4D trajectory, given the airplanes type and using total energy equations of flight mechanics. It generates a complete state vector for each of the simulation time steps, including the engines required thrust.

In this instance, the Engine Module is used without the full thermodynamic modelling of each engine. Taking the thrust, aircraft speed and weather parameters as input, it can use several methods to interpolate the ICAO tables (for turbofans) [14] or FOI database (for turboprops) and thus compute fuel consumption and emission indices for different species at every point of each engine trajectory.
Operational trajectory recordings are not meant for detailed physics computations; thus they often contain numerous inaccuracies and truncations, which do not impinge on their usefulness for the air traffic controllers. However, the Aircraft and Engine Modules included in IESTA are sensitive to, for instance, gaps ands jumps in the tracks they process. Appropriate methods and computations are developed to deal with inaccuracies that would have large enough effects on the simulation results; they are described hereafter.

2.2 Aircraft trajectories

2.2.1 *Engine model selection*

The radar streams provided include the aircraft ICAO type. Each trajectory's aircraft type is looked up in a table that lists: number of engines, engine type (turboprop, piston, turbofan) and most probable model, standard operation weights, wing area. In a few cases, the emissions cannot be computed from that information: the piston type engines are not yet implemented in IESTA, and some engines are not ICAO-certified. Among the 399 trajectories for the study day, three rejections occurred (2 piston aircraft and one business jet equipped with non ICAO certified engines). These trajectories could be allocated to other aircraft types with equivalent emissions. In this case, they are simply ignored as their contribution is deemed negligible. The 396 remaining aircraft trajectories are processed into 824 distinct emission trajectories, one per engine.

2.2.2 *Trajectory completion and correction*

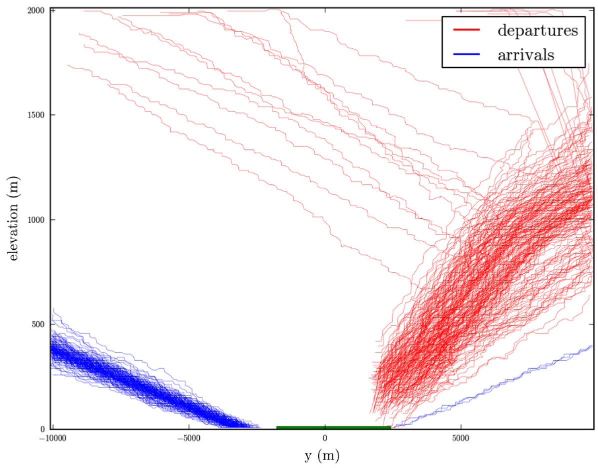

Fig. 1 Vertical profiles of raw aircraft trajectories

As Fig. 1 shows, the tracks extracted from the radar streams need to be repaired. On the take-off side, the ground-tracking radar streams were not correlated to the approach radar ones; thus, only the latter, which include the aircraft identifier, are processable. These partial trajectories (in red on Fig. 1) have to be completed with an initial climbing segment, a runway segment, and taxiing from the apron areas, in reverse chronological order.
The trajectories consist in a succession of (latitude, longitude, altitude, time) coordinates. In order to maintain some physical realism, the runway segments are built starting from one end of the runway at nil speed, each successive point being then reached from its predecessor supposing the aircraft is at its maximum ground acceleration. Different and simplified formulae are chosen for turbofan and turboprop engines.
The turbofans' maximum ground thrust is directly taken from ICAO certification tables. For turboprops, at low speeds, with a figure of merit of 0.75, the maximum thrust is approximately given by

$$\frac{T_m^{\frac{3}{2}}}{Pow_m} \times \sqrt{2 \cdot \rho_0 \cdot A_p} = 0.75,$$

T_m, Pow_m, ρ_0 and A_p denoting the maximum thrust and power, ground air density and propeller area respectively. At higher speeds, more simply,

$$T_m = Pow_m \times \frac{0.8}{S},$$

S being the speed, 0.8 a chosen value of efficiency ratio. Maximum acceleration A_m is then

$$A_m = \frac{T_m \cdot E_n - \rho_0 \cdot A_w \cdot S^2 (C_d - C_f \cdot C_l)}{2 \cdot M} - C_f \cdot G_0,$$

with maximum thrust T_m, engine number E_n, wing area A_w, drag, friction and lift coefficients C_d, C_f and C_l, mass M and gravitational acceleration G_0.
These formulae are adapted to the aircraft model through parameters A_w, M (current mass, decreasing due to fuel consumption), C_d, C_f and C_l. Once the aircraft reaches lift-off speed, the missing initial climbing segment is simply reconstructed as a 4D-interpolation to the first approach radar point of the trajectory. The missing taxiing segments are not added in this trajectory preprocessing phase, as there is no information on the correct taxiway usage; rather, good estimations of the take-offs taxiway emissions are subsequently added as 'Area' sources (see Section 2.3).
The landing trajectories (blue lines in Fig. 1) are problematic as well: due to differences in calibration over the two radar streams (approach and ground), every aircraft appears to land some 2 km before the runway threshold (green). In this case, the trajectory preprocessing consists in, going backwards from the threshold, raising each point's altitude along a standard 3° ILS slope, while keeping its geographical and time coordinates.
Other, minor corrections such as smoothing suspiciously angular tracks (partly due to data precision) could also be performed, but these are

mostly irrelevant regarding the resulting aircraft emissions. The result of these corrections on the 6:00 to 7:00 UTC trajectories is shown in Fig. 2.

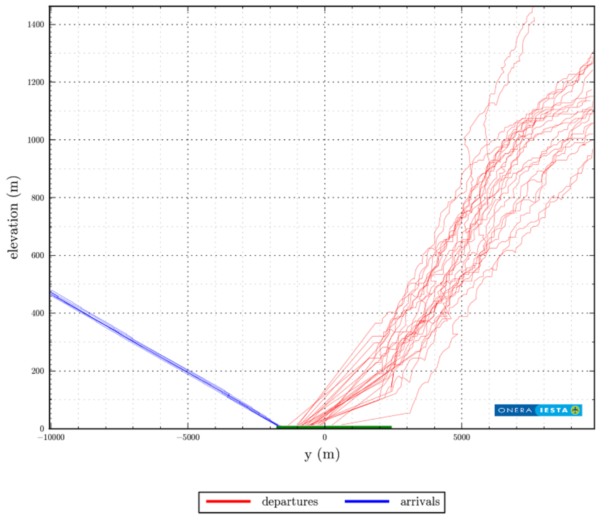

Fig. 2 Vertical profiles of aircraft between 6:00 and 7:00 UTC after correction

2.3 Aircraft and APU emissions

The emissions of these 824 aircraft engines are computed using the interpolation in the ICAO tables rather than using the IESTA thermodynamic model because of a large variety of engines types. The emissions of NO_x, CO, CO_2, SO_2 and smoke number are computed and integrated at the hourly time step.

As the available data don't include aircraft APU emissions, the ICAO/CAEP Airport Air Quality Manual [15] is used to attribute APU emissions to realistic areas and periods. This Manual states that an accepted modelling for short-haul aircraft is an APU operating during 45 min and emitting a total of 700 g NO_x, 30 g UHCs, 310 g CO and 25 g PM_{10}.
The correlation of the arriving aircraft with the departing ones turns out to be quite a cumbersome work, that can hardly be automated without any access to the aircraft callsigns. Finally half of the prescribed emissions are attributed to each of the departures and each of the arrivals.
As expected, the NO_x emissions are the highest near the take-off location on the runway but also near the parkings at the gate as shows Fig. 3.
The temporal variation of the NO_x emissions is directly correlated to the number of emitting engines as displayed on Fig. 4. Three maxima of emissions clearly appear: in the morning, in the early afternoon and in the evening.

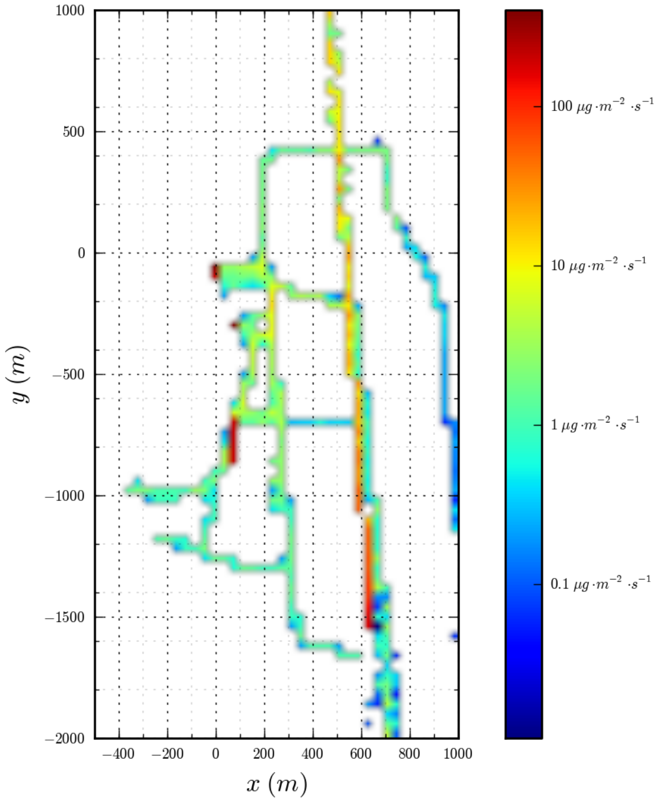

Fig. 3 NO_x emissions averaged between 6:00 and 7:00 UTC. Horizontal resolution: 40 m

2.4 Atmospheric dispersion

2.4.1 Dispersion model

The emissions computed by IESTA / Clean Airport are the main input of the dispersion model. For that case study, the ADMS-Airport [16] [17] Gaussian model only simulates the dispersion and reactions of chemical species and computes air quality data at a local scale; the EMIT module for the aircraft emissions computation is not used at all here.
In ADMS, the concentrations are computed according an analytical formulation which is a

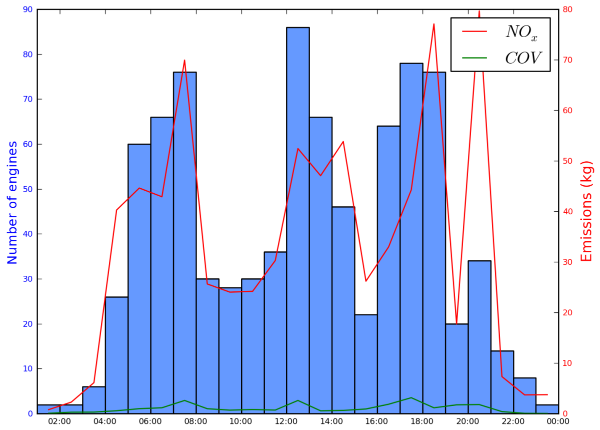

Fig. 4 Hourly NO_x and VOC (COV) emissions and number of engines associated over one day

Gaussian expression and depends on wind and boundary layer conditions through the Monin-Obukhov length and emissions near the sources. A simple chemical scheme allows to simulate ozone concentration and the photochemical cycle between NO, NO_2 and volatile organic compounds (VOC).

Regional measurements from an official Air Quality Monitoring association station, on the day studied, are used as ADMS atmospheric background concentrations. The observation station is located a few kilometers north of the airport and the sampled air masses are not under the airport influence. Concerning the meteorological conditions, the wind, temperature and pressure were measured every 6 minutes on-site at the airport near the control tower.

2.4.2 Emission source models

Once calculated, the emissions can be included in ADMS according to several types of models: Volume, Area, Line, Point and Jet sources (plus Road and Grid sources which are not used here). Their respective characteristics fit the representation of different sources, be they localised and static (e.g. APU emissions), or linear and accelerating (aircraft during take-off).

ADMS-Airport gives access to an additional so-called 'Aircraft source' type. It internally relies on a collection of Jet sources which allows to take into account the rapidly varying speed, thrust and rate of emissions of a set of aircraft following the same line segment. An 'Aircraft source' consists in this line segment, the values of the aircraft speed at the beginning and the end of this segment, their emissions rates in $g \cdot m^{-3} \cdot s^{-1}$ and the number of interpolation points.

Simulation name	Sources Type	APU emissions
AIRC_APU	Jet and Area	ON
SURF_APU	Area	ON
SURF_NOAPU	Area	OFF

Table 1 Characteristics of the three ADMS simulations

In order to compare some different available modelling strategies, a toolbox is built which, given the aircraft emissions and a source layout defined both in terms of vertical slices and horizontal polygons (which leaves us with a partition of the airport into set of right prisms, each modellable as a 'Area' of 'Aircraft Source').

The combination of the Python language and its numeric and scientific libraries turns out to be an efficient open-source way to develop such data handling algorithms. Different visualization tools are also designed, facilitating the analysis step.

Several ways of emissions implementation into the dispersion model are tested here (see Table 1). The first simulation consists in the following strategy: the aircraft in the air and taking off on the runway are modelled as 'Aircraft Sources'. The other aircraft, those on the ground which are arriving or taxiing, are modelled as 'Area Sources'. This simulation is hereafter noted 'AIRC_APU'.

The second simulation consists in the implementation of all emissions as 'Area Sources': APU, taxiing as well as take-off emissions. This simulation is noted 'SURF_APU'.

The last simulation is done to evaluate the impact of APUs on air quality and like the SURF_APU simulation only uses 'Area' emissions but does not include APU emissions. It is noted 'SURF_NOAPU'.

3 Results and validation

3.1 Results analysis

The results of the three simulations are shown on Fig. 5 at 7:00 UTC, i. e. during the morning maximum traffic. For that simulated day, the northerly wind is low and the runway and parking plumes consequently present high NO_x concentrations, with hot spots of more than 200 ppbv[2]. The two first simulations (AIRC_APU and SURF_APU) have comparable results everywhere except near the take-off location on the runway where the AIRC_APU plume seems smoother, more diluted and spatially extended.
Conversely, the simulation SURF_NOAPU presents lower NO_x near the parking.

3.2 Comparison with field measurements

Whereas the AIRC_APU and SURF_APU simulations have similar results, the temporal comparison in confrontation with observations made near the control tower give satisfactory results. In fact, the observed NO_x concentrations are maximum in the morning (at 7:00 UTC), the early afternoon (at 13:00 UTC) and the early evening (at 18:00 UTC), which are the hours of maximum traffic and maximum engines emissions, as computed by IESTA / Clean Airport model and shown on Fig. 4. This hourly variation is also well simulated by the dispersion model (Fig. 6). Although the afternoon peak is overestimated by the model, the two other maxima are in rather good agreement. For the dispersion model, the vertical mixing in the convective atmospheric boundary layer (ABL) is hardly reproducible with the simple ABL parametrization and may result in an overestimation.
In the SURF_NOAPU simulation, the concentrations are underestimated, all day long. This result clearly shows that the APU emissions have a strong impact on air quality and concentrations observed at the airport scale.

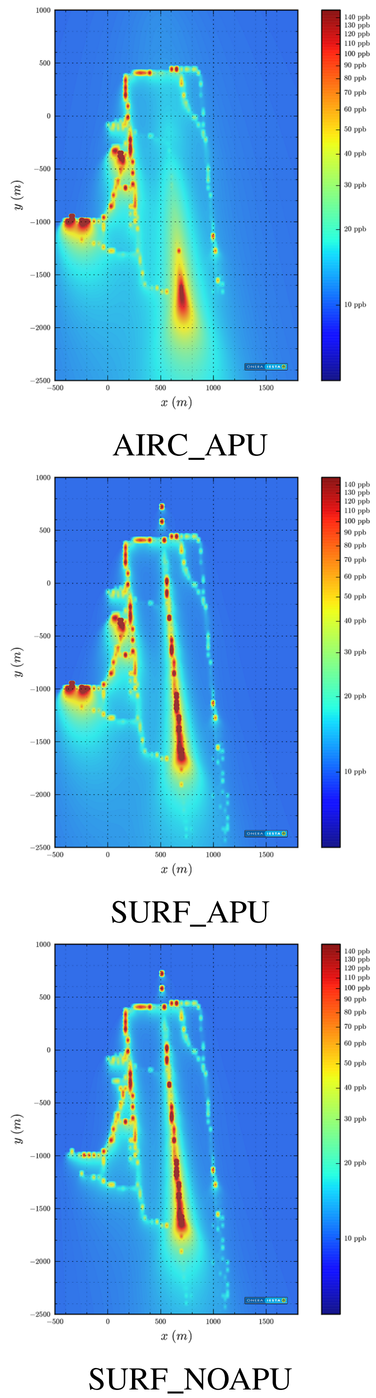

Fig. 5 NO_x concentrations simulated at 7:00 UTC over the airport for the three simulations: the 'AIRC_APU' simulation including aircraft or jet sources model, the 'SURF_APU' simulation with only 'Area' sources and the 'SURF_NOAPU' simulation with 'Area' sources but without APU emissions.

[2]parts-per-billion by volume

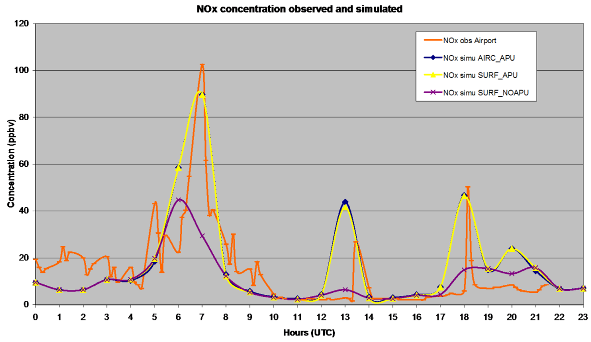

Fig. 6 Comparisons between observed (orange) and simulated NO_x concentration on the 10th of September, for the three simulations (AIRC_APU in blue, SURF_APU in yellow and SURF_NOAPU in purple)

4 Conclusion

An experimental campaign on a regional airport provided air traffic data as well as pollutants concentration and meteorological measurements, which are used to validate the IESTA / Clean Airport model.
The recorded radar streams include spatio-temporal informations and the type of aircraft allows to compute the state vectors and the engines emissions using the IESTA / Clean Airport model. The effort put into correcting and completing the input data, especially aircraft types and trajectories, can mostly be capitalised. However, the operational data provided in such studies is never exactly the same, either as regards its completeness, precision, or format; additional specific preparation will always be needed in each new case.
The IESTA / Clean Airport platform integrated with the ADMS-Airport dispersion model proves able to simulate the atmospheric dispersion at the local time and space scales. In fact, several modes of emissions attributions (as 'Area' or 'Aircraft' sources) are tested. Limitations in the number of active sources have to be circumvented. The comparisons with observed concentrations show a good agreement with the simulated concentrations near the control tower. The contribution of the APUs is a key process for the simulation of the emissions as their impact on air quality is very high.
The temporal variation of the emissions reveals to be crucial, as well as the representation of the vertical mixing in the atmospheric boundary layer.
Nevertheless, the good results observed during this sunny day have to be further confirmed with additional simulations on various meteorological conditions. Some investigation is needed to determine, among the different types of sources ADMS-Aircraft allows (volume, area, line, point, jet, aircraft), the most adequate depending on the aircraft modes (taxiing, take-off) and the best settings.

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