



Influence of aircraft-induced dilution dynamics on near-field ice crystal formation

Margaux Vals¹, Rémy Annunziata¹, and Nicolas Bonne¹

¹DMPE, ONERA, Université Paris-Saclay, Palaiseau, F-91120, France

Correspondence: Margaux Vals (margaux.vals@onera.fr)

Abstract. The influence of aircraft-geometry-induced dynamics on ice crystal formation in contrails is investigated using a detailed 1D microphysics code combined with results from several 3D CFD simulations. Two configurations are considered: one including a complete aircraft geometry and another with an engine alone. For each configuration, two ambient temperatures and two combustion modes are considered, corresponding to soot-poor and soot-rich regimes. These simulations are used to determine the temperature and dilution profiles within the plume, which are then applied to the 1D microphysics code MoMiE. This code represents the various processes of ice crystal formation, notably ice nucleation from volatile particles and from hydrated soot particles. The results show that aircraft-geometry-induced dilution and temperature changes directly impact ice crystal formation, in particular ice particle concentration, number, and size. The difference observed between the engine-only configuration and the complete aircraft geometry is less than 10 % for the number of ice crystals per meter of flight in the soot-poor regime, whereas it ranges from less than 1 % to 21 % in the soot-rich regime. Comparison with results obtained using Schumann's analytical dilution law, commonly used to represent dilution in 1D box models, also shows significant differences. In the soot-poor regime, the CFD-based dilution leads to a 35% underestimation of the ice crystal number relative to Schumann's law at high ambient temperatures, whereas it leads to a 118% overestimation at colder ones. Given that ice crystal number, concentration, and size are key parameters for determining the radiative impact of contrails, these results highlight the importance of the aircraft dynamics in ice crystal formation, but also the need for further study into the role of the dilution process in estimating contrail properties.

1 Introduction

Reducing emissions from the aviation sector has become a major societal challenge, particularly in light of its substantial environmental impact. Among aviation emissions, the so-called non-CO₂ effects have attracted growing attention over recent decades. Condensation trails (contrails) are a prominent component of these non-CO₂ emissions (Lee et al., 2009). They appear as elongated ice clouds that form in the wake of aircraft. While some contrails dissipate rapidly under atmospheric conditions unfavorable to their persistence, others survive and evolve into aviation-induced cirrus clouds that can persist and spread over large spatial scales, depending on the surrounding ambient conditions. It is precisely these induced cirrus clouds that are of particular environmental concern. By interacting with both terrestrial and solar radiation, they perturb the Earth's radiative balance and generate a potentially significant effective radiative forcing (Burkhardt and Kärcher, 2011), estimated to exceed

that associated with aviation CO₂ emissions alone (Lee et al., 2021). Research efforts, therefore, focus on the formation and evolution of contrails, with the dual objective of improving their representation in large-scale climate models and deepening our understanding of the physical processes governing their full life cycle (Kärcher, 2018).

Contrail formation, therefore, constitutes a key stage in the contrail life cycle. This formation process takes place in the immediate vicinity of the aircraft. During flight, the engines emit a plume that is initially hot and characterized by high turbulence and velocities, containing both gaseous combustion products and solid particles such as soot (Petzold et al., 1998). After emission, the plume progressively cools and dilutes into the surrounding atmosphere. This evolution occurs in two distinct stages (Miake-Lye et al., 1993). In the first, the plume follows its own jet dynamics and cools through expansion and turbulent mixing at the nozzle exit. It is during this phase that ice crystals begin to form, once the plume has cooled sufficiently for nucleation sites, such as soot particles (Kärcher et al., 1996) or volatile aerosols (Kärcher, 1998) produced from the emitted gases, to become activated and initiate ice formation. The second stage is then governed by the wingtip vortices generated at the aircraft wingtips. These vortices progressively entrain the plume, thereby transitioning the dynamics from jet-dominated to vortex-controlled behavior (Jacquin and Garnier, 1996). The vortices subsequently stretch, dilute, and redistribute both the plume and the ice crystals within the wake, further modifying the thermodynamic conditions while also supplying additional water vapor, thereby promoting continued ice crystal growth (Paoli et al., 2013).

The contrail formation stage is particularly important because it largely determines the initial number of ice crystals formed within the plume (Lewellen et al., 2014; Lewellen, 2020). These crystals subsequently play a central role in setting how many survive the vortex phase. During the latter one, a part of the ice population is transported downward to lower altitudes by vortex-induced motion and may sublime. The number of ice crystals that persist beyond this stage then strongly influences the optical properties of the resulting ice cloud and, consequently, its radiative impact after the contrail-to-cirrus transition (Unterstrasser and Gierens, 2010a, b). Several factors govern the number of ice crystals formed in the aircraft near field. These include the ambient flight conditions, especially temperature and relative humidity, as well as the composition of the engine exhaust plume (Kärcher and Yu, 2009). The latter depends on a range of engine operating parameters. In particular, the combustion regime affects the soot number emission index and can therefore strongly modulate the number of ice crystals formed (Kärcher, 2018; Voigt et al., 2026). Other parameters may also be influential during these early stages, notably the geometry and characteristics of the aircraft that generate the contrail (Jeßberger et al., 2013; Unterstrasser and Görsch, 2014; Annunziata et al., 2025).

Given the difficulty of performing measurements under the harsh conditions behind an aircraft, contrail formation is investigated primarily through numerical simulation. A range of approaches has been developed in the literature, forming a hierarchy of models with varying levels of complexity, both in terms of microphysical representation and dynamical description (Paoli and Shariff, 2016). Regarding microphysics modeling, the most detailed approaches are box models (Kärcher, 1995; Wong and Miake-Lye, 2010; Rojo et al., 2015; Bier et al., 2022; Yu et al., 2024). These models represent a range of microphysical processes and chemical kinetics, enabling a detailed description of the nucleation sites in the plume and key mechanisms such as coagulation, particle activation, and homogeneous ice formation. However, their dynamical treatment relies on a semi-empirical law for plume dilution (Schumann et al., 1998) or on streamlines extracted from dynamical simulation (Paoli et al.



60 (2008), also called offline coupling). These trajectories are mostly extracted from Large Eddy Simulations (LES) that initialize both a jet and a vortex.

Alternative approaches, such as CFD (which are online coupling), have also been applied to study contrail formation. These methods allow for a more detailed resolution of the plume dilution by solving the Navier-Stokes equations. Various approaches are then employed in the literature, such as LES, initializing a jet and a vortex (Paoli et al., 2013; Lewellen, 2020; Ferreira et al., 2024). With recent advances in computational capabilities, other CFD methods have been developed that incorporate aircraft geometry, enabling the simulation of flow around it. These 3D approaches rely on Reynolds-Averaged Navier-Stokes (RANS) modeling (Guignery et al., 2012; Khou et al., 2015). More recently, a uRANS (unsteady RANS) approach has been applied to an engine alone (Cantin et al., 2022, 2025) with a more comprehensive microphysical representation. These approaches offer a clear advantage in that they eliminate the need to prescribe a dilution or to initialize the flow using simplified analytical representations of jets and vortices. This could be important given the role of jet dilution in the near field, as highlighted in Annunziata et al. (2025). However, despite these advantages, such simulations, especially those involving the full aircraft geometry, remain computationally expensive. They require fine spatial resolution and well-converged flow fields, leading to substantial computational costs. In this context, given the range of geometric modeling strategies employed in CFD studies, from full-aircraft configurations to isolated-engine representations, it is legitimate to question the actual impact of explicitly accounting for the complete aircraft geometry on the resulting contrail properties.

From this perspective, we investigate the effect of incorporating a complete and realistic aircraft geometry on contrail formation simulations in the near field, with particular emphasis on the number of ice crystals formed. To this end, the microphysical calculations are performed using a one-dimensional model that explicitly accounts for the relevant microphysical processes. Comparisons are carried out between three configurations: the complete aircraft, an isolated single-engine configuration, and the semi-analytical model commonly used in the literature (Schumann et al., 1998). In order to account for both the full aircraft geometry and the isolated engine geometry, RANS aerodynamic simulations are performed. The resulting plume dilution histories are then extracted and used as input for the microphysical calculations of ice crystal formation in each case. The main objective is therefore to quantify, first, the impact of the dilution changes induced by the presence of the full aircraft geometry and, second, the role of additional geometric effects on near-field contrail formation and on the resulting number of ice crystals.

85 The paper is organized as follows. Section 2 presents the methodology, including the flow and microphysical models as well as the approach used to determine plume dilution. Section 3 describes the numerical setup. Section 4 then examines the influence of aircraft geometry on the temperature and the dilution profiles within the plume, followed by an analysis of the consequences on the formation of ice crystals in Section 5. Finally, Section 6 summarizes the main conclusions.

2 Methodology

90 2.1 Flow modeling approach

In studies where a box model is coupled with a complex flow field, the dilution profiles are typically extracted from a LES approach, initialized with both a jet and a vortex (Paoli et al., 2008; Vancassel et al., 2014; Bier et al., 2022). In the present



work, the objective is to incorporate a full aircraft geometry and to compare the dilution-induced differences with those of an isolated engine configuration. To achieve this while maintaining a reasonable computational cost, a RANS approach is employed. The flow simulations are performed using the CEDRE multiphysics platform developed at ONERA (Refloch et al., 2011). Specifically, computations are carried out with the CHARME solver, which is dedicated to solving the compressible, reactive, multi-species Navier-Stokes equations.

The RANS computations are carried out using the $k-\omega$ SST (Shear Stress Transport) turbulence model (Menter, 1994). This two-equation model solves transport equations for the turbulent kinetic energy k and the specific dissipation rate ω . The $k-\omega$ SST formulation is selected because it provides an accurate representation of the flow around complex aircraft geometries, particularly in regions characterized by strong adverse pressure gradients, such as those occurring on a wing. Further details on the RANS modeling approach adopted in this work are provided in Annunziata et al. (2025).

A passive scalar tracer is also introduced in the simulations to enable the subsequent evaluation of plume dilution. Its evolution is governed by a transport equation for its Favre-averaged concentration in number per m^{-3} , denoted $\tilde{N}$:

$$\frac{\partial}{\partial t}(\tilde{N}) + \frac{\partial}{\partial x_i}(\tilde{u}_i \tilde{N}) = \frac{\partial}{\partial x_i} \left(D \frac{\partial \tilde{N}}{\partial x_i} - \widetilde{u_i'' N''} \right) \quad (1)$$

where u_i , and D denote, respectively, the velocity components in the three spatial directions, and the diffusion coefficient. The latter is defined by imposing a Schmidt number of unity with respect to air. As the tracer is conserved within the mean flow, its transport across the domain enables the characterization of plume dilution throughout the different simulations.

2.2 Box model approach: MoMiE

Concerning microphysical processes, an offline approach based on a box model is adopted. Therefore, the 1D code MoMiE (Modèle Microphysique pour Effluents), developed at ONERA, is employed to provide a detailed characterization of contrail microphysical processes and of the resulting number of formed ice crystals. It accounts for the different processes involved in the formation of ice particles in the case of classic kerosene engine exhaust and Sustainable Aviation Fuels (SAF) (Sorokin et al., 2001; Vancassel et al., 2010; Rojo et al., 2015). It includes the freezing of soot particles covered with a solution of water, sulfur, and organic compounds (soot nucleation pathway), as well as the freezing of liquid droplets of hydrated sulfates and organics (volatile particle nucleation pathway), accounting for the competition between both ice nucleation modes. Chemi-ionization, Brownian coagulation of particles, ice sublimation, and condensation are also represented. The code computes the different aerosol distributions (size and number) of sulfates, organics, dry soot, activated soot, formed distinctly via the soot nucleation pathway and the volatile particle nucleation pathway. Finally, to account for the diffusion of the plume in the ambient air, the code is applied to both a temperature and dilution profiles that evolve, from the engine exhaust to a few seconds behind the aircraft. Consistent estimation of these profiles requires specific methods described in the following section.



2.3 Dilution calculation methods

2.3.1 Schumann's analytical law

A faithful representation of the dilution and temperature profiles within the plume is therefore important for properly capturing the associated microphysical processes. In the context of contrail studies, dilution is then typically characterized by a dilution factor D . Various strategies have been proposed in the literature to estimate this factor, relying on different levels of flow modeling. Among these, analytical approaches provide simple and computationally efficient parameterizations. When implemented in 1D box models, these approaches do not explicitly resolve the evolution of the plume flow. Instead, dilution is represented using analytical formulations.

As defined by Kärcher (1995), the dilution factor $D(t)$ can be computed through the temporal evolution of the concentration of a passive tracer x within the plume following its emission from the engine exit and could then be written as follows:

$$D(t) = \frac{x_i(t) - x_i^a}{x_i^e - x_i^a} \quad (2)$$

where t is the time, x is the volume mixing ratio in mol/mol, considered respectively for the species " i ", for the ambient air " a " and at the nozzle exit " e ". The assumption of a constant pressure within the plume is usually made, which leads to the following relation:

$$D(t) = \frac{P_i(t) - P_i^a}{P_i^e - P_i^a} = \frac{N_i(t)T(t) - N_i^a T^a}{N_i^e T^e - N_i^a T^a} \quad (3)$$

where N is the concentration in number of particles in m^{-3} , P the pressure in Pa, and T the temperature in K.

The dilution factor can also be expressed in terms of the air-to-fuel ratio and the dilution ratio, providing a convenient formulation for 1D box model simulations. In this formulation, the dilution factor is given by:

$$D(t) = \frac{AFR}{C(t)} \quad (4)$$

with AFR the air-to-fuel ratio, accounting for the dilution at the engine exit, typically varying from 50 to 75 $\text{kg}_{\text{air}}/\text{kg}_{\text{fuel}}$. For the simulations in this paper, it is arbitrary set to 60. $C(t)$ denotes the dilution ratio and can be approximated by Schumann's analytical law Schumann et al. (1998), derived from several measurements:

$$C(t) = 7000(t/t_0)^{0.8}, \quad t_0 = 1 \text{ s}. \quad (5)$$

These parameterizations are then used here to calculate the dilution profile and have demonstrated their robustness across a wide range of studies (Kärcher et al., 1996; Kärcher and Yu, 2009; Bier et al., 2022). They offer the advantage of being straightforward to use, as they do not require an explicit simulation of the carrier flow. However, their simplified formulation limits their ability to represent certain physical features, such as spatial inhomogeneities within the plume as well as differences that may arise from different aircraft configurations, with geometric and compressible effects that can influence the plume behavior during the first instants.



2.3.2 Dilution estimation from 3D simulation

Alternative approaches to analytical parameterizations have also been developed to represent plume dynamics in 1D box models. These approaches then rely on an explicit simulation of the flow field, making it possible to derive the dilution factor directly from the simulated plume evolution. They can therefore provide a more realistic representation of dilution effects associated with phenomena such as jet-vortex interactions, while also allowing realistic engine and aircraft geometries to be incorporated into the simulations.

One such approach consists of extracting multiple trajectories from three-dimensional LES (Vancassel et al., 2014; Bier et al., 2024). However, this strategy cannot be applied in the present paper, as the trajectories extracted from a 3D RANS simulation do not account for turbulent diffusion and therefore do not fully represent the effective plume dilution. Instead, the evolution of a passive tracer from the engine exit to the downstream boundary of the 3D computational domain provides a more representative measure of the effective dilution. Accordingly, the mass conservation of all particles contained within the plume can be expressed as:

$$\rho(t)U(t)A(t) = \rho^e U^e A^e + \dot{m}^a(t) \quad (6)$$

where $\rho(t)$, $U(t)$, and $A(t)$ are respectively the density, the velocity, and the cross section of the plume at time t , and ρ^e , U^e , and A^e are the same variables taken at the engine exhaust. $\dot{m}^a(t)$ is the mass of particles that are entrained from the ambient field per second. The dilution factor in that case can be defined as follows:

$$D(t) = \left(1 + \frac{\dot{m}^a(t)}{\rho^e U^e A^e} \right)^{-1} = \frac{\rho^e U^e A^e}{\rho(t)U(t)A(t)}. \quad (7)$$

Note that the conservation of the mass flux inherently accounts for the different compressibility effects occurring within the plume — arising from the axial divergence of the jet, via the term $\frac{U^e}{U(t)}$ as mentioned in (Bier et al., 2024), as well as from the non-isobaric behavior of the jet at the engine exit, via the term $\frac{\rho^e}{\rho(t)}$. On the other hand, the conservation of the number of passive tracer i emitted by the engine within the plume can be expressed as:

$$N_i(t)U(t)A(t) = N^e U^e A^e \quad (8)$$

with $N_i(t)$ and N^e the concentration of the particles of type i in m^{-3} respectively at time t and at the engine exhaust. Finally, combining Equation 7 and Equation 8 then leads to:

$$N_i(t+1) = N_i(t) \frac{D(t+1)}{D(t)} \frac{\rho(t+1)}{\rho(t)}. \quad (9)$$

This expression can then be used to determine the concentrations of the various plume constituents based on the dilution of the plume within the simulated flow. Given that the passive tracer number density N is set to 10^{12} m^{-3} at the engine exit (see next section), the plume is defined as the region where $N > N_{\min}$ with $N_{\min}$ arbitrarily set to 100 m^{-3} . We verify the conservation of the passive tracer quantity by checking that $\dot{N}_{\text{tot}} = \int_{N > N_{\min}} N U dA$ along time within a range of error of $\pm 0.001\%$, where $\dot{N}_{\text{tot}}$ is the total number per second of particles introduced at the engine exit, and $\int_{N > N_{\min}}$ denotes integration over the cross-section defined by the criterion $N > N_{\min}$. The temperature within the plume, as well as the dilution factor calculated with



equation 7, are extracted from the 3D simulations, from the engine exit to the downstream boundary of the computational domain.

3 Computational setup

To generate the dilution and temperature profiles used in MoMiE, three cases are considered in this study. The first case corresponds to the classic analytical Schumann's law described in section 2.3.1. The other two cases rely on the inclusion of a geometric model and the explicit simulation of the flow field using the RANS approach, as well as downstream dilution (calculated as described in section 2.3.2). The second case then corresponds to the complete aircraft configuration, including the wings, engines, fuselage, and tail. Finally, the third case consists solely of the engine and its nacelle, without the surrounding aircraft geometry.

The aircraft model employed is the Common Research Model (CRM) developed by NASA (Vassberg et al., 2008). This geometry is then representative of a Boeing 777, with a wingspan $b = 58.8$ m. The tail assembly and engine modeling have subsequently been added by ONERA. The geometry is illustrated in Figure 1. The aircraft parameters, atmospheric conditions, and numerical settings employed in this study are summarized in Table 1 and further detailed in the following paragraphs.

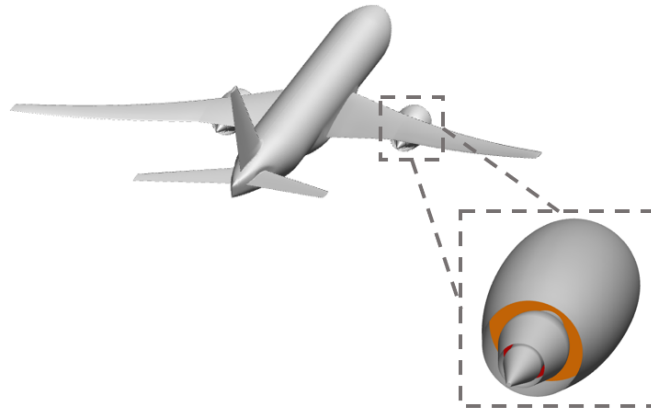


Figure 1. CRM and engine geometry. The orange plane indicates the bypass outlet, while the red corresponds to the primary engine exhaust

The engine considered is representative of an Ultra-High Bypass Ratio (UHBR) turbofan, characterized by a bypass ratio of 12. The primary exhaust forms an annular outlet with an area of $A_c = 0.75$ m². At the primary exit, total temperatures and pressures are imposed in the red area shown in Figure 1. As the nozzle is included in the geometry, the flow can develop right up to the nozzle outlet. For MoMiE simulations, it is useful to know the temperature at the red area, which is $T_c = 600$ K. More information on engine boundary conditions for the engine can be found in Annunziata et al. (2025). According to the engine specifications, the fuel consumption rate is $\dot{m}_c = 0.67$ kg/s and the overall efficiency $\eta = 0.33$. The RANS simulations are carried out assuming a cruise at Mach 0.85 at $P^a = 264$ hPa. For the atmospheric temperature, a cold case at $T^a = 215$ K and a warmer case at $T^a = 223$ K are examined. In the simulations, the ambient relative humidity with respect to ice RH_i^a is set to



Table 1. Summary of the geometric, engine, atmospheric, and numerical parameters used in the simulations

Aircraft parameters		Engine exit conditions	
Wingspan b	58.8 m	Air-to-fuel ratio AFR	60
Core outlet area A_c	0.75 m^2	Core total temperature T_c	600 K
Bypass ratio	12	Water vapor emission index EI_{H_2O}	$1.26 \text{ kg.kg-fuel}^{-1}$
Cruise Mach number	0.85	Fuel sulfur content (FSC)	$195 \times 10^{-6} \text{ kg.kg-fuel}^{-1}$
Fuel mass flow rate $\dot{m}_c$	0.67 kg s^{-1}	Soot number density N_{soot}	$10^{10} / 10^{12} \text{ m}^{-3}$
Overall efficiency η	0.33	Soot number emission index EI_{soot}	$3.6 \times 10^{12} / 3.6 \times 10^{14} \text{ kg-fuel}^{-1}$
Atmospheric conditions		Numerical parameters	
Ambient temperature T^a	215 / 223 K	Domain length L_x	$22b$
Ambient pressure P^a	264 hPa	Simulation duration	5 s
Humidity (ice) RH_i^a	100%	Time step Δt	0.001 s

195 100%. The computational domain extends $L_x = 22b$ downstream of the aircraft, allowing for the simulation of jet development for approximately 5 seconds in the wake of the entire aircraft or the engine alone.

Regarding the parameters and conditions employed in the MoMiE box model, the simulations are performed with a water vapor emission index of EI_{H_2O} of $1.26 \text{ kg.kg-fuel}^{-1}$ and a fuel sulfur content (FSC) of $195 \times 10^{-6} \text{ kg.kg-fuel}^{-1}$. Because soot emission number is a key parameter governing ice crystal formation (Kärcher and Yu, 2009), two representative values are
 200 considered for each in this study: a soot-poor case with $N_{soot} = 10^{10} \text{ m}^{-3}$ and a soot-rich case with at $N_{soot} = 10^{12} \text{ m}^{-3}$. These values correspond, respectively, to soot number emission indices of 3.6×10^{12} and $3.6 \times 10^{14} \text{ kg-fuel}^{-1}$.

All configurations considered in this study are summarized in Table 2. For clarity, the cases are labeled according to their configuration: for example, the "CRM dilution" case at 215 K in the soot-rich regime is denoted *C215R*, while the "engine-only dilution" case at 223 K with low soot content is referred to as *E223P*, and the "Schumann's law" dilution case at 215 K with
 205 low soot content as *S215P*.

4 Influence of the aircraft geometry on temperature and dilution within the plume

The first analysis focuses on the temperature and dilution profiles obtained from the MoMiE simulations, with particular emphasis on the impact of including the complete aircraft geometry, rather than the engine alone, on these fields. The results obtained for the two configurations, CRM and engine-only, can also be compared with those obtained for the dilution calculated
 210 using Schumann's analytical law. To this end, Figure 2 first presents the temperature, the dilution factor calculated as described in Section 2.3.2, and the plume cross-sectional area as a function of time. These quantities are evaluated for the three dilution cases and for the two ambient temperatures considered. In each plot, the CRM and engine-only configurations are represented by red and blue curves, respectively. The black curves correspond to the cases using Schumann's dilution parameterization.



Table 2. Summary of the simulation cases for MoMiE. Each case name encodes the configuration used for the dilution calculation (S: Schumann’s analytical law, C: CRM, E: engine-only), the ambient temperature (215 or 223 K), and the soot regime (P: poor, R: rich)

Case name	Configuration	Ambient temperature [K]	Soot regime [$\text{m}^{-3} / \text{kg-fuel}^{-1}$]
S215P	Schumann’s law	215	$10^{10} / 3.6 \times 10^{12}$
S215R	Schumann’s law	215	$10^{12} / 3.6 \times 10^{14}$
S223P	Schumann’s law	223	$10^{10} / 3.6 \times 10^{12}$
S223R	Schumann’s law	223	$10^{12} / 3.6 \times 10^{14}$
C215P	CRM	215	$10^{10} / 3.6 \times 10^{12}$
C215R	CRM	215	$10^{12} / 3.6 \times 10^{14}$
C223P	CRM	223	$10^{10} / 3.6 \times 10^{12}$
C223R	CRM	223	$10^{12} / 3.6 \times 10^{14}$
E215P	Engine-only	215	$10^{10} / 3.6 \times 10^{12}$
E215R	Engine-only	215	$10^{12} / 3.6 \times 10^{14}$
E223P	Engine-only	223	$10^{10} / 3.6 \times 10^{12}$
E223R	Engine-only	223	$10^{12} / 3.6 \times 10^{14}$

First, the figure shows that the temperature, dilution factor, and area profiles evaluated along the plume from the two 3D configurations differ from the ones obtained with Schumann’s law from the very beginning. Although cooling and dilution are more pronounced between 0 and 0.07 s for Schumann’s law dilution case, this trend rapidly reverses, and the other two configurations ultimately exhibit a greater dilution effect. Indeed, from ~ 0.1 s the plume area simulated using the Schumann’s dilution law is two to three times smaller than that obtained with the other two configurations.

Furthermore, the most pronounced differences between CRM and engine-alone configurations are observed in the right-hand plots (third column) from approximately $t = 0.5$ s onward, with clear discrepancies between the CRM and engine-only simulations in terms of dilution. Simulations with the full CRM geometry exhibit the strongest dilution effect, with the dilution factor decreasing more rapidly than in the engine-only configuration. This behavior can be expected, since the CRM simulation captures the full aircraft-wake dynamics. In particular, the wing-generated vortex system deflects and traps the plume, promoting enhanced dispersion and efficient mixing with ambient air (Paoli et al., 2004). By contrast, in the engine-only case, dilution is driven solely by turbulent diffusion throughout the end of the domain, which results in a comparatively larger dilution factor. This behavior is also clearly reflected in the plume area curves, which show a substantially larger plume cross-section for the CRM configuration than for the engine-only case.

Although these differences are most apparent in the plot, owing to the magnitude of vortex-induced spreading, additional discrepancies are also visible in the immediate vicinity of the aircraft. In particular, two specific features can be identified in the temperature profile before 0.5 s (see the left-hand plots, first and second columns). In these first instants, the temperature profile of the CRM decreases more steeply than that of the engine-only configuration, for which the cooling slows down from 0.01 to 0.1 s. This feature is also visible in the dilution factor and area profiles (see the left zoom plots and blue arrows on the

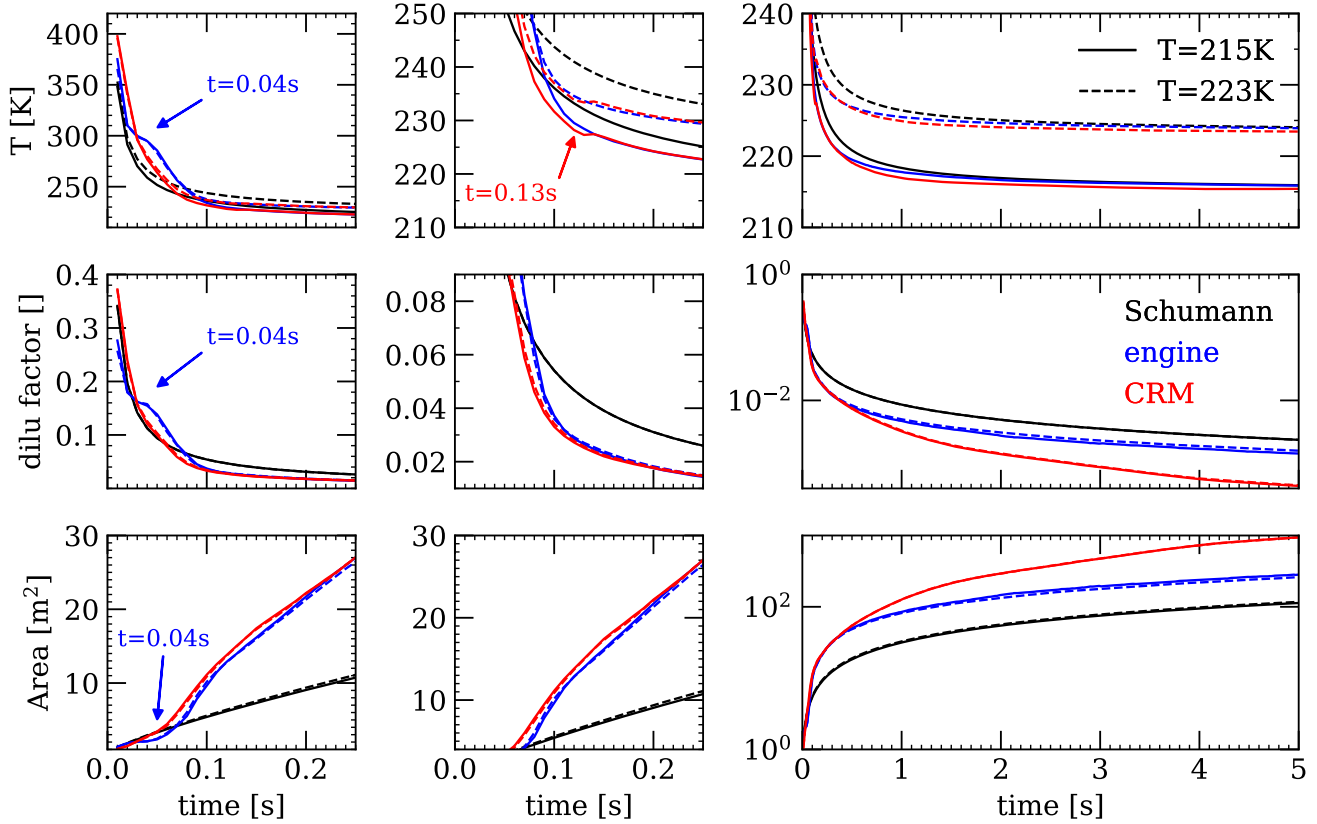


Figure 2. Temperature (first line), dilution factor (second line, calculated as described in equation 7), and plume area (third line) over time. Black: Schumann’s law dilution. Blue: engine-only 3D simulation dilution. Red: CRM 3D simulation dilution. The first and second columns are zoomed between zero and 0.25 s, while the third column covers the total duration of the simulation, from zero to five seconds. The different columns do not have the same minimum and maximum values for the y-axis. The blue arrows show the specific behavior in the first instants of the engine-only dilution profile caused by the dynamics at the engine exhaust (see text). The red arrow shows the specific behavior of the temperature profile observed for the CRM geometry case in the first instants and caused by the presence of the aircraft tail (see text).

temperature, the dilution factor, and the area profiles in Figure 2). The slightly higher temperature observed in the engine-only case can be attributed to the differences in flow dynamics induced by the presence or absence of the aircraft geometry.

235 Actually, in the CRM case, the nozzle exit is located beneath the wing and connected to it by the pylon. This arrangement gives rise to two distinct effects. First, the presence of the wing helps preserve the shock structure at the nozzle exit. Second, the pylon generates an additional, relatively weak vortex (Doty et al. (2004), or see the upper part of the jet in Figure 3a). For the jet and the resulting plume, these two effects both enhance cooling relative to the engine-only case. The preserved shock structure promotes greater expansion and therefore lower temperatures. In addition, the pylon-induced vortex enhances turbulent mixing

240 within the jet, leading to further cooling. Together, these mechanisms explain the slightly elevated temperatures found in the engine-only case.

The two temperature profiles meet again around 0.1 s, before a small bump of less than one Kelvin appears this time in the CRM case around 0.13 s (see the right zoom plots and red arrow on the temperature profile in Figure 2). This bump is not visible on the dilution factor profile, nor on the plume area profile, and seems characteristic of the temperature field. In fact, by plotting the temperature excess fields $T - T^a$, using a slice at the center of the jet as well as slices at various times (between 0.12 s and 0.15 s) behind the CRM and the engine alone (Figure 3), it is possible to see that this bump is related to the presence of the tail assembly in the case of the full CRM geometry.

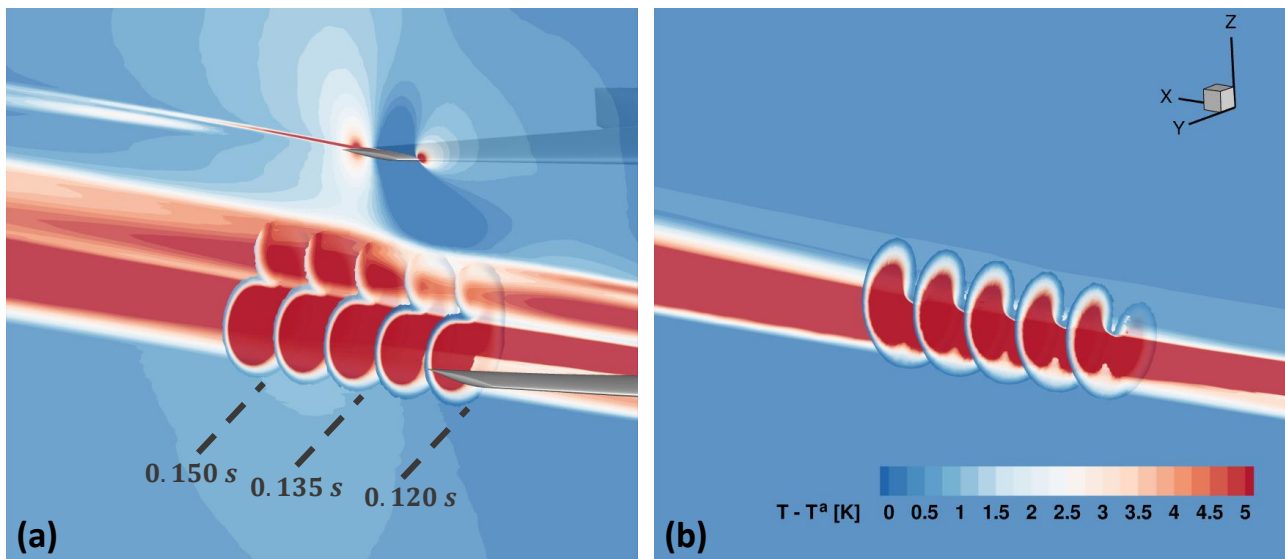


Figure 3. Temperature excess $T - T^a$ fields with a y -slice in the jet axis plane and x -slices in the transverse jet plane at the time of the temperature bump, for the CRM configuration (a) and the engine case (b)

As shown in Figure 3a, in the CRM configuration, the jet moves beneath the horizontal tailplane (HTP). The upper part of the jet, namely the portion that has interacted with the vortex generated by the pylon, then undergoes an expansion driven by the low-pressure region induced beneath the HTP, visible as a zone of reduced temperature. Since the HTP is not a lifting surface, a low-pressure region develops on its underside. The jet subsequently experiences re-compression as the flow re-equilibrates with the surrounding atmosphere at higher pressure, producing the warmer region that follows the cooling zone. This marked expansion followed by compression causes the upper part of the jet to cool from approximately 0.12 s onward, and then to reheat from about 0.135 s. This sequence explains the temperature difference of a few kelvin observed at these times between the CRM and engine-only cases: the latter is not subjected to such aerodynamic effects and instead evolves as a more conventional free jet in the atmosphere, as illustrated in Figure 3b.

These differences, whether associated with the presence of the vortex, the geometry (i.e., the pylon and tail), or compressibility effects, highlight the influence of including the complete aircraft geometry in the simulations. The resulting flow is more heterogeneous and complex than that obtained for the engine-only configuration, which in turn affects the plume's evo-



260 lution history and finally both the plume dilution and the resulting mean temperature. The following section addresses the consequences of these effects on the microphysics and characteristics of contrail formation.

5 Influence of the aircraft geometry on ice crystal formation

5.1 Ice particle concentration

If the effects discussed in the previous section influence the dilution and aerodynamics fields across the different cases, it is relevant to assess whether these differences translate into changes in the simulated microphysical properties. To this end, Figure 4 shows the temporal evolution of the ice crystal concentration within the plume for each case. The color coding of the curves remains consistent with that used above, while the written values indicate the ice crystal concentration at the end of the simulations, at $t = 5$ s. The objective here is to assess the influence of dilution on the evolution of ice crystal concentration. The effects of ambient temperature and soot conditions are examined in greater detail in the following section.

270 The effects of dilution and temperature variations on ice crystal concentrations within the plumes are apparent at two distinct levels. First, they are reflected in the two geometry-induced features identified in the temperature profiles and discussed in the previous section, each of which affects ice crystal formation in a different way. The presence of the pylon and the persistence of the shock waves at the engine exit, which further cools the plume, promote earlier ice nucleation. This effect is particularly pronounced under colder ambient conditions, where the rapid formation of volatile species and potential nucleation sites within the plume is enhanced. These observations are consistent with the findings of Garnier et al. (2014), which indicate that compressibility effects can influence the formation and evolution of ice crystals in the immediate vicinity of the engine. In the present simulations, the resulting crystal concentrations are therefore sensitive to the presence or absence of the complete aircraft geometry, which modifies the aerodynamic field in this region.

Similarly, the second geometry-induced feature, associated with the aircraft tail, also influences ice crystal nucleation. In particular, the temperature bump observed at $t = 0.13$ s in the CRM configuration, resulting from compression effects near the tail, is also reflected as a corresponding bump in the ice crystal concentration (see left-hand figures in fig. 4). This temperature perturbation delays the subsequent evolution of ice crystal nucleation. Although the aircraft tail is often omitted in simulations of contrail formation processes, these results suggest that it can also have a direct influence on the formation of ice crystals in the aircraft near-field. This effect is in addition to its direct influence in the vortex regime demonstrated by Bouhafid and Bonne (2026).

Finally, beyond the geometric effects observed during the initial stages, Figure 4 also shows that, at $t = 5$ s, the ice crystal number concentration can be up to four times higher in the engine-only simulation than in the simulation including the complete CRM geometry (see also Figure A1 and Figure A2). These results highlight the influence of the complete aircraft geometry and, in particular, of the associated wingtip vortices, which increase the area covered by the plume (Figure 2) and enhance plume mixing. This enhanced mixing leads to a more rapid decrease in particle concentration within the plume. The same observation can be made for Schumann's dilution law, which presents the higher concentrations in ice crystals, to be directly linked to the lower dilution effect displayed in fig. 2. This effect may be particularly relevant because it implies different spatial

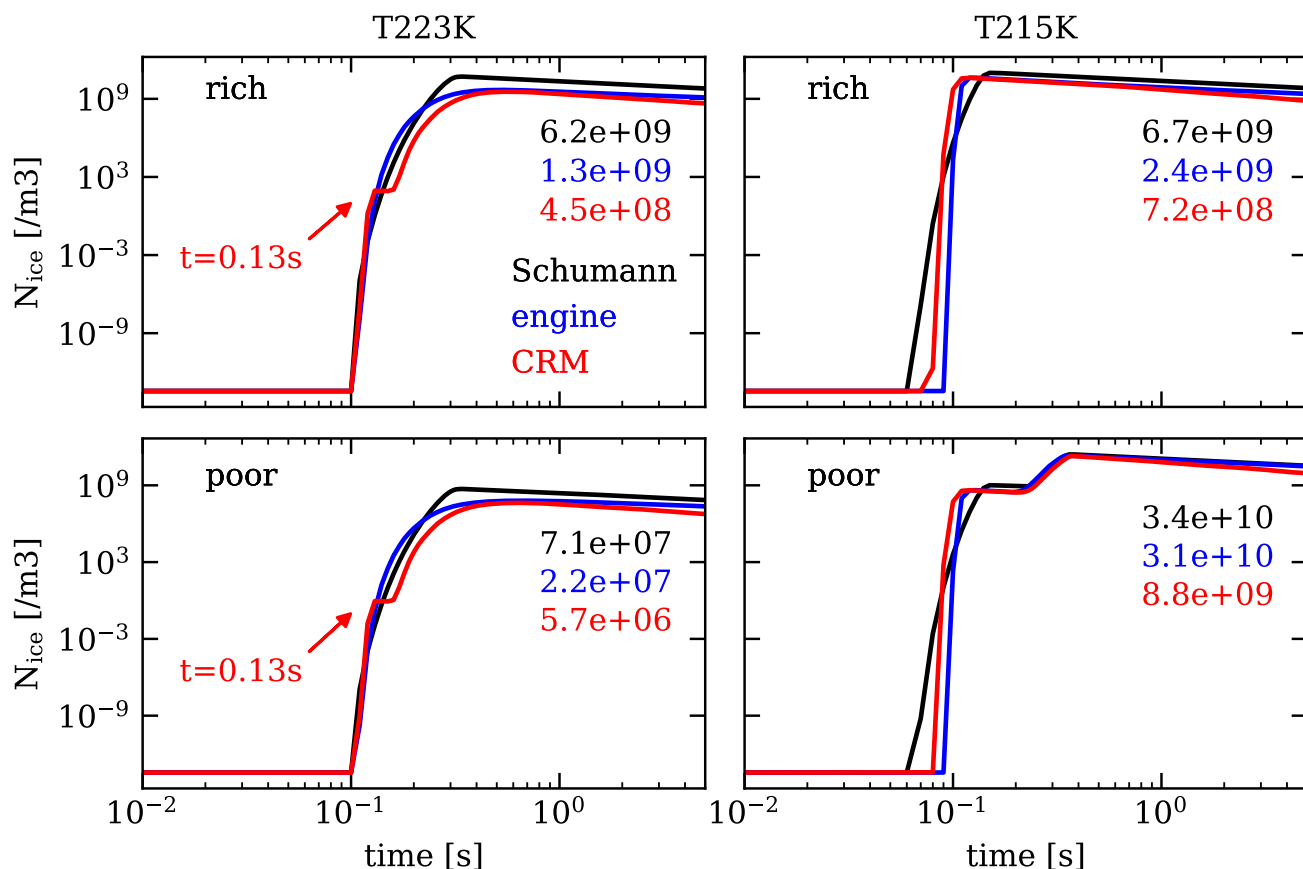


Figure 4. Ice crystal concentration in m^{-3} over time for Schumann's law (black), the engine-only case (blue), and the CRM case (red), and for the two tested ambient temperatures (left: 223 K, right: 215 K) and the two soot regimes (upper: rich, lower: poor).

distributions of ice crystals within the plume. At the beginning of the vortex regime, different distributions may, as shown by Unterstrasser (2014); Annunziata et al. (2025, 2026), influence the subsequent ice crystal sublimation or persistence within the
 295 vortex regime and beyond. This is notably due to their different relative position with respect to the vortices.

5.2 Ice particle number per meter

While analyzing the concentration of ice crystals within the plume is relevant, since this quantity is directly linked to plume dilution and spatial distribution, both of which depend on the configuration, the number of ice crystals formed per meter of flight is considered crucial for determining radiative forcing (Unterstrasser and Gierens, 2010b). The latter quantity provides
 300 an integrated measure of the total ice crystal formation, it therefore allows for overcoming the differences in plume spreading and enables a more direct comparison of the total number of crystals formed across the different configurations. The number

of ice crystals per meter, obtained by integrating the ice particle concentration over the plume cross-section, is then plotted in Figure 5.

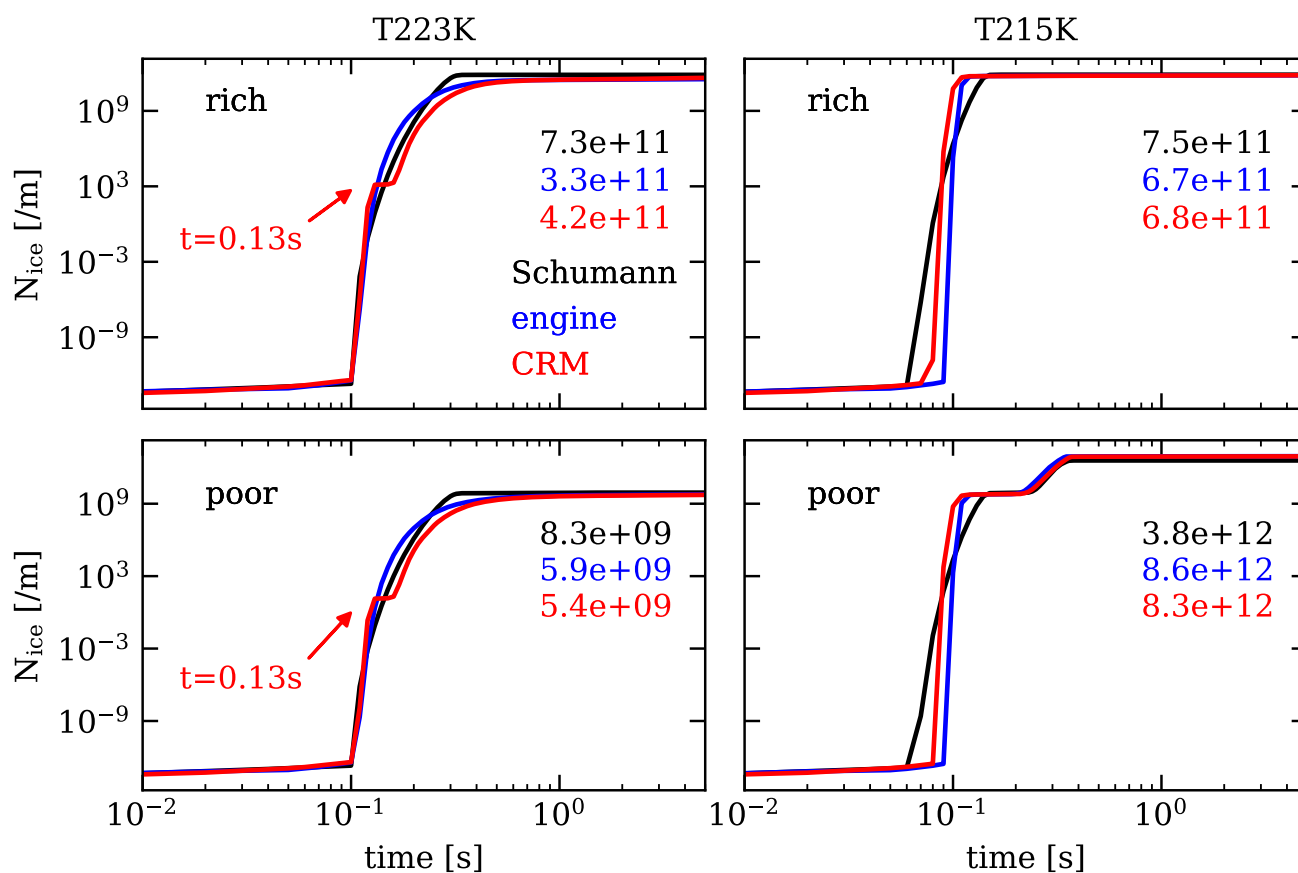


Figure 5. Same layout as Figure 4 applied to the ice crystals number per meter in m^{-1} .

In the soot-rich regime at 223 K, the soot nucleation pathway dominates ice formation. This nucleation mode starts rapidly within the first tenth of seconds, when the saturation has sharply increased and reached supersaturation due to the rapid temperature drop. Figure 6a shows the ratio of the ice particle apparent emission index to the non-volatile emission index at $t = 5$ s. This indicates that only 64 % and 50 %, for the CRM and engine-alone configuration, respectively, of the soot particles have been activated to ice crystals at 5 s simulation, versus 97 % for Schumann's law dilution. Indeed, saturation is controlled by both temperature and water vapor pressure; during dilution, its evolution depends on the competition between three effects: the drop in temperature (which tends to increase saturation), the reduction in the amount of water vapor initially emitted (which tends to reduce saturation), and the entrainment of water vapor from the ambient air (which tends to increase saturation). The quick and sharp temperature decrease observed in the very first instants with Schumann's law, described in section 4, combined with the lower dilution observed from around $t = 0.07$ s in comparison to the other two cases studied here, seems decisive in



triggering ice crystal formation, and leads to a final higher number of ice crystals (see also Figure A2). As mentioned in the previous section, the dilution driven by the CRM configuration is impacted by the presence of the tailplane, which seems to slow down the ice particle formation at $t = 0.13$ s. However, in this case we observe slightly more ice crystals formed per meter of flight in the end, than in the case of the engine-alone configuration (21 %, see Figure A2). This could be explained by the ambient air entrainment that drives dilution, which also contributes to increasing the water content within the plume.

At the same ambient temperature but under soot-poor conditions, the soot nucleation pathway still dominates the ice formation mode. This time, all or almost all soot particles have been activated and subsequently formed ice crystals, respectively for Schumann's dilution law and for the two 3D configurations (see Figure 6a), due to the higher amount of water vapor distributed over fewer soot particles. In that case, the effect of the tailplane, which slightly slows the temperature drop for the CRM configuration at $t = 0.13$ s, appears to be decisive, and the engine-alone configuration produces slightly (9 %, see Figure A2) more ice crystals than the CRM geometry configuration.

In the soot-rich regime at 215 K, the soot nucleation pathway still dominates the ice formation mode. The decrease in temperature is steeper than at 223 K, and all soot particles activate rapidly to ice crystals. Indeed, at 5 s simulation, the ratio of the emission index of the ice crystals over that of the non-volatile particles equals one for Schumann's dilution law, as well as for the two configurations, engine-alone and CRM geometry (see Figure 6b).

Conversely, at 215 K in the soot-poor regime, the nucleation pathway involving volatile compounds predominates once all soot particles have been activated (see Figure 6b). This mode of nucleation requires more time for ice particle formation, primarily due to the small size of the clusters, and occurs slightly later in the plume's life cycle (~ 0.3 s as shown in Figure 5). In this case, simulations C215P and E215P overestimate the ice particle number by a factor of ~ 3 (or by around 126 %, see Figure A2) in comparison to the results obtained using Schumann's dilution law. This is likely related to the timing of freezing via the volatile nucleation pathway, which occurs after 0.07 s, when Schumann's dilution law becomes "slower" than those derived from the 3D simulations (see 2), and the temperature is higher, limiting the ice crystal formation in comparison to the two other configurations.

Once again, the difference observed between the CRM and the engine-alone configurations might be related to the slight temperature difference caused by the presence of the tailplane in the CRM dilution case, making the temperature slightly higher than that of the engine-alone configuration at $t = 0.13$ s (see section 4), i.e. during the very brief time interval when nucleation appears to be triggered. The engine-alone configuration leads to 4 % more ice particles than the CRM geometry configuration, see also Figure A2).

Overall, the number of ice crystals formed is governed by the combined effects of the soot-emission regime, ambient temperature, and plume dilution specific to each configuration. At higher temperatures, ice formation is primarily governed by soot particle activation. The fraction of activated soot particles depends on the number of such particles, as well as on the competition between the effects of variations in temperature and water vapor concentration within the plume. At lower temperatures, however, the plume cools much more rapidly in both configurations, so that nearly all soot particles are activated into ice crystals. In the soot-poor regime, the total number of ice crystals formed thus becomes more sensitive to subsequent nucleation involving volatile compounds.

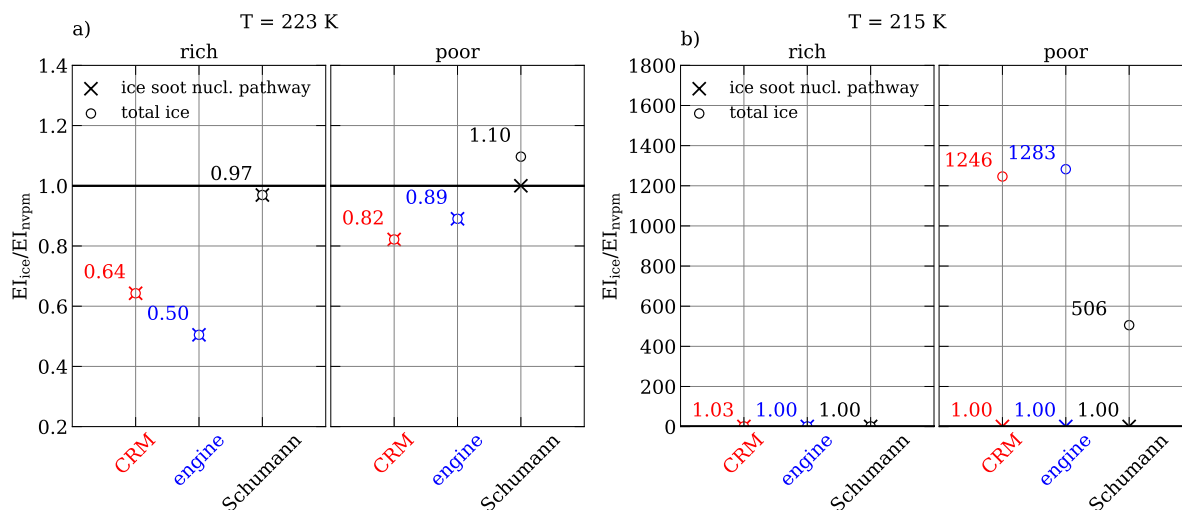


Figure 6. Ratio of the apparent emission index of ice crystals at $t = 5$ s over the initial emission index of non-volatile particles plotted for the two soot regimes, for the three dilution configuration cases, for the case of the 223 K ambient temperature (a) and the case of the 215 K ambient temperature (b). The crosses represent the ice particles formed by the soot nucleation pathway, while circles represent the total ice particles (soot and volatile nucleation pathway). Note that crosses and circles are superimposed in all cases except in C215P and E215P.

5.3 Ice particle size distribution

Finally, in addition to the concentration and number of particles per meter of flight, ice crystal size distribution is also a key parameter for characterizing contrails and determining their radiative forcing (Schumann et al., 2011). The distribution of ice particles in terms of size and number concentration is plotted in Figure 7 for the different cases at 5 s. The continuous and the dashed lines correspond to the ice particles formed via the soot nucleation pathway and the volatile nucleation pathway respectively.

Figures A1 and A2 show the mean radius determined for each case by integrating the particle radius over the distribution plotted in Figure 7. At $T = 223$ K we observe two size modes in the soot-rich regime, essentially composed of particles formed via the soot nucleation pathway, for the three configurations. Conversely, almost only one mode is seen in the soot-poor regime, which can be directly correlated to the analysis made for the ice particle number in the previous section with Figure 6a. The two modes account for the limited formation of ice crystals in the case of high ambient temperature combined with soot-rich regime conditions. In this case, larger ice crystals are observed for the engine-only case, with a mean ice particle radius 9 and 37 % higher than for the CRM case (see Figure A2), respectively for the soot-rich and soot-poor regime. Under these regime conditions, the soot nucleation pathway is promoted, and at this early stage of contrail formation, the water vapor driving ice growth essentially originates from the engine exhaust. This explains why larger ice crystals are expected in the case of a slower dilution, since the water vapor concentration emitted into the plume remains "available" for condensation for a longer time. This is corroborated by the comparison with Schumann's dilution law. For the latter, we also observe a mode of particles

formed via volatile nucleation pathway. This is consistent with the ratio of the ice crystal emission index to the soot particle emission index observed in Figure 6, which is slightly greater than unity in the case of S223P.

At the lower temperature $T = 215$ K, in the soot-rich regime and for all studied cases, particle formation via the soot nucleation pathway still predominates, and the mean ice crystal radius varies little among the different cases (differences within 3 % between the different cases as shown in Figure A1 and A2). Conversely, in the soot-poor regime, the volatile nucleation pathway predominates, with the emergence of an additional mode of lower-sized particles. Particles formed via the soot nucleation pathway are approximately 40% larger in Schumann's law case than in the two other cases. This may result from slower dilution and the timing of ice nucleation triggered by the activation of volatile particles, as water vapor deposition concentrates on the larger particles, which, in this case, are precisely those initially formed via the soot nucleation pathway. Furthermore, the full CRM geometry case exhibits slightly larger crystals than the engine-only case, a difference attributable to the lower number of ice crystals formed under these conditions. Indeed, the higher the number of ice crystals, the smaller their radius, due to the distribution of available water vapor within the plume.

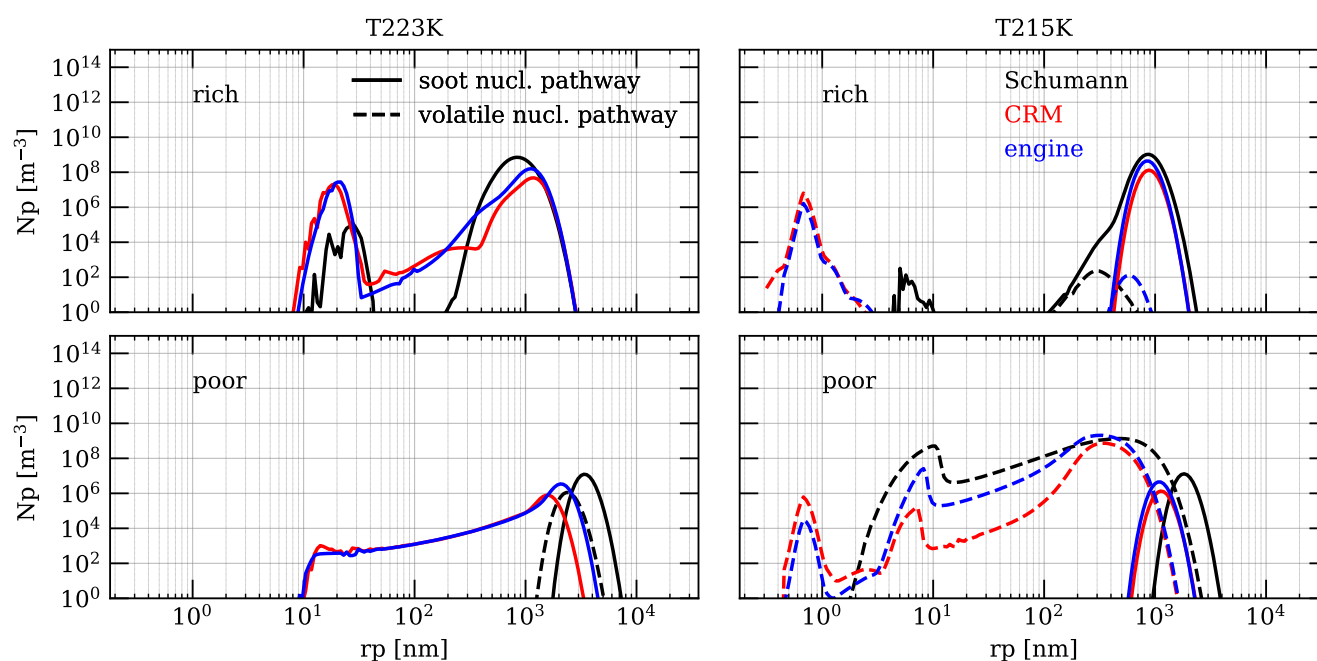


Figure 7. Particle size distribution for Schumann's law (black), the engine-only case (blue), and the CRM case (red), at $t = 5$ s, for the two tested ambient temperatures (left: 223 K, right: 215 K) and the two soot regimes (upper: rich, lower: poor). Continuous line: ice crystals formed from activated soot (soot nucleation pathway); dashed line: ice crystals formed from activated volatile particles (volatile nucleation pathway).

6 Conclusions

Four 3D RANS simulations have been used to generate different dilution conditions, extracted as time-dependent dilution factors and temperature profiles, for two different aircraft configurations and two ambient temperatures of 223 and 215 K. The first configuration consists of a full aircraft geometry, the CRM, while the second consists of the engine alone. These dilution profiles have been prescribed into a contrail microphysical code to investigate, first, the impact of dilution changes induced by the presence of a full aircraft geometry and, second, the role of additional geometry-related effects on near-field contrail formation and on the resulting number of ice crystals.

The results show that the presence of the entire aircraft geometry directly affects the timing of ice particle formation, the ice particle concentration, the number of ice particles per meter of flight, and their size. Indeed, in addition to the main aircraft wake characterized by the wingtip vortices, two distinct features are particularly apparent in the simulation with full CRM geometry in comparison to the engine alone. First, the pylon located above the engine seems to significantly contribute to the initial mixing of the plume at the exhaust and to the continuous decrease of temperature. Second, the presence of the tailplane appears to play a significant role in the timing of ice formation, as it locally increases the temperature, which consequently slows down the cooling of the plume.

These results show that neglecting the full aircraft geometry may lead to either an underestimation or an overestimation of ice crystal concentration (difference of a factor of 2 to 4), ice crystal number (9 % to −21 % relative difference), and ice crystal size (−3 to 37 % relative difference), depending on the ambient temperature and soot regime considered. These differences may be significant, given that these three parameters are key inputs for estimating the radiative impact of contrails.

Moreover, comparison with the results obtained using the usual Schumann's analytical dilution law also shows an underestimation of the ice particle number per meter of flight between 9 and 42 %, except in the soot-poor regime with the ambient temperature of 215 K, where, conversely, it shows an overestimation of two times Schumann's expected values. Schumann's law is an empirical law derived from several in-flight measurements taken on the plumes of older aircraft types (typically B727, B747, supersonic Concorde, as described in Schumann et al. (1998)). This analytical law is widely used as a reference in current literature, and would benefit from being updated and adapted to the current aircraft fleet. The comparison also highlights the need to account for the interplay of the various effects of dilution: the decrease in temperature, the reduction in the concentration of species within the plume, and the entrainment of ambient air and its constituents.

Furthermore, in addition to the study by Annunziata et al. (2025), the present results demonstrate not only the importance of dilution changes for ice crystal formation but also the impact of accounting for the full aircraft geometry in the formation process. As already shown by Bouhafid and Bonne (2026) in the vortex regime, the aircraft tail plays a role in the early formation of ice crystals, while the wing pylon also affects the very first stages of plume evolution. These geometrical features influence ice crystal formation in particular through the compressibility effects they induce, which have been shown to be important for contrail formation by Garnier et al. (2014).

While the present study highlights these effects using an offline coupling strategy for microphysics, based on RANS simulations coupled with a box model, it would be valuable to extend this approach further. First, the study presented here takes into



account the average dilution and does not reflect the variability within the plume, whereas temperature and dilution can vary by several degrees and several orders of magnitude, respectively, between the center and the periphery of the plume. Consequently, the next step of this work will involve applying the method presented here to multiple trajectories extracted from the 3D field, following the same principle as that used in Vancassel et al. (2014), to examine the implications for the comparison between the two geometries. A future perspective would be to perform a similar analysis using a fully coupled disperse phase CFD model. Such an online coupling would make it possible to account for plume inhomogeneities and water-vapor depletion within the plume, which cannot be represented by a box model (Bier et al., 2022). The analysis could be extended with the CFD simulation into the vortex and dissipation regimes, and potentially beyond, in order to assess how important the inclusion of realistic aircraft geometry remains for predicting ice crystal survival during the vortex phase and, later, the transition towards contrail cirrus. This remains an open question in light of the results obtained by Annunziata et al. (2026), which show that the initial dilution effects fade in the far field. However, these conclusions remain limited by the microphysical model used, which does not allow for a precise estimate of the number of ice crystals.

Code availability. The CEDRE simulation code employed in this work is proprietary to ONERA. Access to and use of the software requires a valid license key and is subject to institutional licensing agreements. For this reason, the code cannot be made publicly available. The Modèle Microphysique pour Effluents (MoMiE) model has been developed by and is the proprietary intellectual property of ONERA, France, and is not publicly available. The use of the MoMiE code requires research collaboration within the framework of a contractual partnership (contact margaux.vals@onera.fr or nicolas.bonne@onera.fr). Researchers interested in the methodology are encouraged to contact the corresponding authors for further information.

Author contributions. N.B. and M.V. conceptualised the projet. R.A. and N.B. performed the 3D RANS simulations. M.V. performed the microphysics model runs. M.V., R.A. and N.B. discussed and analyzed the model results. M.V. and R.A. wrote the paper.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This research has been supported by the French Ministère de la Transition Ecologique et Solidaire under the CLIMAVIATION programme (grant no. DGAC N2021-39), with support from France's Plan National de Relance et de Résilience (PNRR) and the European Union's NextGenerationEU.



References

- Annunziata, R., Bonne, N., and Garnier, F.: Numerical investigation of engine position effects on contrail formation and evolution in the near-field of a realistic aircraft configuration, *Aerospace Science and Technology*, p. 110703, <https://doi.org/10.1016/j.ast.2025.110703>, 2025.
- 440 Annunziata, R., Bonne, N., and Garnier, F.: Engine Position Effects on Contrail Evolution for a Realistic Aircraft Configuration, *Journal of Aircraft*, 0, 1–16, <https://doi.org/10.2514/1.C038870>, 2026.
- Bier, A., Unterstrasser, S., and Vancassel, X.: Box model trajectory studies of contrail formation using a particle-based cloud microphysics scheme, *Atmospheric Chemistry and Physics*, 22, 823–845, <https://doi.org/10.5194/acp-22-823-2022>, 2022.
- Bier, A., Unterstrasser, S., Zink, J., Hillenbrand, D., Jurkat-Witschas, T., and Lottermoser, A.: Contrail Formation On Ambient Aerosol
 445 Particles For Aircraft With Hydrogen Combustion: A Box Model Trajectory Study, *Atmospheric Chemistry & Physics*, pp. 2319–2344, <https://doi.org/10.5194/acp-24-2319-2024>, 2024.
- Bouhafid, Y. and Bonne, N.: Simulation of a contrail formation and early life cycle for a realistic airliner geometry, *Atmospheric Chemistry and Physics*, 26, 1053–1078, <https://doi.org/10.5194/acp-26-1053-2026>, 2026.
- Burkhardt, U. and Kärcher, B.: Global radiative forcing from contrail cirrus., *Nature Clim Change*, 1, 54–58,
 450 <https://doi.org/10.1038/nclimate1068>, 2011.
- Cantin, S., Chouak, M., Morency, F., and Garnier, F.: Eulerian–Lagrangian CFD-microphysics modeling of a near-field contrail from a realistic turbofan, *International Journal of Engine Research*, 23, 661–677, <https://doi.org/10.1177/1468087421993961>, 2022.
- Cantin, S., Chouak, M., and Garnier, F.: Effects of fuel sulfur content and nvPM emissions on contrail formation: a CFD-microphysics study including the role of organic compounds, *Journal of Aerosol Science*, 188, 106 612, <https://doi.org/10.1016/j.jaerosci.2025.106612>, 2025.
- 455 Doty, M., Henderson, B., and Kinzie, K.: Turbulent Flow Field Measurements of Separate Flow Round and Chevron Nozzles with Pylon Interaction Using Particle Image Velocimetry, 10th AIAA/CEAS Aeroacoustics Conference, <https://doi.org/10.2514/6.2004-2826>, 2004.
- Ferreira, T., Alonso, J. J., and Gorlé, C.: Developing a Numerical Framework for the High-Fidelity Simulation of Contrails: Sensitivity Analysis for Conventional Contrails, *AIAA AVIATION FORUM AND ASCEND 2024*, <https://doi.org/10.2514/6.2024-3775>, 2024.
- Garnier, F., Maglaras, E., Morency, F., and Vancassel, X.: Effect of Compressibility on Contrail Ice Particle Growth in an Engine Jet,
 460 *International Journal of Turbo & Jet-Engines*, 31, 131–140, <https://doi.org/doi:10.1515/tjj-2013-0039>, 2014.
- Guignery, F., Montreuil, E., Thual, O., and Vancassel, X.: Contrail microphysics in the near wake of a realistic wing through RANS simulations, *Aerospace Science and Technology*, 23, 399–408, <https://doi.org/10.1016/j.ast.2011.09.011>, 35th ERF: Progress in Rotorcraft Research, 2012.
- Jacquín, L. and Garnier, F.: On the Dynamics of Engine Jets behind a Transport Aircraft, Rep. AGARD CP-584, 1996.
- 465 Jeßberger, P., Voigt, C., Schumann, U., Sölch, I., Schlager, H., Kaufmann, S., Petzold, A., Schäuble, D., and Gayet, J.-F.: Aircraft type influence on contrail properties, *Atmospheric Chemistry and Physics*, 13, 11 965–11 984, <https://doi.org/10.5194/acp-13-11965-2013>, 2013.
- Kärcher, B.: A trajectory box model for aircraft exhaust plumes, *Journal of Geophysical Research: Atmospheres*, 100, <https://doi.org/10.1029/95JD01638>, 1995.
- 470 Kärcher, B.: Formation and radiative forcing of contrail cirrus, *Nature Communications*, 9, <https://doi.org/10.1038/s41467-018-04068-0>, 2018.



- Khou, J.-C., Ghedhaïfi, W., Vancassel, X., and Garnier, F.: Spatial Simulation of Contrail Formation in Near-Field of Commercial Aircraft, *Journal of Aircraft*, 52, 1927–1938, <https://doi.org/10.2514/1.C033101>, 2015.
- Kärcher, B.: Physicochemistry of aircraft-generated liquid aerosols, soot, and ice particles: 1. Model description, *Journal of Geophysical Research: Atmospheres*, 103, 17 111–17 128, <https://doi.org/10.1029/98JD01044>, 1998.
- Kärcher, B. and Yu, F.: Role of aircraft soot emissions in contrail formation, *Geophysical Research Letters*, 36, <https://doi.org/10.1029/2008GL036649>, 2009.
- Kärcher, B., Peter, T., Biermann, U. M., and Schumann, U.: The Initial Composition of Jet Condensation Trails, *Journal of Atmospheric Sciences*, 53, 3066 – 3083, [https://doi.org/10.1175/1520-0469\(1996\)053<3066:TICOJC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1996)053<3066:TICOJC>2.0.CO;2), 1996.
- Lee, D., Fahey, D., Skowron, A., Allen, M., Burkhardt, U., Chen, Q., Doherty, S., Freeman, S., Forster, P., Fuglestad, J., Gettelman, A., De León, R., Lim, L., Lund, M., Millar, R., Owen, B., Penner, J., Pitari, G., Prather, M., Sausen, R., and Wilcox, L.: The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, *Atmospheric Environment*, 244, 117 834, <https://doi.org/10.1016/j.atmosenv.2020.117834>, 2021.
- Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C., Lim, L. L., Owen, B., and Sausen, R.: Aviation and global climate change in the 21st century, *Atmospheric Environment*, 43, 3520–3537, <https://doi.org/10.1016/j.atmosenv.2009.04.024>, 2009.
- Lewellen, D. C.: A Large-Eddy Simulation Study of Contrail Ice Number Formation, *Journal of the Atmospheric Sciences*, 77, 2585 – 2604, <https://doi.org/10.1175/JAS-D-19-0322.1>, 2020.
- Lewellen, D. C., Meza, O., and Huebsch, W. W.: Persistent Contrails and Contrail Cirrus. Part I: Large-Eddy Simulations from Inception to Demise, *Journal of the Atmospheric Sciences*, 71, 4399 – 4419, <https://doi.org/10.1175/JAS-D-13-0316.1>, 2014.
- Menter, F. R.: Two-equation eddy-viscosity turbulence models for engineering applications, *AIAA Journal*, 32, 1598–1605, <https://doi.org/10.2514/3.12149>, 1994.
- Miake-Lye, R. C., Martinez-Sanchez, M., Brown, R. C., and Kolb, C. E.: Plume and wake dynamics, mixing, and chemistry behind a high speed civil transport aircraft, *Journal of Aircraft*, 30, 467–479, <https://doi.org/10.2514/3.46368>, 1993.
- Paoli, R. and Shariff, K.: Contrail Modeling and Simulation, *Annual Review of Fluid Mechanics*, 48, 393–427, <https://doi.org/10.1146/annurev-fluid-010814-013619>, 2016.
- Paoli, R., Hélie, J., and Poinot, T.: Contrail formation in aircraft wakes, *Journal of Fluid Mechanics*, 502, 361–373, <https://doi.org/10.1017/S0022112003007808>, 2004.
- Paoli, R., Vancassel, X., Garnier, F., and Mirabel, P.: Large-eddy simulation of a turbulent jet and a vortex sheet interaction: particle formation and evolution in the near field of an aircraft wake, *Meteorologische Zeitschrift*, 17, 131–144, <https://doi.org/10.1127/0941-2948/2008/0278>, 2008.
- Paoli, R., Nybelen, L., Picot, J., and Cariolle, D.: Effects of jet/vortex interaction on contrail formation in supersaturated conditions, *Physics of Fluids*, 25, 053 305, <https://doi.org/10.1063/1.4807063>, 2013.
- Petzold, A., Ström, J., Ohlsson, S., and Schröder, F.: Elemental composition and morphology of ice-crystal residual particles in cirrus clouds and contrails, *Atmospheric Research*, 49, 21–34, [https://doi.org/10.1016/S0169-8095\(97\)00083-5](https://doi.org/10.1016/S0169-8095(97)00083-5), 1998.
- Reffloch, A., Courbet, B., Murrone, A., Villedieu, P., Laurent, C., Gilbank, P., Troyes, J., Tessé, L., Chaineray, G., Dargaud, J., Quémerais, E., and Vuillot, F.: CEDRE Software, *AerospaceLab Journal*, <https://hal.science/hal-01182463>, 2011.
- Rojo, C., Vancassel, X., Mirabel, P., Ponche, J.-L., and Garnier, F.: Impact of alternative jet fuels on aircraft-induced aerosols, *Fuel*, <https://doi.org/10.1016/j.fuel.2014.12.021>, 2015.



- Schumann, U., Schlager, H., Arnold, F., Baumann, R., Haschberger, P., and Klemm, O.: Dilution of aircraft exhaust plumes at cruise altitudes, *Atmospheric Environment*, [https://doi.org/10.1016/S1352-2310\(97\)00455-X](https://doi.org/10.1016/S1352-2310(97)00455-X), 1998.
- Schumann, U., Mayer, B., Gierens, K., Unterstrasser, S., Jessberger, P., Petzold, A., Voigt, C., and Gayet, J.-F.: Effective Radius of Ice Particles in Cirrus and Contrails, *Journal of the Atmospheric Sciences*, 68, 300 – 321, <https://doi.org/10.1175/2010JAS3562.1>, 2011.
- Sorokin, A., Vancassel, X., and Mirabel, P.: On volatile particle formation in aircraft exhaust plumes, *Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science*, [https://doi.org/10.1016/S1464-1917\(01\)00047-2](https://doi.org/10.1016/S1464-1917(01)00047-2), 2001.
- 515 Unterstrasser, S.: Large-eddy simulation study of contrail microphysics and geometry during the vortex phase and consequences on contrail-to-cirrus transition, *Journal of Geophysical Research: Atmospheres*, 119, 7537–7555, <https://doi.org/10.1002/2013JD021418>, 2014.
- Unterstrasser, S. and Gierens, K.: Numerical simulations of contrail-to-cirrus transition – Part 1: An extensive parametric study, *Atmospheric Chemistry and Physics*, 10, 2017–2036, <https://doi.org/10.5194/acp-10-2017-2010>, 2010a.
- Unterstrasser, S. and Gierens, K.: Numerical simulations of contrail-to-cirrus transition – Part 2: Impact of initial ice crystal number, radiation, stratification, secondary nucleation and layer depth, *Atmospheric Chemistry and Physics*, 10, 2037–2051, <https://doi.org/10.5194/acp-10-2037-2010>, 2010b.
- 520 Unterstrasser, S. and Görsch, N.: Aircraft-type dependency of contrail evolution, *Journal of Geophysical Research: Atmospheres*, 119, 14,015–14,027, <https://doi.org/10.1002/2014JD022642>, 2014.
- Vancassel, X., Mirabel, P., and Garnier, F.: Numerical simulation of aerosols in an aircraft wake using a 3D LES solver and a detailed microphysical model, *International Journal of Sustainable Aviation*, 1, 139–159, <https://doi.org/10.1504/IJSA.2014.065480>, 2014.
- 525 Vancassel, X. P., Garnier, F. A., and Mirabel, P. J.: In *Plume Physics and Chemistry*, *Encyclopedia of Aerospace Engineering*, <https://doi.org/10.1002/9780470686652.eae351>, 2010.
- Vassberg, J., Dehaan, M., Rivers, M., and Wahls, R.: Development of a Common Research Model for Applied CFD Validation Studies, 26th AIAA Applied Aerodynamics Conference, <https://doi.org/10.2514/6.2008-6919>, 2008.
- 530 Voigt, C., Märkl, R., Sauer, D., Dischl, R., Renard, C., Seeliger, K., Yu, F., Kaufmann, S., Bräuer, T., Jurkat-Witschas, T., Le Chenadec, G., Moreau, J., Requena-Esteban, E., Bonne, N., Vals, M., Roche, A., Zelina, J., Dörnbrack, A., Eirenschmalz, L., Heckl, C., Horst, E., Lichtenstern, M., Marsing, A., Neumann, G., Roiger, A., Scheibe, M., Stock, P., Giez, A., Eckel, G., and Le Clercq, P.: Substantial aircraft contrail formation at low soot emission levels, *Nature*, <https://doi.org/10.1038/s41586-026-10286-0>, 2026.
- Wong, H.-W. and Miake-Lye, R. C.: Parametric studies of contrail ice particle formation in jet regime using microphysical parcel modeling, *Atmospheric Chemistry and Physics*, 10, 3261–3272, <https://doi.org/10.5194/acp-10-3261-2010>, 2010.
- 535 Yu, F., Kalcher, B., and Anderson, B. E.: Revisiting Contrail Ice Formation: Impact of Primary Soot Particle Sizes and Contribution of Volatile Particles, *Environmental Science and Technology*, 58, 17 650–17 660, <https://doi.org/10.1021/acs.est.4c04340>, 2024.



Appendix A: Numerical summary of results

Figure A1 displays the values of the variables defining the characteristics of the contrail after 5 seconds simulation. Figure A2
540 shows the relative difference between those values obtained for the different cases of dilution calculation.

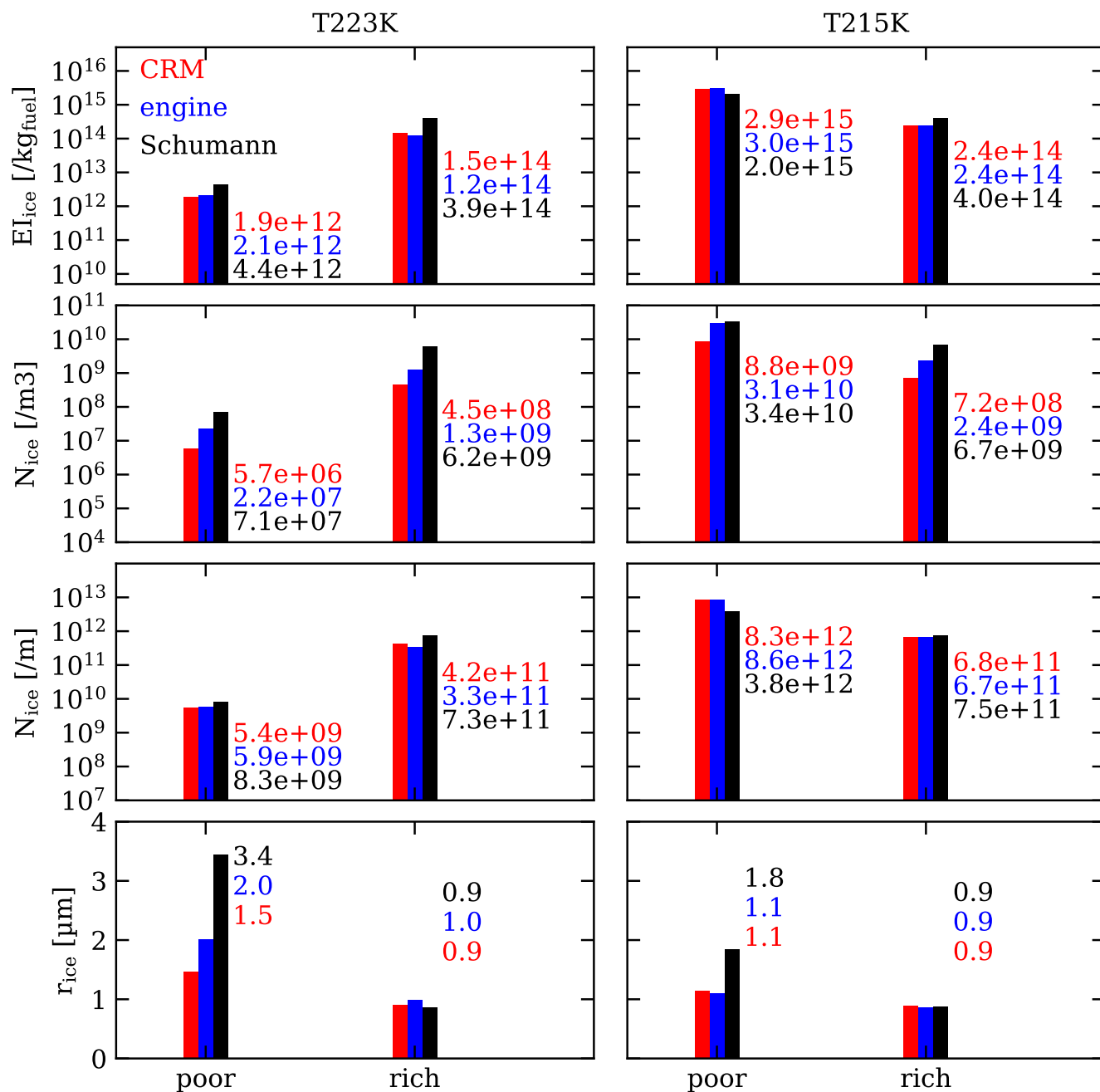


Figure A1. Apparent emission index of ice in kg_{fuel}^{-1} , ice crystals concentration in m^{-3} , ice crystals number per meter in m^{-1} , and averaged ice crystals radius in μm at $t = 5$ s simulation for the two tested ambient temperatures and the two tested soot regimes, and the chosen reference plume boundary threshold $N_{min} = 100 m^{-3}$.

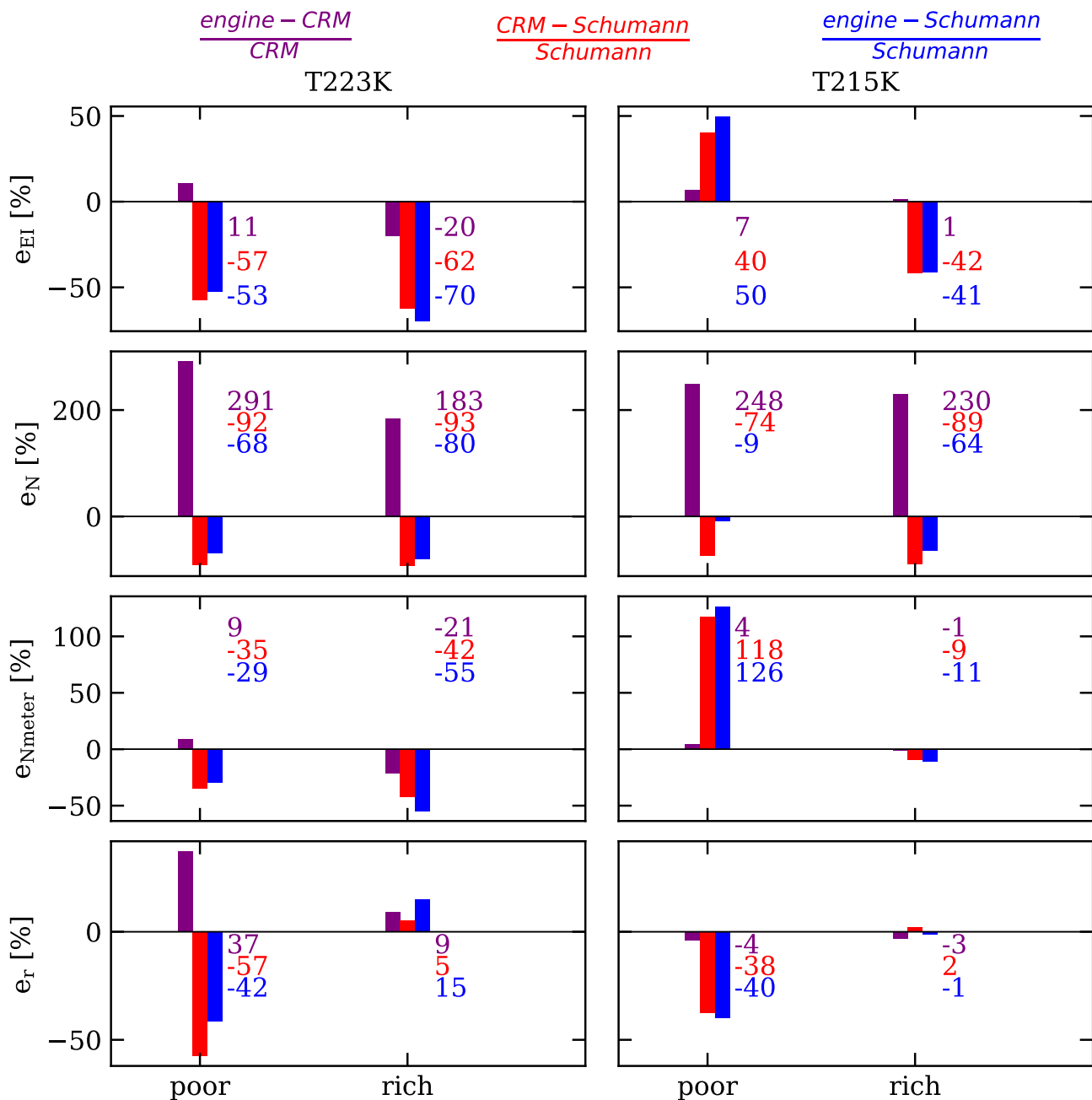


Figure A2. Same layout as Figure A1 applied to the relative difference e_x between the studied cases, with x being the different variables of emission index EI , ice crystals concentration N , ice crystals number N_{meter} and ice crystals radius r , for the chosen reference plume boundary threshold $N_{min} = 100 \text{ m}^{-3}$. Purple: relative difference between the engine-only and the CRM geometry cases ($\frac{engine - CRM}{CRM}$). Red: relative difference between the CRM geometry and Schumann's law cases ($\frac{CRM - Schumann}{Schumann}$). Blue: relative difference between the engine-only geometry and the Schumann's law cases ($\frac{engine - Schumann}{Schumann}$).