



Simplifying assumptions made by contrail-cirrus models lead to irreconcilable differences in geometric and optical contrail properties

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Abstract. Targeted flight rerouting for contrail avoidance relies on computational models to predict which avoidance actions would provide the most warming reduction. In the absence of empirical data for model validation, we propose using intercomparison to evaluate whether the lifetime total extinction of contrails (a proxy for climate impact) – as predicted by a high-fidelity contrail model – can be robustly predicted by lower-fidelity models when simulating contrails individually without feedbacks with a coupled weather model. We compare three contrail-cirrus models in the diffusion regime: CoCiP (a 0D plume model), APCEMM (a 2D simplified model), and EULAG-LCM (a large eddy simulation model applied on a 2D grid) under prescribed meteorological conditions. We identify that differential sedimentation and turbulence might be necessary to simulate a contrail in a physically consistent way. Since monodisperse 0D models are unable to represent differential sedimentation, the CoCiP and EULAG-LCM results have a low Pearson correlation coefficient of 0.50, compared to 0.93 between APCEMM and EULAG-LCM. The 0D and monodisperse nature of CoCiP affects its response by varying amounts in different regions of the parameter space. The presence of an explicit turbulence solver in EULAG-LCM enhances the ice crystal loss and increases the total ice mass, leading to a contrail with a higher settling velocity than in APCEMM, which parametrises turbulence. APCEMM contrails hence last longer and are larger. Hence, APCEMM overpredicts the lifetime total extinction by ~30 % relative to EULAG-LCM, demonstrating that a strong correlation between models does not imply agreement in the predicted plume-scale properties.

1 Introduction

Recent estimates of the climate impacts from aviation indicate that the net aviation effective radiative forcing (ERF; a metric of climate impact) has increased by 51 % from 2005 to 2018, with carbon dioxide accounting for 34 % of the 2018 aviation ERF and condensation trails (contrails) accounting for 57 % (Lee et al., 2021). Unlike proposed methods to reduce carbon dioxide emissions from aircraft, contrail avoidance through the rerouting of flights does not require modifications to the airframe, engine, fuel, or existing physical infrastructure and hence has the lowest potential time to implementation (Smith et



al., 2026). However, developing robust methods for contrail avoidance through rerouting (“contrail avoidance”) will be necessary to ensure that avoidance actions have the intended effect. So far, two types of strategies have emerged in the literature: those *neutral* strategies targeting a random subset of all persistent contrails (contrails that last over 10 minutes), and those *targeted* strategies targeting a specific subset of the persistent contrails, usually those responsible for the highest predicted warming (Teoh et al., 2020a, 2020b).

Contrails form when the Schmidt-Appleman criterion is satisfied (Schumann, 1996), and they persist only when the ambient humidity exceeds the ice saturation threshold. Therefore, neutral avoidance strategies only require the ability to predict the location of ice-supersaturated regions (ISSRs) and the temperature at cruise altitudes but are inherently less fuel efficient than targeted strategies if accurate prediction is possible. Meanwhile, warming-targeted strategies require accurate time-evolving meteorological data, as well as fit-for-purpose contrail models that can predict warming of the contrails. Nevertheless, both types of strategies face barriers to implementation. Neutral strategies will on average yield benefits proportional to the size of the intervention (notwithstanding response nonlinearity). Teoh et al. (2024) estimate that 5% of all flown distance produce contrails, so avoiding even 10% of contrail formation would mean modifying the flight plans for at minimum 0.5% of all flown distance. If a targeted strategy is followed instead, the contrail models which would be used to identify priority contrails need to be lightweight, well-understood, and consistent with either more accurate models or ground-truth data at both early and late lifetimes. However, an extensive ground truth dataset suitable to constraining contrail evolution does not exist in the literature and may not ever be available at the required fidelities. Therefore, good understanding of the available models is required for warming-targeted contrail avoidance to make more informed and robust choices about what contrails should be avoided.

Ideally, contrail models should be coupled with numerical weather prediction (NWP) models or global climate models (GCMs) to capture the meteorological feedbacks associated with each contrail avoidance scenario (as has been previously done by e.g. Schumann et al., 2015; Bock and Burkhart, 2016; Zhang et al., 2024; and Schumann and Seifert, 2025), hence enabling the estimation of the climate impact of the scenarios – not just their isolated radiative effects. However, in practice NWP and GCM simulations are too computationally expensive to be performed in the highly dynamic operational environment, so contrail cirrus models are typically not fully (two-way) coupled with a NWP model and simply use NWP data as their input.

At present, the most popular (Akhtar Martínez et al., 2025) plume-scale contrail model is CoCiP (Schumann, 2012), an open-source model which assumes a Lagrangian Gaussian plume, making it effectively zero-dimensional. Two-dimensional models exist at a range of fidelities, for example EULAG-LCM (Sölch and Kärcher, 2010) is a 2D/3D large eddy simulation (LES) code. EULAG-LCM consists of the EULAG fluid dynamics solver, fully coupled with the particle-based ice microphysical model LCM to produce state-of-the-science contrail simulations with detailed representation of both fluid mechanics and ice microphysics. While EULAG-LCM is a stand-alone model and not meant to be coupled with a NWP, its background conditions could be made to reflect some given NWP data. Alternatively, APCEMM is a simpler open-source 2D model (Fritz et al., 2020) which prioritises ice microphysics but uses a simplified representation of the contrail fluid mechanics. The most computationally demanding contrail models simulate the plume in 3D, but in general such an approach is computationally very expensive due to the size of the modelling domain required (Sölch and Kärcher, 2010; Lewellen, 2014; Paoli et al., 2017).



65 Given the variety of the assumptions used in the currently available contrail models and the lack of ground truth data, contrail model comparisons are critical to understanding the advantages, limitations, and implications of the modelling choices of each model. However, there are few such comparisons in the literature, hindering rational evaluation of model accuracy and fitness-for-purpose.

To our knowledge, the only peer-reviewed study evaluating the sensitivity of different contrail models to meteorological conditions compared CoCiP and APCEMM under synthetic meteorological scenarios, with varying meteorological parameters (Akhtar Martínez et al., 2025). Their results show that the predicted lifetime-integrated total extinction (a proxy metric for the energy forcing of each contrail) is on average ~3 times greater in APCEMM than in CoCiP for the given conditions. Furthermore, they show that the sensitivity of the models to changes in the relative humidity of the ice supersaturated layer has opposing signs for CoCiP and APCEMM, indicating disagreement directly relevant to decision-making in targeted contrail avoidance. The reason for this disagreement was stated to be that CoCiP is a monodisperse model in the ice crystal radius space, whereas APCEMM uses 38 ice crystal radius bins. This allows the APCEMM simulation to produce a contrail core and a precipitation plume through differential sedimentation of ice crystals, something which is not possible with the Gaussian plume representation that CoCiP uses. Although the analysis by Akhtar Martínez et al. (2025) revealed potentially significant shortcomings of 0D monodisperse models, the comparison included only a handful of scenarios with constant background humidity and did not consider the effect of synoptic-scale vertical motions, which are positively correlated with climate impact (Lewellen, 2014). Furthermore, the study could provide only limited insights regarding the mechanistic causes of differences. Despite the paucity of contrail model comparisons and the limited scope of existing ones, trials attempting contrail avoidance are already being performed (Sonabend-W et al., 2024), and European legislation has been written to create a monitoring, reporting, and verification (MRV) framework for non-CO₂ effects including contrails (Eichinger et al., 2025). The European MRV and many of the flight trials of contrail avoidance schemes rely on CoCiP (embedded in the EU Non-CO₂ Aviation Emissions Tracking System, NEATS) for the prediction of contrail locations and the evaluation of the delta in warming caused by contrails. Although CoCiP is the only plume-scale model currently deployed at a global-scale due to its grid implementation (Engberg et al., 2025) and high computational speed, the lack of full-lifetime validation and the disagreement with higher-fidelity models need prompt addressing to support the evaluation of legislation and avoidance schemes. Without this, at best we risk not achieving the maximum warming reduction for a given number of deviations. At worst, we risk developing schemes which are actively counterproductive while also producing perverse incentives for industry decarbonisation.

To help address this, we evaluate the effects of the modelling choices in contrail models of different fidelities. We compare three contrail models: CoCiP, APCEMM, and EULAG-LCM. Through the inclusion of two 2D models of different fidelities in the comparison, we aim to identify the components of contrail models that are necessary for simulating long-lived contrails in a physically consistent way. We also aim to classify these into choices or fundamental limitations of each model type. Furthermore, we constrain the scope of this study to focus on the evolution of long-lived persistent contrails during the first 8 hours of lifetime to ensure our insights are relevant for most contrails, given that only 6 % of contrails are estimated to persist past 8 hours (Gierens and Vazquez-Navarro, 2018). Finally, by performing sensitivity simulations involving changes in the

model configuration of EULAG-LCM, we partially explain the mechanisms through which some modelling choices affect the
 contrail evolution and hence cause discrepancies across models.

1.1 Contrail-cirrus models

We now review the capabilities and modelling choices of the codes compared in this study: CoCiP, APCEMM, and EULAG-LCM. We only consider the diffusion regime representation of these models in which they all aim to simulate physical processes in a single cross-section of a contrail perpendicular to the flight direction (hereafter simplified to “back view”, as defined in Fig. 1).

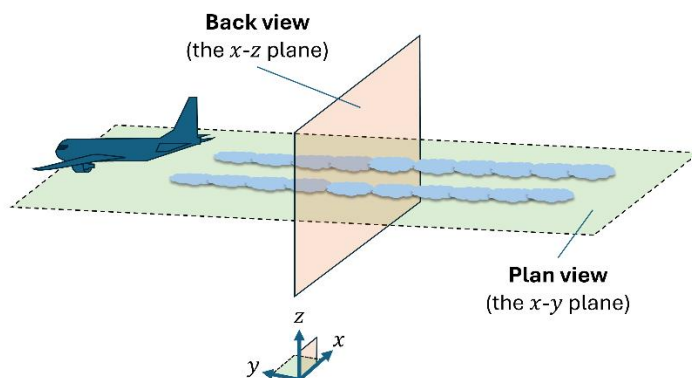


Figure 1: Coordinate system used throughout this investigation. The x coordinate is horizontal and perpendicular to the flight direction. The y coordinate is horizontal and parallel to the flight direction. The z coordinate is vertical. The back view provides a vertical cross-section of the contrail, as seen from behind the aircraft. The plan view provides a top-down view of the contrail. Taken from Akhtar Martínez (2026) with permission.

1.1.1 CoCiP

In the diffusion regime, the Contrail Cirrus Prediction model (CoCiP) tracks the back view of the contrail in terms of a single point in space which is associated with a Gaussian plume (Schumann, 2012). CoCiP makes several simplifying assumptions that maximise computational speed.

First, the Gaussian plume assumption is used primarily for estimations of the contrail area, width, and depth (Eqs. 3 and 8 in Schumann, 2012) which are used for calculations of the optical depth (Eqs. 58-60 in Schumann, 2012), ice mass growth (Eqs. 42-44 in Schumann, 2012), and loss mechanisms to reduce the ice crystal number (Eqs. 48 and 52 in Schumann, 2012). Despite a potentially large volume occupied by the ageing contrail-cirrus, the meteorological conditions are evaluated only at the plume centre, neglecting any variability in properties or conditions across the plume. Second, CoCiP assumes a monodisperse ice particle size distribution (PSD) in the representation of all crucial microphysical processes. CoCiP uses the volume-weighted mean crystal radius (r , calculated from the total ice mass and total ice number) to estimate a bulk sedimentation speed for the entire plume. Contrail vertical growth by differential sedimentation is hence accounted for only through the addition of a



vertical diffusion term that scales linearly with the centroid fall speed. For completeness, we bring attention to the parametrisation of the ice crystal losses due to aggregation (Eq. 52 in Schumann, 2012), in which CoCiP assumes that the size spectrum has width of order r in radius space. This is the only instance where PSD properties other than the mean are specified. CoCiP is typically applied in an *offline* approach (one-way coupling), where meteorological background data are provided by a numerical weather prediction (NWP) model and with no feedback to the meteorology. Consequently, any water uptake by the plume does not result in a decrease in the water vapour in the meteorology – resulting in a water budget that is not closed. Since CoCiP interfaces with the meteorology at the contrail centre, the lack of a closed water budget has the most impact where the contrail has a large depth or has a low settling speed. Some of these modelling choices may cause the premature sublimation of the contrail (see the Supplementary Material and Akhtar Martínez et al., 2025). Nevertheless, CoCiP model studies with a closed water budget are rare due to the requirement to fully couple a climate or NWP model with CoCiP (Schumann et al., 2015; Schumann and Seifert, 2025).

Finally, CoCiP heavily relies on parametrisations for the microphysics and turbulence instead of resolving them directly. Combined with the above, this allows CoCiP simulations to run much faster than 2D models such as APCEMM (Akhtar Martínez and Jarrett, 2024). The combination of the model simplicity and its efficient implementation has allowed CoCiP to be used in global studies (Teoh et al, 2024), contrail avoidance trials (Sonabend-W et al., 2024), and the European MRV scheme (Eichinger et al., 2025).

1.1.2 APCEMM

The Aircraft Plume Chemistry, Emissions, and Microphysics Model (APCEMM) (Fritz et al., 2020) uses an Eulerian solver to represent a single contrail cross section. In APCEMM, solid, liquid, and gas phases are all represented as gridded quantities. However, the grid itself moves with the plume, making the model partly Lagrangian.

APCEMM includes an explicit representation of homogeneous freezing of water-activated particles, deposition and sublimation (with a Kelvin correction), and aggregation (turned off in the diffusion regime). Furthermore, APCEMM uses a sectional ice microphysics scheme with 38 ice particle radius bins as a discrete approximation to the particle size distribution (PSD), which allows it to represent differential sedimentation (Akhtar Martínez et al., 2025). The ice radius bin edges are fixed, but “the modal radius of each bin is allowed to increase within the bin bounds to accommodate the increase in ice crystal sizes with time” (Akhtar Martínez et al., 2025). To close the water budget, APCEMM preserves the change in the molecular concentration of water vapour caused by the contrail as a gridded quantity, imposing changes in local meteorology through changes in the grid’s boundary conditions. APCEMM makes more simplifying assumptions than EULAG-LCM and fewer than CoCiP. APCEMM assumes spherical ice particles and uses a crude representation of turbulence. Grid-scale turbulence is roughly approximated through turbulent diffusion and through random temperature perturbations at each grid cell, with the perturbation values uniformly distributed between -1 and 1 K, a simplification of a method used by Lewellen (2014). Neither grid-scale eddies nor sub-grid scale turbulence are explicitly modelled in APCEMM.



155 1.1.3 EULAG-LCM

The CFD (computational fluid dynamics) model EULAG (Smolarkiewicz et al., 2014) is a large eddy simulation (LES) model that is used to solve the anelastic approximation of the Navier-Stokes equation, an equation of state, and several tracer transport equations (e.g. for water vapour). LCM is an ice microphysics model (Sölch and Kärcher, 2010; Unterstrasser and Sölch, 2014), which relies on a particle-based representation of ice crystals and is fully coupled to EULAG, thus making EULAG-LCM.

The microphysical processes considered in the present study are deposition/sublimation (including a Kelvin correction term) and sedimentation. Available ice nucleation mechanisms in the diffusion regime are disabled in this study as we deliberately focus on scenarios where a single contrail evolves in an otherwise cloud-free environment. Like APCEMM, processes in EULAG-LCM like diffusional ice crystal growth and sedimentation depend on a previously specified ice crystal habit. In the present simulations, hexagonal columns following empirical relations by Mitchell (1996) are assumed.

Ice crystals are represented by simulation particles (SIPs), each corresponding to a defined number of ice crystals with identical properties (ice crystal size, discrete position, etc.). The SIPs move according to EULAG grid-mean velocity, a sedimentation speed, and turbulent velocity fluctuations.

The setup of the EULAG-LCM simulations contributing to this study is identical to the one in Lottermoser and Unterstrasser (2026). Contrail-cirrus simulations are performed in a 2D domain perpendicular to flight direction with a resolution of 10 m in both the x and z directions and large enough to contain the spreading contrail. The initial contrail is described by $O(10^7)$ SIPs, following the recommendations issued by Unterstrasser and Sölch (2014).

EULAG-LCM has widely been used in previous studies focusing on the contrail evolution during the vortex phase (e.g. Unterstrasser, 2014; Unterstrasser, 2016) and the transition into contrail-cirrus (e.g., Unterstrasser et al, 2017a; Unterstrasser et al, 2017b).

1.2 Key modelling differences of contrail-cirrus models

This section summarises the key modelling differences between CoCiP, APCEMM, and EULAG-LCM (see Table 1). First, CoCiP represents ice quantities using an analytical (Gaussian plume) model while EULAG-LCM uses Lagrangian tracking for ice quantities, whereas APCEMM treats ice quantities on a grid. This makes APCEMM susceptible to numerical diffusion. Second, CoCiP assumes a monodisperse PSD, whereas APCEMM and EULAG-LCM represent size-resolved microphysics. This allows APCEMM and EULAG-LCM to represent differential sedimentation, which has been shown to drive the longer lifetimes and larger total extinction values from APCEMM simulations when compared to equivalent CoCiP simulations (Akhtar Martínez et al., 2025). This may also be partially caused by the fact that APCEMM can represent spatially heterogeneous sublimation of the contrail due to its binned grid, whereas the entire CoCiP contrail sublimates simultaneously due to its 0D nature.



APCEMM and EULAG-LCM interact with a local plume-scale copy of the ambient water vapour and temperature fields (local feedbacks), a feature which is absent in CoCiP; though CoCiP has been previously embedded in a global climate model, including grid-scale feedbacks – see Schumann et al., 2015; and Schumann and Seifert, 2025. In APCEMM, local feedback history is erased for a particular grid cell when its ice crystal number falls under a specified threshold. This is done to better represent the time-evolving boundary conditions imposed on the simulations. In CoCiP, the absence of water vapour feedback can cause the repeated uptake of the same water into the contrail ice crystals, artificially boosting their mass and changing their microphysical properties.

Finally, the turbulence representation differs greatly between models. CoCiP uses parametrisations for the shear enhancement, ice number loss, and diffusivity that include turbulence terms. APCEMM uses a rough approximation of the method used in Lewellen (2014) for the grid-scale turbulent temperature fluctuations but relies simply on numerical diffusion to represent turbulent motions, while EULAG-LCM fully resolves large eddies for the grid-scale turbulence and uses a turbulence closure scheme for the sub-grid turbulence. We investigate the differences between turbulence implementations in Sec 3.1.4.

In summary, the model differences currently thought to have the strongest implications are the PSD representation, the meteorology feedback, and turbulence. These have the potential of changing the microphysical and geometric properties of the simulated contrails when comparing 0D models to higher-dimensional models. We hence aim to explore the extent to which the aforementioned modelling approaches affect the contrail properties.

Table 1: Key modelling differences between CoCiP, APCEMM, and EULAG-LCM. In this experiment, the location of the contrail does not change so the Eulerian and Lagrangian approaches to tracking the contrail centre are equivalent.

<i>Model property</i>	<i>CoCiP</i>	<i>APCEMM</i>	<i>EULAG-LCM</i>
<i>Dynamics</i>	0D in space (Lagrangian tracking)	Gridded (Eulerian framework)	Gridded (Eulerian framework)
<i>Representation of ice crystals</i>	0D in radius space (monodisperse)	38 size bins	Particle-based approach
<i>Tracking of location</i>	Moving plume	Moving domain	Moving domain
<i>Plume-scale local meteorology feedback</i>	Fully offline	Online in contrail grid cells	Fully online
<i>Ice crystal habits</i>	Pre-determined mix (see Table 2 in Schumann et al., 2011)	Spheres only	Hexagonal columns only



<i>Turbulence representation</i>	Parametrisation in diffusivity, ice crystal number loss, and shear	Grid scale turbulent diffusion and temperature fluctuations	Grid scale eddies, sub-grid turbulence closure scheme
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205 2 Experimental design

2.1 Objectives and simulation setup

This work determines how modelling choices affect the simulated evolution of the contrail in the diffusion regime, with a special interest in the contrail-to-cirrus transition and the contrail-cirrus lifecycle. We limit the study to only consider isolated contrails and no natural cirrus. This means that no contrail-cirrus or contrail-contrail interactions are included. We also focus on the sensitivities to meteorological parameters, and variations in aircraft parameters (e.g. the type of aircraft or soot emission index) are not considered.

To eliminate the variability due to the different implementations of the jet and vortex regimes, we initialise all simulations directly at the onset of the diffusion regime with equivalent profiles of ice mass and ice number (see Table 2, and Figs. 2, 4, and 5) as provided by prior EULAG-LCM simulations of the contrail vortex phase (Lottermoser and Unterstrasser, 2025). While that study mainly treated contrails from hydrogen propulsion, its reference simulations with an apparent ice emission index $EI_{\text{icenum}} = 2.8 \times 10^{14} \text{ kg}^{-1}$ are typical of kerosene combustion. The latter simulation results are used in the present study and are initialised by assuming an A350-like aircraft with ice crystal number $N_{0,\text{ref}} = 3.38 \times 10^{12} \text{ m}^{-1}$ at the end of the jet regime (see Eq. 1 in Lottermoser and Unterstrasser, 2025). This corresponds to an initial wake vortex circulation of $520 \text{ m}^2 \text{ s}^{-1}$ (Lottermoser and Unterstrasser, 2025) and an assumed aircraft velocity of 250 m s^{-1} .

More specifically, the EULAG-LCM contrail-cirrus simulations use data from the EULAG-LCM vortex phase output (see flow chart in Fig. 2). The simulation domain of the vortex phase (indicated by the white rectangle in Fig. 3) is embedded into the larger domain of the contrail-cirrus simulations. In the embedded domain, the initialisation of water vapour, temperature and velocity perturbations fields is based on the EULAG-LCM vortex phase output. This information is, however, not used in the APCEMM and CoCiP initialisation, where only ice data from the vortex regime are used to initialise the contrail microphysical quantities. The only parameters affecting the initialisation are the ambient temperature (T_{CA}) and the ambient relative humidity with respect to ice (RH_i) at cruise (Table 2). The initialisation strategy (summarised in Fig. 2) allows us to start with the closest representation possible given the constraints of the individual contrail models.

To identify the relative importance of the components of each contrail model, we adopt a staged approach to the analysis of the model outputs. In Section 3, we investigate the evolution of integral quantities (as defined in Section 2.3.1) and distributed quantities, namely the ice crystal mass and number concentration, for a baseline case. Section 4 follows with an analysis of the correlations in the dataset, an analysis of the sensitivity to the meteorological parameters (as defined in Section 2.1), and a quantitative investigation of the origin of differences between models.



Table 2: Initial ice crystal number and mass, as obtained from the 3D EULAG-LCM simulations of the vortex regime depending on T_{CA} and RH_i .

$T_{CA,0}, K$	$RH_{i,0}, \%$	$N_{tot,init}, m^{-1}$	$I_{tot,init}, kg\ m^{-1}$
217	110	9.48×10^{11}	0.075
217	120	2.17×10^{12}	0.214
225	110	4.31×10^{11}	0.112
225	120	1.51×10^{12}	0.530

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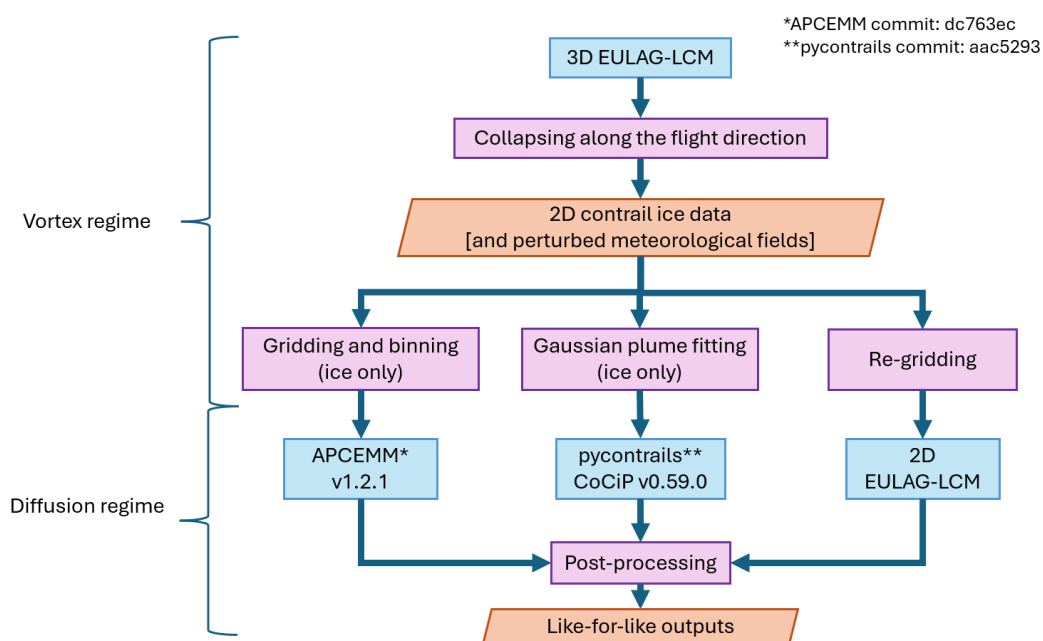
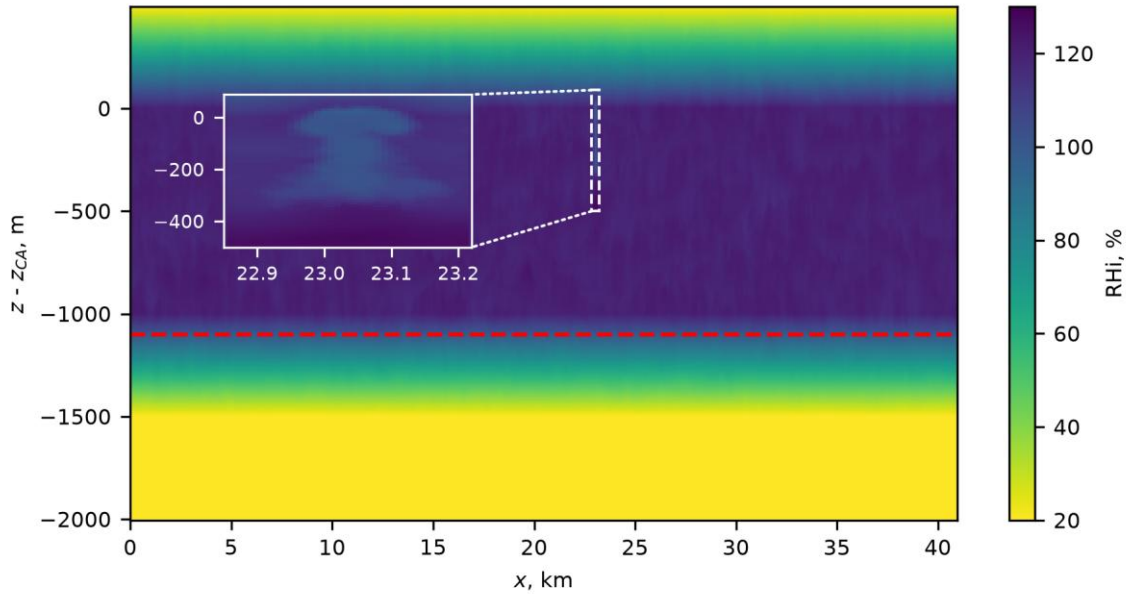


Figure 2: Flow chart showing the experimental setup. Blue rectangles indicate contrail models, orange rhombi indicate outputs, and purple rectangles indicate data processing.



240 **Figure 3: EULAG-LCM RHi field at initialisation ($t=0$) of the diffusion regime simulations. The dashed red line indicates the lower saturation threshold (the altitude beneath which $RHi < 100$ %) at initialisation. The white dashed rectangle indicates the contrail location.**

2.2 Meteorology

Similar to previous studies using contrail models in idealised meteorology (Unterstrasser and Gierens, 2010a, 2010b; Lewellen et al., 2014; Lewellen, 2014; Unterstrasser et al., 2017a, 2017b; Lottermoser and Unterstrasser, 2026; Akhtar Martínez et al., 2025), we use a layer with a trapezoidal profile (see Fig. 4) for the relative humidity with respect to ice (RHi). We choose to vary the meteorological parameters that are most likely to impact the physical processes in the diffusion regime of the contrail: the layer depth (d in m), the initial layer RHi (RHi_0 , dimensionless), wind shear ($\frac{du}{dz}$ in s^{-1} , where u is the horizontal velocity perpendicular to the flight direction and z is the vertical coordinate), the initial temperature at the cruise altitude ($T_{CA,0}$ in K), and the updraught velocity of the entire domain (w_{syn} in $cm\ s^{-1}$). We define the *meteorology space* to be the space spanned by a vector containing these meteorological variables.

Our parameter settings (see Table 3) partially overlap with those described in Lottermoser and Unterstrasser (2026), spanning a range of meteorological conditions relevant to contrail-cirrus evolution. We also define a baseline case for which we present 2D quantities (marked by the asterisks in Table 3). Parameters that are not varied take the following values: the relative humidity with respect to ice outside of the supersaturated layer is set to 20 %, and the total updraught distance (defined as the updraught speed times the updraught duration) is fixed to be 200 m (corresponding to an adiabatic cooling of around 2 K). The temperature profiles are prescribed according to a Brunt-Väisälä frequency of $0.01\ s^{-1}$.



We represent synoptic-scale updraughts by applying adiabatic cooling to the simulation domain instead of explicitly resolving a homogeneous vertical motion, allowing us to minimize the vertical extent of the domain required in the EULAG-LCM Eulerian grid. The temperature evolution $\frac{dT}{dt}$ is calculated as

$$\frac{dT}{dt} = \frac{d\tilde{T}}{dt} - \frac{g}{c_p} w_{\text{syn}}, \quad (1)$$

where $\frac{d\tilde{T}}{dt}$ is the change in the temperature field in the absence of updraughts, $\frac{g}{c_p} = 9.8 \text{ K km}^{-1}$ is the dry adiabatic lapse rate, and the updraught velocity w_{syn} is $\frac{dz}{dt}$. This results in a sustained increase of the background relative humidity throughout the entire simulation domain while the updraught progresses (see Fig. 4). This setup follows that described in Unterstrasser et al. (2017a).

Table 3: Values of the meteorological parameters used in this investigation. We define the baseline case to take the parameter values marked by an asterisk. The default value for the updraught velocity is zero.

Parameter	Units	Low value	High value
Initial peak relative humidity, RH_{i0}	%	110	120*
Updraught velocity*, w_{syn}	cm s^{-1}	2	5
Initial release temperature, $T_{\text{CA},0}$	K	217*	225
Peak supersaturation depth, d	m	500	1000*
Vertical wind shear, s	s^{-1}	0.002*	0.006

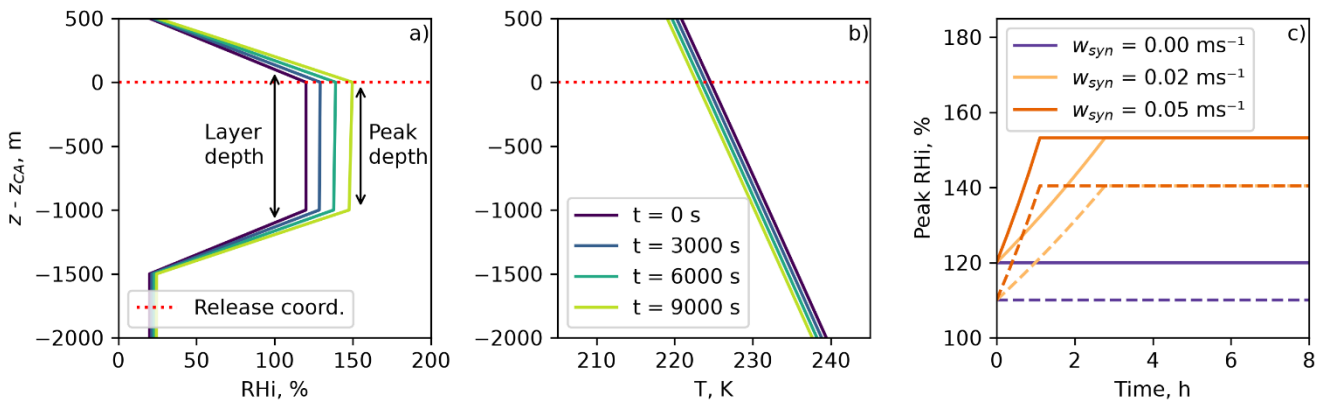




Figure 4: Evolution of the layer relative humidity profile (a), temperature profile (b), and peak RHi for an example case (c). The dotted horizontal red line is the cruise altitude assumed, where the contrail is released from.

2.3 Metrics

275 Throughout this study, we use a coordinate system (visualized in Fig. 1) consisting of the x axis (perpendicular to the flight direction; pointing starboard), the y axis (along the flight direction; pointing towards the aircraft from the rear), and the z axis, pointing vertically upwards. We define the location of the contrail release as our origin, meaning that the flight altitude corresponds to a z value of 0.

2.3.1 Contrail ice properties

280 The spatial distributions of the contrail ice crystal mass and number concentrations are provided as 2D cross-sections (I in kg m^{-3} and N in m^{-3}) in APCEMM and EULAG-LCM. Similarly, these 2D cross-sections can be reconstructed from the CoCiP outputs through Eq. 1 of Schumann (2012). We integrate I and N over the cross-section of the contrail to obtain the total ice crystal mass and number per unit distance in the flight direction, I_{tot} in kg m^{-1} and N_{tot} , in m^{-1} :

$$I_{\text{tot}}(t) = \iint I(x, z; t) dA, \quad (1)$$

285 $N_{\text{tot}}(t) = \iint N(x, z; t) dA, \quad (2)$

where dA is an elemental area – equal to $dx dz$. We also compute 1D profiles of the total ice crystal mass and number in the lateral and vertical directions (I_x, I_z in kg m^{-2} and N_x, N_z in m^{-2} ; see Appendix B for the relevant equations). From the ice crystal mass and number it is straightforward to derive the mean particle radius $\bar{r}$. An example calculation of the vertical profile of the mean radius is given:

290 $\bar{m}(z; t) = \frac{I_z(z; t)}{N_z(z; t)}, \quad (3)$

$$\bar{r}(z; t) = \left(\frac{3\bar{m}(z; t)}{4\pi\rho_{\text{ice}}} \right)^{\frac{1}{3}}, \quad (4)$$

ρ_{ice} is the density of ice, taken to be 916.7 kg m^{-3} in this study. For the computations of the mean radius, we assume mass-equivalent spheres in the post-processing of all model data.

To circumvent the need to specify additional parameters for radiative transfer calculations, we use the total extinction E as a proxy metric for instantaneous radiative impact of individual contrails (Unterstrasser and Gierens, 2010a, 2010b; Unterstrasser et al., 2017a, 2017b; Lottermoser and Unterstrasser, 2026, Akhtar Martínez et al., 2025):

$$E(t) = \int \int \chi(x, z, t) dx dz = \int \tau_z(x, t) dx = \tau B, \quad (5)$$



where τ_z is the vertical optical depth at a specific horizontal location, τ is the width-averaged optical depth, and B is the contrail width (for CoCiP only). To consider cumulative effects, we define the time-integrated total extinction $\hat{E}$ as in Unterstrasser (2020):

$$\hat{E}(t) = \int_0^t E(t) dt. \quad (6)$$

We define $\hat{E}^* = \hat{E}(t = 8 \text{ h})$ to be the lifetime quantity. We use the lifetime total extinction ($\hat{E}^*$, in h m) as a proxy for the radiative impact over the lifetime of the contrail in this study. Nevertheless, the true radiative impact depends on parameters beyond those specified in this study (e.g. the incident radiation at the contrail layer).

305 2.3.2 Geometric contrail properties

To evaluate the geometric properties of the contrail, we introduce four metrics: the width (B in m), the depth (D in m), the centre of mass vertical position (z_m in m), and the centre of number vertical position (z_n in m). For CoCiP, we take the width and depth output by the model to ensure consistency with previous works (see Eq. B4 in Appendix B). For APCEMM and EULAG-LCM, which do not impose a prescribed contrail shape, the width and depth take the minimum values required to form bounds containing 95 % of the contrail ice mass (see Appendix B). In terms of the ice crystals enclosed, the CoCiP width and depth contain 84 % of the ice crystals in the contrail, assuming a normal distribution along the x and z axes. Using the same assumption, we calculate that the 95 % width applied to CoCiP is always 1.38 times greater than the CoCiP model output width. Given that this is a constant factor, our choice to use the CoCiP model outputs does not affect the underlying differences between CoCiP and the other models.

315 The centre of mass and centre of number vertical locations can be calculated as follows:

$$z_m(t) = \frac{\int z I_Z(z;t) dz}{\int I_Z(z;t) dz}, \quad (7a)$$

$$z_n(t) = \frac{\int z N_Z(z;t) dz}{\int N_Z(z;t) dz}. \quad (7b)$$

Equation 7 can also be modified to calculate the centre of mass and centre of number horizontal locations (x_m and x_n respectively). In CoCiP, z_m and z_n are aligned with the plume centre by construction and match this definition.

320 We denote the time derivative of z_m ($\dot{z}_m$) and z_n ($\dot{z}_n$) as pseudo fall speeds. This is because changes in those two quantities are not necessarily due to sedimentation alone but are also affected by ice crystal loss or altitude-dependent ice mass growth. In addition to evaluating scalar and 2D quantities, we also compare the vertical and horizontal (1D) profiles of some quantities as simulated by the different models. To quantify the similarity between two 1D profiles, we define the overlap metric (O , dimensionless) as twice the area overlapped by the 1D profiles of the models divided by the sum of the area under each profile. Consequently, perfect agreement between two profiles corresponds to an overlap factor of 100 % and complete disagreement between two profiles yields 0 %. Taking the ice mass horizontal profile for an example computation:



$$O = \frac{2 \int \min(I_X^A, I_X^B) dx}{\int I_X^A dx + \int I_X^B dx}, \quad (8)$$

where A and B correspond to two different models. Equation 8 can be adapted to work for other 1D profiles, including vertical ones if integrating along z .

330 2.3.3 Sensitivity

We define a sensitivity metric that captures the effect of changing the i -th meteorological parameter. To do this, consider the sets of simulations in which the i -th parameter takes a high value (S_i^{hi} , Eq. 9a), or a low value (S_i^{lo} , Eq. 9b):

$$S_i^{\text{hi}} = \{\text{sim} \in S \mid \theta_i(s) = \theta_i^{\text{hi}}\}, \quad (9a)$$

$$S_i^{\text{lo}} = \{\text{sim} \in S \mid \theta_i(s) = \theta_i^{\text{lo}}\}, \quad (9b)$$

335 where θ_i is a meteorological parameter, sim is a simulation, and S is the set containing all simulations. The “lo” and “hi” superscripts indicate whether the parameter takes the low or high value in Table 3 respectively. We then define the sensitivity metric by considering the sum of the lifetime total extinction across different sets of simulations:

$$\gamma_i = (\sum_{S_i^{\text{hi}}} \hat{E}^* - \sum_{S_i^{\text{lo}}} \hat{E}^*) / \sum_{S_i^{\text{lo}}} \hat{E}^*. \quad (10)$$

By modifying the sensitivity metric to include the effect of a second parameter with index j , we define:

$$340 \quad \gamma_{i|j=\text{state}} = (\sum_{S_i^{\text{hi}} \cap S_j^{\text{state}}} \hat{E}^* - \sum_{S_i^{\text{lo}} \cap S_j^{\text{state}}} \hat{E}^*) / \sum_{S_i^{\text{lo}} \cap S_j^{\text{state}}} \hat{E}^*. \quad (11)$$

where the state can either be “lo” or “hi”.

γ_i is the sum of the lifetime total extinction in all runs in which the i -th parameter takes the high value minus the same quantity when the i -th parameter takes the low value, normalised by the latter. Similarly, $\gamma_{i|j=\text{state}}$ is the same quantity as γ_i calculated over the subset of runs with the j -th parameter being low ($\gamma_{i|j=\text{lo}}$) or high ($\gamma_{i|j=\text{hi}}$), as determined by the state.

345 2.4 Practical considerations

According to Monte Carlo simulations performed on a simplified model using satellite observations in a study by Gierens and Vazquez-Navarro (2018), only 6 % of contrails persist beyond 8 h. Although this is an estimate on a limited dataset and which inherently excludes large contrails with low optical depth which cannot be identified by satellite (e.g. Euchenhofer et al., 2025), we limit the maximum contrail lifetime in our study to be 8 h. This also limits the effects of using idealised meteorological scenarios with simplified patterns of background humidity evolution.

Furthermore, both EULAG-LCM and APCEMM include randomness from the turbulence representations which can complicate simulation comparisons. Those in APCEMM happen because of the implementation of turbulent temperature fluctuations, whereas EULAG-LCM explicitly models random turbulence in the 2D fields and in the SIP trajectories (see



Sect. 1.1). Since the APCEMM turbulent temperature fluctuations happen every 10 minutes in all grid cells by a random amount in the range $[-1, 1]$ K, the random number generation seed is fixed to 0 in APCEMM. The seed has a negligible effect on the integral quantities of the contrails, but the turbulent temperature fluctuations do increase the ice loss processes, so it remains enabled. For EULAG-LCM, we perform the simulations four times with different seeds and average the integral properties and 1D profiles across all simulations of the same meteorology (see Fig. 13 in Unterstrasser et al., 2017a). However, EULAG-LCM 2D fields are only shown for one specific seed.

Finally, the pycontrails implementation of CoCiP only logs results starting from one timestep after initialisation. To estimate the upper bound of the error caused by this, we use a second set of simulations to calculate the relative error of the omission of the first timestep. These reference simulations prepend the total extinction at the second timestep as the total extinction at $t=0$. With this, the relative cumulative error across all simulations is 0.4 %, and the maximum relative error in any given simulation is 1.0 %. Therefore, we consider this artifact small enough to ignore in this investigation.

3 Model intercomparison under the baseline meteorology

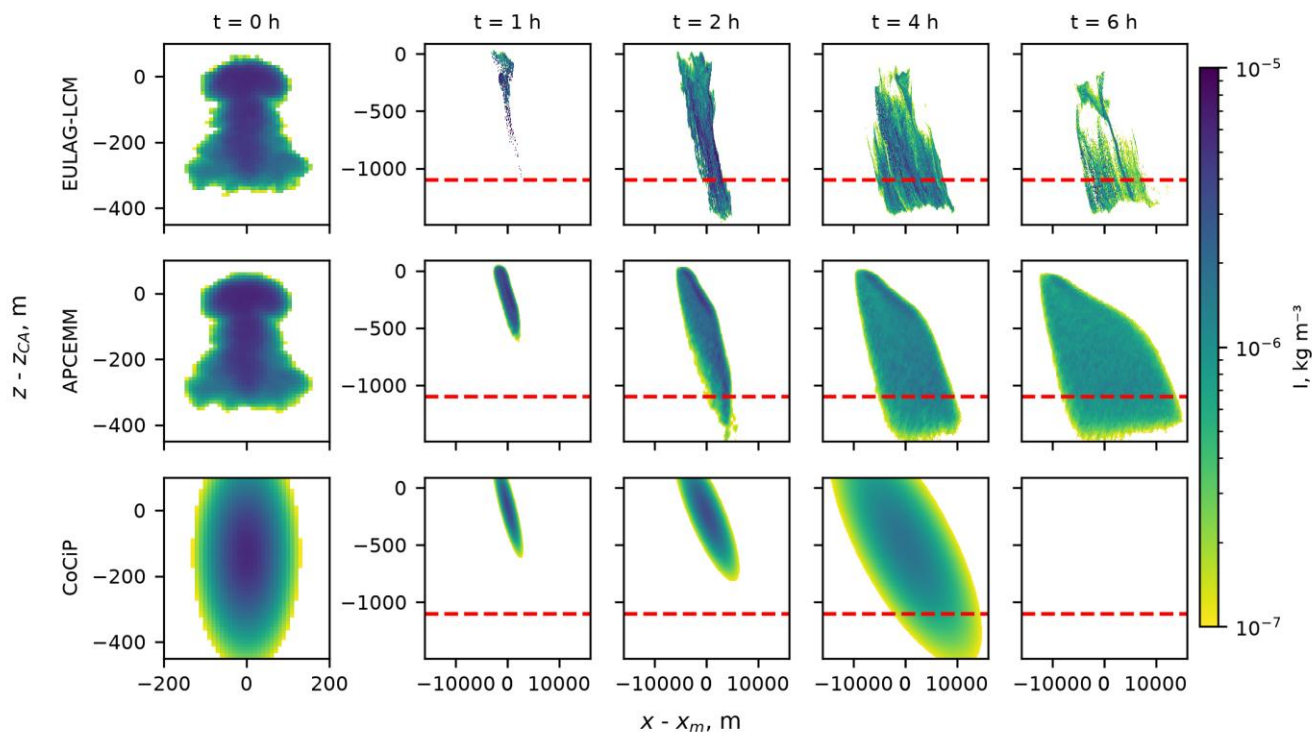
We now consider the evolution of the contrail generated under the default conditions (see Table 3). We use 0 cm s^{-1} updraught velocity to simplify the interpretation of the results. We then consider the time evolution of 2D fields, 1D fields, and contrail integral properties. CoCiP Gaussian plumes are reconstructed on a 2D grid with the same resolution as that used by the EULAG-LCM simulations.

3.1 Results from the contrail models evaluated over the baseline meteorology

3.1.1 Evolution of the 2D cross-sections

Figures 5 and 6 show the evolution of the ice crystal mass and number concentrations respectively. The leftmost column in these figures shows the results of the harmonisation of the initial conditions (see Appendix A). For EULAG-LCM and APCEMM, the structures arising at the end of the vortex phase are visible and approximately matching between the two models. Any discrepancies between these initialisations result directly from the use of a different grid in APCEMM and EULAG-LCM. The CoCiP profile is elliptical, as determined by its parametrisation.

From Figs. 4 and 5, we also identify a contrail core and a precipitation plume in both EULAG-LCM and APCEMM, but not in CoCiP. The precipitation plume reaches the subsaturated air after between 1 and 2 h. Both EULAG-LCM and APCEMM show that the contrail core has a high ice crystal number concentration (reaching $\sim 10^8 \text{ m}^{-3}$ in both models), whereas the precipitation plume has a low ice crystal number concentration (beneath $\sim 10^5 \text{ m}^{-3}$ in both models). Nevertheless, the structure of the contrail differs between EULAG-LCM and the other models. Unlike APCEMM and CoCiP, the EULAG-LCM contrail is not smooth, with clearly defined structures in the contrail core and precipitation plume. Although both the APCEMM and CoCiP contrails are smooth, the CoCiP contrail grows in all directions, remaining ellipse-shaped, whereas the APCEMM contrail only grows downwards and horizontally.



385

Figure 5: Time evolution of the ice crystal mass concentration I for EULAG-LCM (top row), APCEMM (middle row), and CoCiP (bottom row) for the baseline case. Regions are shaded white if the plotted quantity is below the lower limit of the colour scale and are not necessarily zero. The dashed red line indicates the lower saturation threshold (the altitude beneath which $\text{RH}_i < 100 \%$), which does not move since there is no updraught velocity in the baseline case.

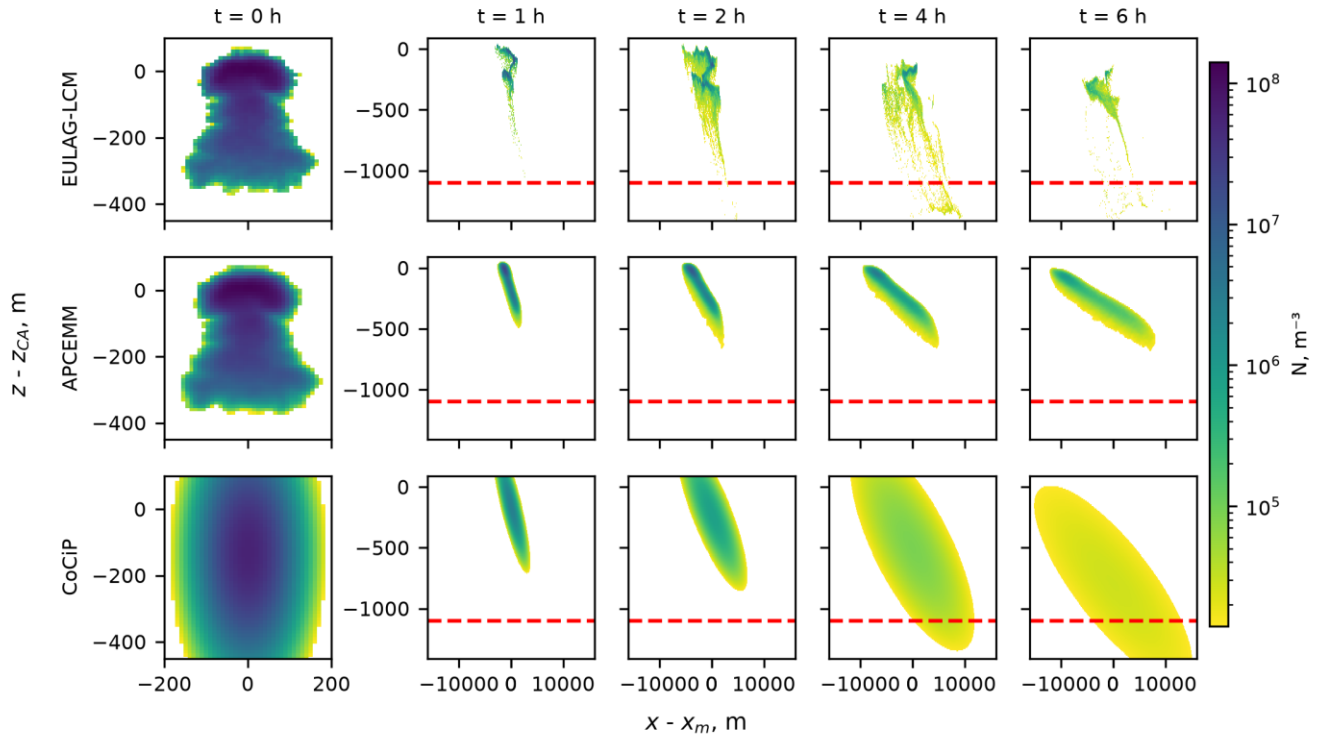


Figure 6: Time evolution of the ice crystal number concentration N for EULAG-LCM (top row), APCEMM (middle row), and CoCiP (bottom row) for the baseline case. Regions are shaded white if the plotted quantity is below the lower limit of the colour scale and are not necessarily zero. The dashed red line indicates the lower saturation threshold (the altitude beneath which $RH_i < 100\%$), which does not move since there is no updraught velocity in the baseline case.

3.1.2 Evolution of 1D profiles

Figure 7 shows the evolution of the ice mass horizontal distribution (hereafter I_x distribution) for each model at the baseline case. The first panel shows good agreement between the EULAG-LCM, APCEMM, and CoCiP I_x distributions at initialisation, with a CoCiP/EULAG-LCM overlap factor of 97% and an APCEMM/EULAG-LCM overlap factor of 97 %. Considering both CoCiP and APCEMM, their contrail widths (36 km and 22 km at 6 h respectively) grow faster than in EULAG-LCM (11 km at 6h) such that after 6 h the CoCiP/EULAG-LCM overlap factor is 26 % whereas the APCEMM/EULAG-LCM overlap factor is 56 %.

Figures 5 and 8a) show that the ice mass vertical distribution (hereafter I_z distribution) is bimodal upon initialisation in APCEMM and EULAG-LCM, but monomodal in CoCiP due to its Gaussian shape. The disagreement in the distribution shape is reflected in the overlap factors (77 % for CoCiP/EULAG-LCM and 97 % for APCEMM/EULAG-LCM at initialisation). As the contrail evolves, the EULAG-LCM and APCEMM I_z distributions become monomodal, and the distributions change from having a long tail towards lower altitudes to having a long tail towards higher altitudes. Furthermore, Fig. 8b) shows that the EULAG-LCM and APCEMM N_z distributions are skewed towards lower altitudes throughout the contrail lifetimes,



reflecting the high ice crystal number in the contrail core seen in Fig. 6. Considering Fig. 8a) and Fig. 8b) together reveals that the precipitation plume comprises few ice crystals of high mass. This is confirmed by the ice crystal radius vertical profile in Fig. 8c).

Despite EULAG-LCM and APCEMM having qualitatively similar profiles, they also have systematic differences. First, the EULAG-LCM N_Z profile has a consistently lower centre of number than the APCEMM N_Z profile (Fig. 9d), causing the APCEMM/EULAG-LCM overlap factor to decrease from 99 % to 66% as the simulations proceed from initialisation to 6 h. This is because the contrail depth in the gridded models is approximately equal to the distance between the contrail centre of number and the lower saturation threshold (the altitude beneath which $RH_i < 100$ %), provided the precipitation plume has reached the lower saturation threshold, and the APCEMM plume upper limit descends more slowly than that in EULAG-LCM. Since all the CoCiP profiles remain symmetric (due to the Gaussian plume assumption), the overlap of its N_Z profile with EULAG-LCM decreases from 60 % to 36 % after 6 h. Furthermore, APCEMM is the only model that retains a peak value of N_Z greater than 10^{10} m^{-2} past 2 h in Fig. 8b, at a location corresponding to the APCEMM contrail core. Moreover, in the 1 h and 2 h panels of Fig. 8b, APCEMM has at least double the maximum N_Z than either EULAG-LCM or CoCiP.

Overall, there is good qualitative agreement between the EULAG-LCM and APCEMM profiles despite the systematic differences discussed above. The agreement of the 2D models with CoCiP is poor because of its Gaussian plume approximation, an assumption that constrains the contrail shape and prevents consideration of the local meteorological conditions and contrail properties anywhere other than at the plume centre. By design, CoCiP sacrifices the ability to reproduce an accurate spatial distribution of its tracked quantities in favour of achieving fast computational speeds.

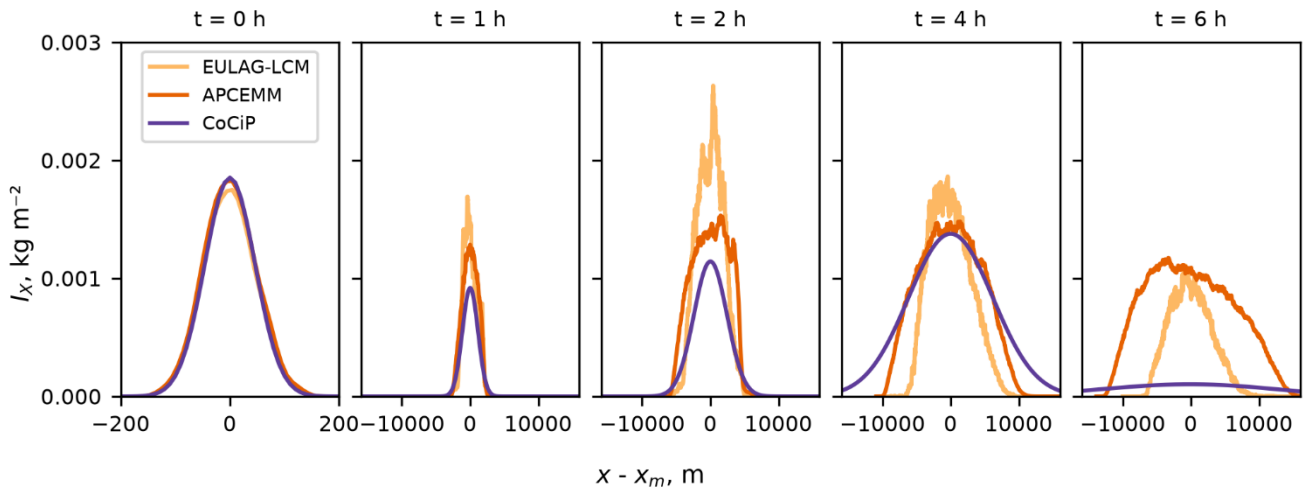


Figure 7: Time evolution of the ice mass distribution I_X , along the horizontal axis for the baseline case. The EULAG-LCM profiles have been smoothed with a moving average at times > 0 .

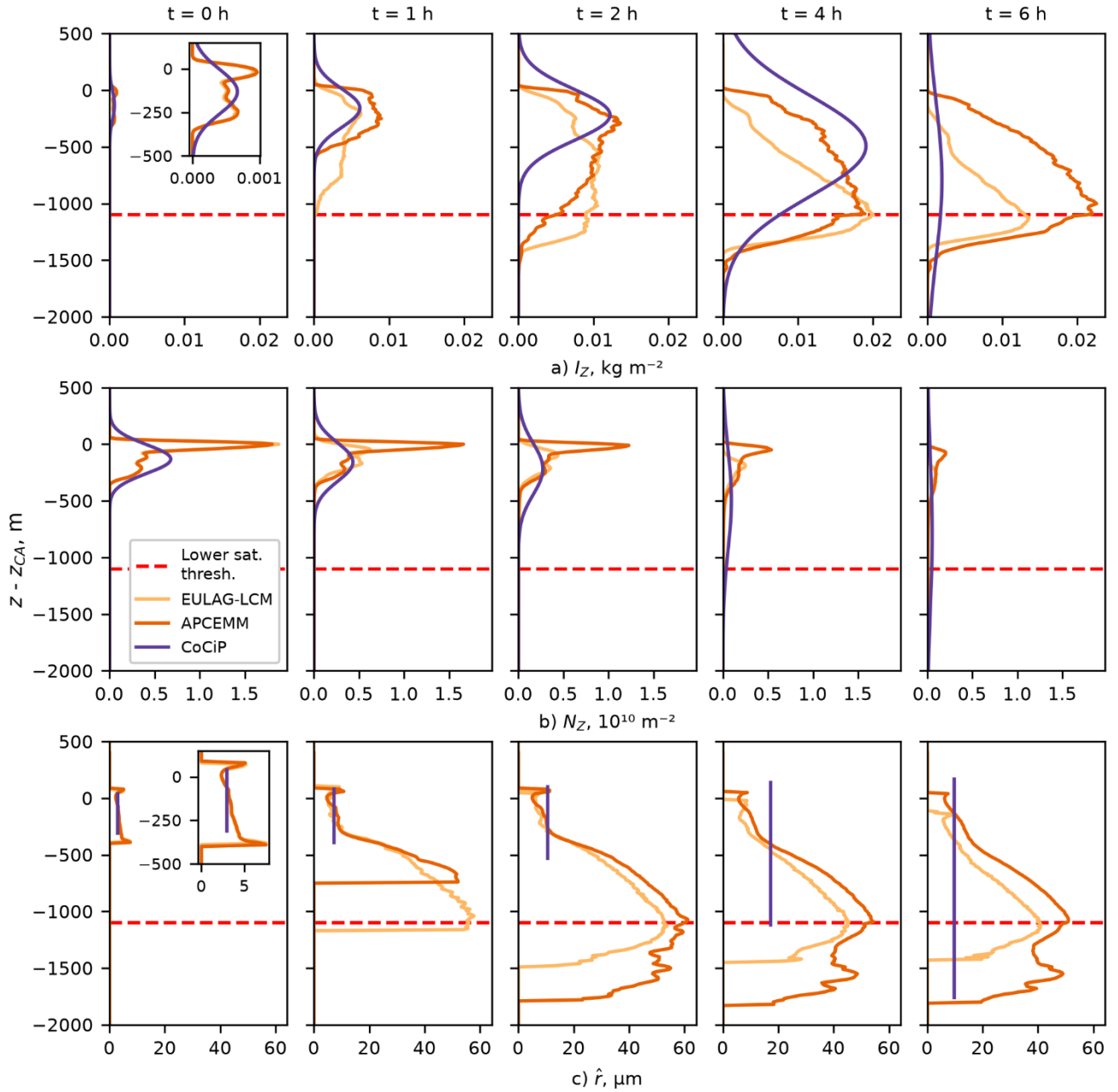


Figure 8: Time evolution of the ice mass (I_Z ; a), ice crystal number (N_Z ; b), and mean ice crystal radius ($\bar{r}$; c) vertical distributions for the baseline case. The EULAG-LCM profiles have been smoothed with a moving average at times > 0 . The CoCiP mean crystal radius is constant, reflecting the monodisperse assumption. Since the CoCiP mean ice crystal radius is uniform in the whole plume, its profile has been truncated outside of the contrail width boundary as determined by CoCiP. The dashed red line indicates the lower saturation threshold (the altitude beneath which $\text{RH}_i < 100\%$), which does not move since there is no updraught velocity in the baseline case.

3.1.3 Evolution of contrail integral properties

Figure 9 shows the evolution of the integral and geometrical contrail properties for the baseline meteorology. Excluding the ice mass and the total extinction, the time evolution of the contrail properties in APCEMM and EULAG-LCM is qualitatively similar (Fig. 9). All models show a decreasing z_m throughout the contrail lifetime. Both EULAG-LCM and APCEMM show a high and increasing $\dot{z}_m$ (on average 300 and 210 m/h respectively) within the first 2 h of the simulation (Fig. 9c). After this $\dot{z}_m$ reduces, achieving an approximately constant value of 38 and 49 m/h in EULAG-LCM and APCEMM respectively. This is also supported by Fig. 9h), which shows that EULAG-LCM has a higher average ice particle mass for until ~5.5 h. CoCiP also experiences a change from an accelerating decrease in z_m (with an average $\dot{z}_m$ of 43 m/h in the first two hours) until ~4 h. However, changes in behaviour happen to most other CoCiP contrail properties at 4 h (Fig. 9). In particular, the ice crystal number remains approximately constant at just over 10^{12} in CoCiP (corresponding to a loss of 56 % of the initial ice crystal number), whereas APCEMM and EULAG-LCM continue to show reductions in ice crystal number after this point.

Within the first 2 h, the ice number loss is approximately 2.5 times lower for APCEMM (21 % of the initial ice crystal number) than for EULAG-LCM (52 % of the initial ice crystal number) (Fig. 9b). Despite this initial discrepancy, EULAG-LCM and APCEMM have lost a similar proportion of the initial ice crystals by the time that the contrails reach an age of 8 h (93 % and 85 % respectively). Furthermore, the average $\dot{z}_n$ is larger in EULAG-LCM (71 m/h) than in APCEMM (42 m/h; Fig. 9d). From Fig. 6, the contrail core comprises ice number densities at least an order of magnitude higher than in the precipitation plume in both models, meaning that the centre of number effectively tracks the contrail core. Therefore, the contrail core in EULAG-LCM descends faster than the contrail core in APCEMM.

Another difference between APCEMM and EULAG-LCM is in the total ice mass and total extinction (Figs. 9a and 9g respectively). The total extinction peaks shortly after 3 hours in EULAG-LCM, and after 4 hours in APCEMM and CoCiP. The maximum total extinction in the models is 1040 m, 1590 m, and 1840 m in EULAG-LCM, APCEMM, and CoCiP respectively. After the peak, the total extinction in EULAG-LCM and CoCiP decreases rapidly, reaching an approximately constant value of ~500 m at 6 h in both models. The APCEMM total extinction also decreases, but much more slowly than in the other models, reaching a value of 1420 m at 8 h. The total ice mass behaves like the total extinction in CoCiP and EULAG-LCM but not in APCEMM, with the total ice mass in APCEMM reaching a maximum at around 7 h instead.

Considering the width and depth of the contrails (Fig. 9e and 9f), we can see that the APCEMM contrail has a higher width throughout the contrail lifetime, but the EULAG-LCM contrail has a higher depth than APCEMM prior to 2 h, at which point APCEMM overtakes EULAG-LCM. The centre of mass and centre of number evolution are qualitatively similar for EULAG-LCM and APCEMM, with the EULAG-LCM contrail having a lower location for both quantities throughout the contrail lifetime. The geometric quantities in CoCiP evolve according to the Gaussian assumption and hence result in disagreement of their evolution with the corresponding quantities in EULAG-LCM and APCEMM.

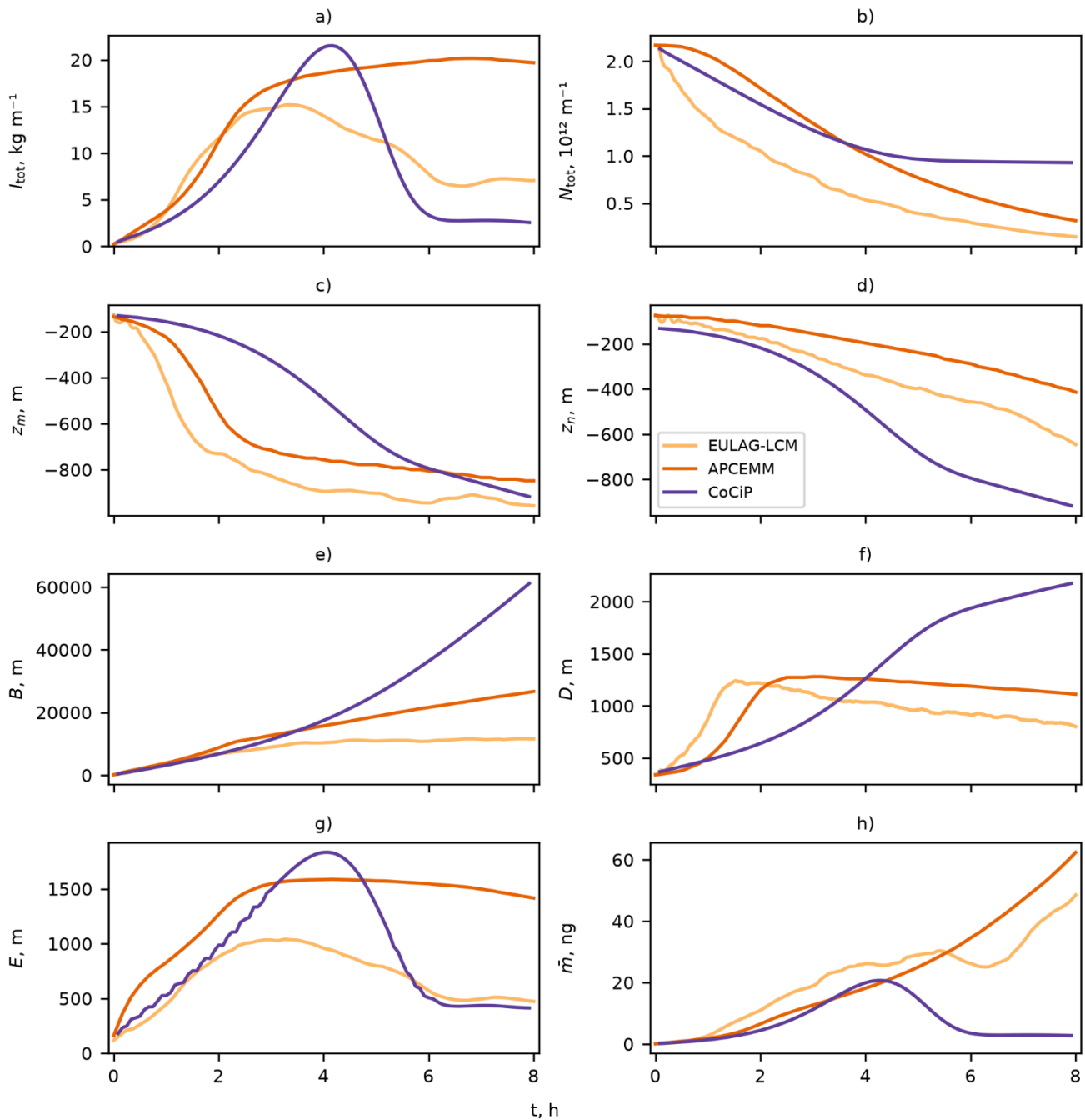


Figure 9: Time evolution of the total ice mass (I_{tot} ; a), total ice number (N_{tot} ; b), centre of mass vertical position (z_m ; c), centre of number vertical position (z_n ; d), width (B ; e), depth (D ; f), total extinction (E ; g), and the mean ice crystal mass ($\bar{m}$; h) of the contrail simulations using the baseline meteorology produced by EULAG-LCM, APCEMM, and CoCiP.



3.2 Discussion based on simulations evaluated on the baseline meteorology

3.2.1 Comparison of EULAG-LCM with APCEMM

EULAG-LCM and APCEMM have qualitatively similar profiles and geometric properties with some systematic differences.

475 In the horizontal profile, the APCEMM contrail spreads laterally more than the EULAG-LCM contrail. This occurs because the APCEMM contrail has a larger vertical extent than the EULAG-LCM contrail past 2 h, enhancing the distortion from wind shear. This larger vertical extent in APCEMM is driven by the slow sedimentation of the contrail core, increasing the vertical extent of the contrail relative to that simulated in EULAG-LCM. The fact that the precipitation plume also settles more quickly in EULAG-LCM than in APCEMM (300 vs 210 m/h settling speeds of the centre of mass respectively) explains why the

480 contrail mass peaks earlier, driven by the greater ice number loss in EULAG-LCM compared to APCEMM.

Figures 5 and 6 show structure in the EULAG-LCM contrail which is not present in APCEMM. This structure is a result of eddies of different scales mixing and distorting parts of the contrail core with moist ambient air within the first hour (see Fig. 14 and Sect. 5). The eddies responsible for this large-scale initial mixing originate from the background turbulence assumed in EULAG-LCM and from the vortex breakdown in the vortex phase of the contrail. Furthermore, grid-scale turbulent

485 mixing also increases the in-situ ice crystal losses due to small changes in temperature. This contributes to the rapid drop in the total ice crystal number seen in Fig. 9b for EULAG-LCM but not for APCEMM and explains the discrepancy in the proportion of ice crystals lost between EULAG-LCM and APCEMM. This phenomenon is further explored in Sect. 5.

The turbulence-enhanced in-situ ice crystal losses result in a lower number of ice crystals in EULAG-LCM with an average mass per ice crystal higher than APCEMM until ~6 h. Combined with potential numerical effects and differences in the ice

490 crystal sedimentation formulation, this causes both the centre of mass and centre of number (which tracks the contrail core) to fall faster in EULAG-LCM than in APCEMM. The higher ice crystal number with a lower average mass in APCEMM allows for ice crystals to remain in the layer for longer, hence resulting in a higher total ice mass and total extinction for APCEMM than for EULAG-LCM throughout the contrail lifetime. This effect is enhanced by the increased mixing of fresh air caused by the higher horizontal diffusion of the APCEMM plume compared to the EULAG-LCM plume. This causes more moisture to

495 become available and hence increases the total ice mass in the APCEMM contrail.

Overall, it is likely that the disparities in ice mass and total extinction between APCEMM and EULAG-LCM emerge cumulatively from the differences in the solver numerics, sedimentation formulations, turbulence representation and transport processes of the ice quantities.

3.2.2 Comparison of EULAG-LCM and APCEMM with CoCiP

500 In some cases (including the baseline case), the CoCiP contrail sublimates within the ice-supersaturated layer. Discussion of the cause of these alongside potential remedies is provided in the Supplementary Information. Nevertheless, some of the behaviours identified in Akhtar Martínez et al. (2025) are still visible in the baseline case presented here – namely the



differences in the contrail morphology between CoCiP and the higher-fidelity models. These causes of the morphological differences are now discussed.

505 Unlike EULAG-LCM and APCEMM, CoCiP lacks a distinct contrail core and precipitation plume (Figs. 5 and 6) due to its Gaussian plume assumption. Furthermore, due to the evaluation of all contrail properties at the centre, the CoCiP plume is not affected by the subsaturated layer (Figs. 5 and 6) until the centre itself leaves the supersaturated layer. This is unlike the EULAG-LCM and APCEMM contrails which experience a cutoff due to the heterogeneous sublimation which is also apparent in the vertical 1D distributions (Figs. 5, 6 and 8). This results in the monotonic growth of the contrail width and depth in CoCiP
 510 (Figs. 9e and 9f).

3.2.3 Implications

The analysis conducted in the above sections has revealed that the expected structure of the contrail (a contrail core and a precipitation plume) is associated with the staged evolution of contrail properties (as described in Akhtar Martínez et al., 2025). The key component necessary for this is the ability to represent differences in crystal radius across the plume. In EULAG-
 515 LCM this capability is represented through the Lagrangian SIPs, and in APCEMM the ice crystal radius bins facilitate the formation of the contrail core and the precipitation plume by allowing for differential sedimentation. This agrees with the previous comparison of CoCiP and APCEMM (Akhtar Martínez et al., 2025).

We also identify what is likely to be another important component for contrail modelling: the inclusion of a realistic turbulence representation. The turbulence in EULAG-LCM enhances the in-situ ice crystal loss, causing local deviations in the
 520 temperature and humidity. The in-situ loss results in a PSD that shifts towards higher ice crystal masses, increasing the sedimentation rate of the contrail core. The APCEMM contrail, which does not model grid-scale turbulence explicitly (it only uses diffusion and temperature fluctuations to approximate turbulence at the grid-scale), retains a higher ice crystal number and a corresponding lower average ice crystal mass (until ~6 h). This means that the APCEMM ice crystals persist for longer, settle more slowly, and thus extend the vertical and horizontal extent of the contrail due to shear, causing a larger total
 525 extinction than the EULAG-LCM contrail throughout the entire lifetime. Nevertheless, it is not possible to rule out that some of the above differences between APCEMM and EULAG-LCM may be caused or exacerbated due to further differences, for example in the solver numerics and in the formulations of the settling velocities.

4 Model intercomparison under all parametrized meteorological scenarios

The lack of a suitable ground truth to validate the modelled long-term evolution of contrails means that warming-targeted
 530 contrail avoidance strategies that rely on cross-model agreement may not succeed if they choose to reach agreement in the absolute sense, even when using models with many shared components. Such agreements or disagreements could be misleading on a case-by-case basis. Hence, we propose an exploration into whether relative changes can provide better insights into which contrails would be better to avoid.



In this section, we move from considering a single case to instead consider an ensemble of simulations covering a broad variety of meteorological conditions. We analyse the ensemble agreement in the magnitude of the integrated total extinction, and we consider absolute and signed sensitivities to each of the meteorological variables. We also consider whether relative changes can provide more information to contrail avoidance strategies than magnitudes as model outputs.

4.1 Results

4.1.1 Parity

Figure 10c shows the relationship between the APCEMM and EULAG-LCM lifetime total extinction, and between the CoCiP and EULAG-LCM lifetime total extinction separately. The predicted lifetime total extinction from APCEMM is on average 1.29 times the predicted lifetime total extinction from EULAG-LCM (given by the slope of the orange line). The Pearson correlation coefficient is 0.93, showing that the APCEMM results are strongly correlated with the EULAG-LCM results. Similarly, the lifetime total extinction predicted by CoCiP is 0.31 times the lifetime total extinction from EULAG-LCM (given by the gradient of the purple line). The Pearson correlation coefficient for EULAG-LCM and CoCiP results is 0.50. The fit line gradient between the lifetime total extinction from APCEMM and CoCiP is 3.14 in this study, implying that CoCiP contrails have on average approximately one third the lifetime extinction of those in APCEMM with a corresponding Pearson correlation coefficient of 0.63.

We normalise the lifetime total extinction by the median run of each model in Fig. 10b and 10d. Normalisation by the median splits the contrail model evaluations such that half of them lie in the range $[0,1]$, and the other half in the range $[1, \infty]$. This effectively reduces the scale discrepancy between the model results, highlighting the variability of the model results instead. The effects of the normalisation by the median can be seen by comparing the histograms in Fig. 10. Before the normalisation (Fig. 10a) most of the CoCiP contrails predict lifetime total extinction beneath 10000 m h, whereas APCEMM and EULAG-LCM commonly predict lifetime total extinctions up to 20000 m h, and occasionally beyond 30000 m h. After the normalisation (Fig. 10b), most simulations have a normalised lifetime total extinction beneath 3 in all models, showing better agreement than prior to the normalisation. However, APCEMM and EULAG-LCM still have some outliers above this.

The normalised APCEMM results are ~ 0.80 times the normalised EULAG-LCM results, whereas the CoCiP results are ~ 0.59 times the normalised EULAG-LCM results. The normalised CoCiP lifetime total extinction results are hence closer in value to the normalised EULAG-LCM results when compared to the raw values. Considering the relationship between APCEMM and CoCiP (which is not directly shown in Fig. 10), the linear fit gradient of the normalised results is 1.03, which indicates that normalisation improved the CoCiP and APCEMM result agreement. The Pearson correlation coefficients remain the same as in Fig. 10a as they are mathematically unaffected by multiplicative rescaling of either axis.

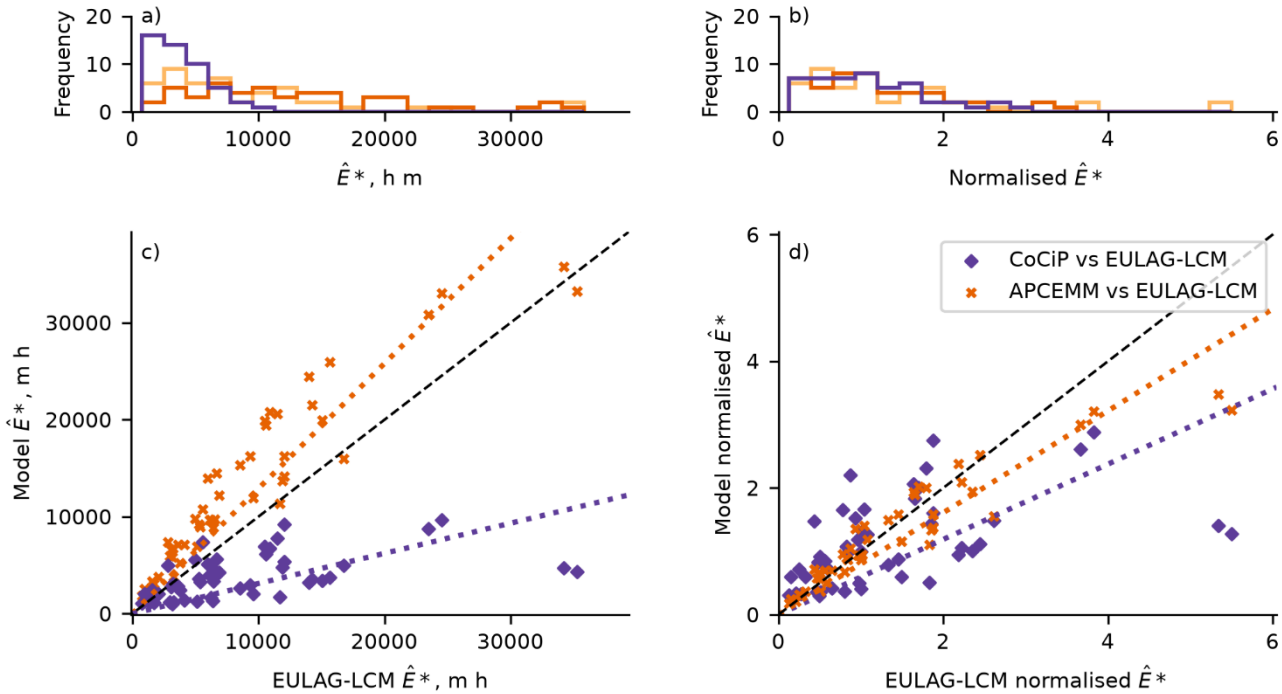


Figure 10: Panels a and b contain histograms showing the distribution of the lifetime total extinction in each model. Panels c and d contain parity plots showing the correlation between EULAG-LCM and APCEMM (orange), and EULAG-LCM and CoCiP (purple) for the lifetime total extinction. The dashed black diagonal line is the line of parity. Panels a and c use the absolute value of the lifetime total extinction, whereas panels b and d use the values normalised by the median value across all simulations by the given model.

4.1.2 Sensitivity

Figure 11 shows the primary sensitivities (bars) and the secondary effect sensitivities (scatter) to meteorological variability, as defined by Eqs. 10 and 11.

We find that EULAG-LCM is more sensitive to increases in shear than APCEMM (primary sensitivities of 1.05 and 0.36 respectively). The higher sensitivity of EULAG-LCM to shear is due to the higher depth-to-width aspect ratio in the EULAG-LCM contrails relative to the APCEMM contrails (Fig. 12). This is due to two factors. First, the EULAG-LCM precipitation plume precipitates faster due to the increased ice crystal number loss (corresponding to fewer but larger crystals before the plume reaches subsaturated air) and perhaps due to differences in solver numerics and in the implementation of the sedimentation. This leads to a higher initial contrail depth and a higher depth-to-width aspect ratio. Second, the APCEMM contrail spreads horizontally through turbulent diffusion more than the EULAG-LCM contrail spreads horizontally due to the background eddies. Since APCEMM (unlike EULAG-LCM) represents ice in an Eulerian grid, the spreading is exacerbated by numerical diffusion (which is inherent to all transport schemes employing an Eulerian grid). Nevertheless, this reduces the depth-to-width aspect ratio of the APCEMM contrail throughout the contrail lifetime. As discussed in Sections 3.1.4 and 5, a



higher aspect ratio leads to a larger amount of mixing with fresh ambient air for a given shear in the 2D models, resulting in EULAG-LCM having a higher sensitivity to shear than APCEMM. CoCiP has a lower primary sensitivity to shear (0.22) than the 2D models because the entire CoCiP plume moves together due to the monodisperse assumption, and has a high z_m which is boosted by the increased ice uptake due to shear. This lower lifetime limits the increase in total extinction of the CoCiP plume.

As seen in Table 2, simulations with higher background temperature have a smaller number of surviving ice crystals at the end of the vortex phase. The simulations with higher temperature but the same relative humidity also have higher specific humidity throughout the domain. In combination, there are fewer ice crystals that take up a larger amount of water vapour when increasing the ambient temperature. These have a higher associated settling velocity and total extinction, which have competing effects on the lifetime total extinction. The effect of the increased total extinction and the decreased lifetime may overpower each other at different regions of the meteorology space, depending on the modelling choices. For EULAG-LCM, all else being equal, simulations with a higher background temperature almost always have increased lifetime total extinction relative to simulations with lower temperature (a primary sensitivity to temperature of 0.26), except for when RH_{i0} is low (a secondary sensitivity of -0.04). This is because decreasing the RH_{i0} yields a further decrease in the initial ice crystal number (see Table 2). In APCEMM, the sensitivity to temperature is almost zero in this study. Furthermore, the secondary sensitivities to temperature in APCEMM for the high shear, low updraught velocity and low peak depth cases disagree in sign with those in EULAG-LCM. In CoCiP, all sensitivities to temperature are large in magnitude and negative (primary sensitivity of -0.50) because the higher settling speed affects the whole plume uniformly, shortening the contrail lifetime. This is a substantial difference between CoCiP and the 2D models.

Increasing RH_{i0} increases the number of ice crystals at the start of the diffusion regime. Thus, the larger amount of available water is distributed over more ice crystals throughout the contrail lifetime. In all models, this increases the lifetime total extinction by increasing the instantaneous total extinction and by potentially increasing the lifetime of the contrails in some scenarios. The lifetime increase is not guaranteed due to the trade-off between lifetime and ice crystal mass.

Similarly, the updraught velocity acts to increase the degree of supersaturation without affecting the initial ice crystal number. Increasing the updraught velocity from $w_{syn} = 0.00 \text{ m s}^{-1}$ to $w_{syn} = 0.02 \text{ m s}^{-1}$ makes more water vapour become available for ice crystal growth, hence increasing the total extinction in EULAG-LCM and APCEMM. This is corroborated by the fact that the sensitivities in EULAG-LCM and APCEMM are strongly positive (1.37 and 1.19 respectively). However, the CoCiP sensitivity for the same change in synoptic-scale updraughts remains close to zero (0.08). There are two likely reasons for this. First, the CoCiP contrail only considers the meteorology at its centre, and hence the effects of the cooling are limited when the CoCiP contrail precipitates fast and enters subsaturated air. Alternatively, the small CoCiP sensitivity may also result from the fact that CoCiP does not deplete the local humidity field, so increasing the available water vapour has a smaller effect in CoCiP than in APCEMM and EULAG-LCM – which do deplete the local water vapour field, limiting ice growth. Conversely, increasing the updraught velocity from $w_{syn} = 0.02 \text{ m s}^{-1}$ to $w_{syn} = 0.05 \text{ m s}^{-1}$ does not increase the additional water vapour that becomes available since the final cooling (2 K) is the same in both scenarios with a positive updraught velocity (see



Fig. 4c). Hence, only the rate at which this additional water vapour becomes available is changed, resulting in near-zero sensitivities for all three models. This is consistent with the findings reported by Unterstrasser (2020) and Lottermoser & Unterstrasser (2026).

Finally, all three models consistently show a positive sensitivity with respect to increases in the depth of the supersaturated layer (or the “peak depth”). EULAG-LCM is more sensitive than APCEMM and CoCiP (primary sensitivities of 1.16, 0.60, and 0.39 respectively) to the peak depth. This is because the depth-to-width aspect ratio in both EULAG-LCM simulations is higher than the corresponding APCEMM simulations (Fig. 13) due to both numerical and turbulent diffusion in APCEMM. Given that increasing the aspect ratio increases the water mass that is exposed to precipitating ice crystals (see Appendix C), the increased sensitivity to the supersaturated layer depth in EULAG-LCM is expected. In CoCiP the sensitivity is also smaller than in EULAG-LCM and APCEMM because the higher peak depth primarily increases the contrail lifetime by 22% (cumulatively across all simulations), but the total extinction only increases when the CoCiP contrail centre enters the additional supersaturation associated with a higher peak depth (Fig. 13b), at which point the sedimentation velocity of the entire contrail is already high (Fig. 13a).

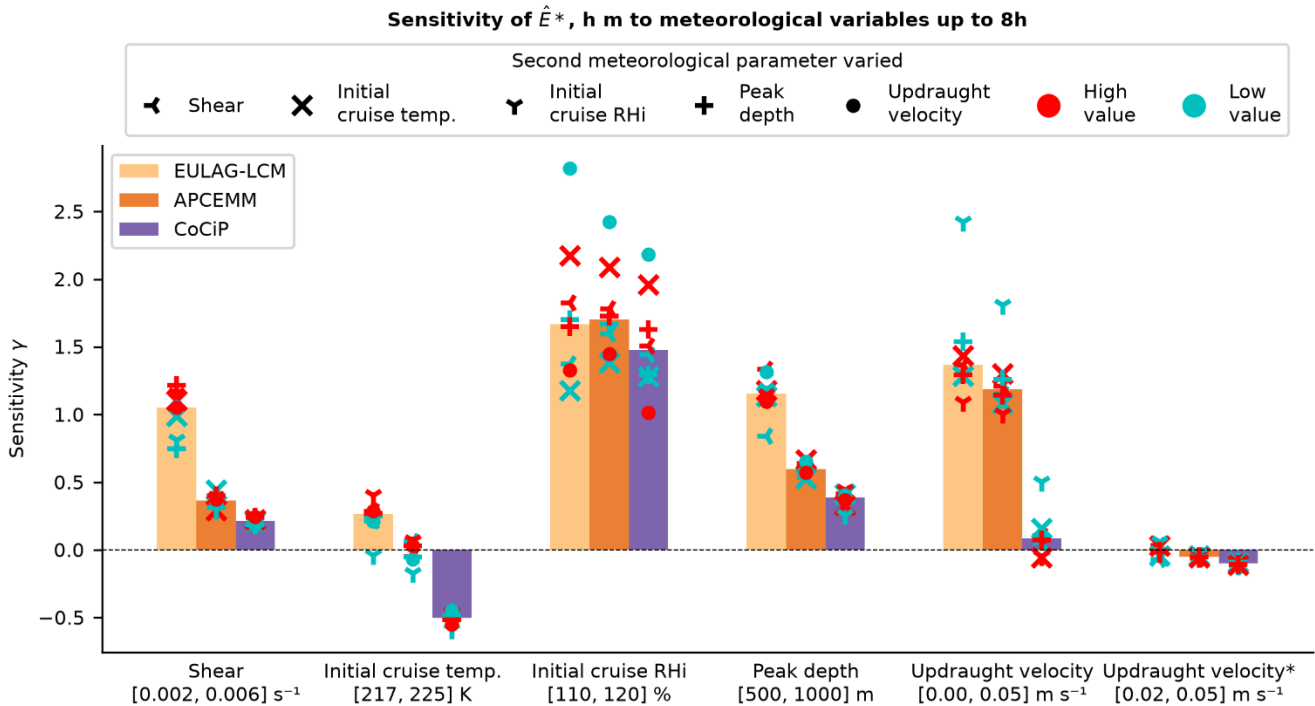


Figure 11: Primary effect sensitivities (γ_i ; bars) and secondary effect sensitivities ($\gamma_{i|j=state}$; scatter) of the lifetime total extinction produced in each model to increases in the corresponding meteorological variable (see Eqs. 10-11). The sensitivity γ_i is the average effect of increasing a meteorological variable across all runs. Similarly, $\gamma_{i|j=state}$ is the same quantity calculated for the subset of runs in which a second meteorological parameter is either low (blue; state = lo) or high (red; state = hi) according to the values in Table 3. An integral time horizon of 8 h is used, and runs with 0.02 m s^{-1} updraught velocity are excluded from all sensitivity calculations, except for those in the last entry marked with an asterisk – where the 0.00 m s^{-1} updraught velocity is replaced with 0.02 m s^{-1} in the sensitivity calculations.

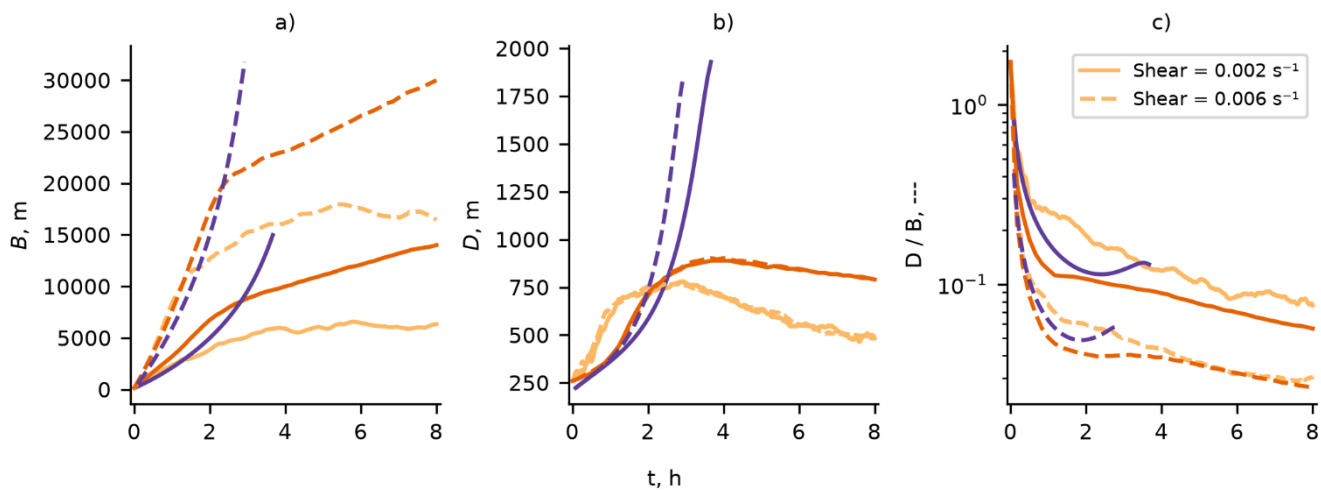


Figure 12: Contrail width (B ; a), contrail depth (D ; b), and depth to width aspect ratio (c) for the case in which all meteorological variables take the baseline value throughout – except for the shear, which takes its low value (solid line), and its high value (dashed line) according to Table 3. The models correspond to the colours: EULAG-LCM (yellow), APCEMM (orange), CoCiP (purple).

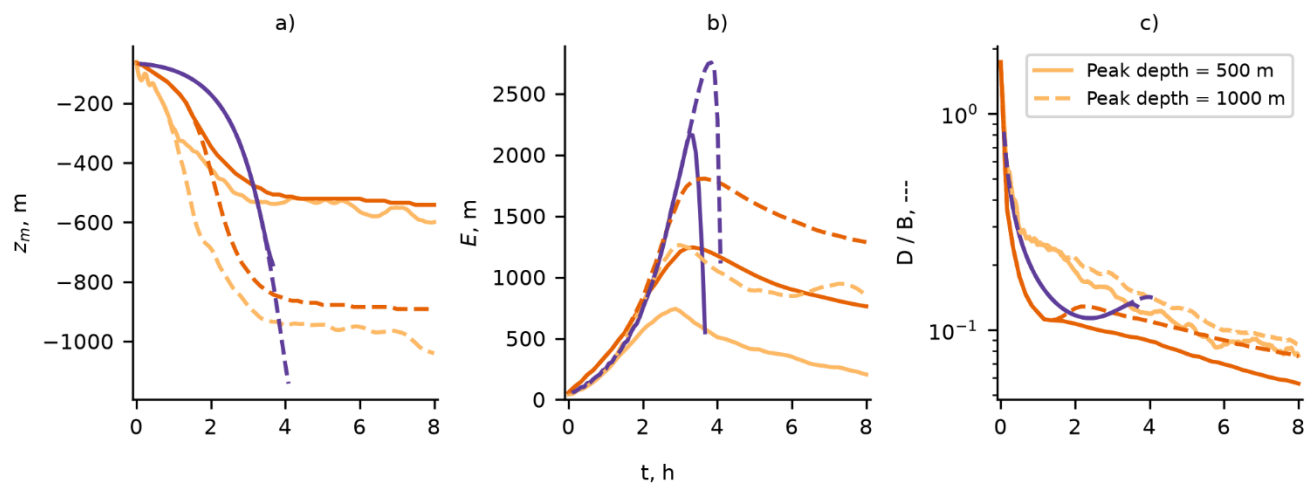


Figure 13: Centre of mass location (z_m ; a), centre of number location (z_n ; b), and depth to width aspect ratio (c) for the case in which all meteorological variables take the baseline value throughout – except for the peak depth, which takes its low value (solid line), and its high value (dashed line) according to Table 3. The models correspond to the colours: EULAG-LCM (yellow), APCEMM (orange), CoCiP (purple).

4.1.3 Comparison of the sensitivities to prior literature

In this subsection we compare the sensitivities to the prior literature, namely Lewellen (2014) and Akhtar Martínez et al. (2025).



650 Table 1 and Table 3 in Lewellen (2014) indicate that only two meteorological variables shared with this study had sensitivities of the lifetime-integrated ice crystal surface area (analogous to the lifetime total extinction employed here) with a consistent sign across all meteorological scenarios considered. Lewellen (2014) found that varying w_{syn} from -0.04 m s^{-1} to 0.04 m s^{-1} resulted in a positive sensitivity (Table 1 and Table 3 in Lewellen, 2014). In this study, varying w_{syn} from 0.00 m s^{-1} to 0.02 m s^{-1} results in a positive sensitivity in EULAG-LCM and APCEMM, but it results in a small ambiguous sensitivity in
655 CoCiP. However, in this study varying w_{syn} from 0.02 m s^{-1} to 0.05 m s^{-1} results in a small, ambiguous sensitivity in EULAG-LCM, and a small negative sensitivity in CoCiP and APCEMM (Fig. 11). Moreover, Lewellen (2014) found that varying d from 500 m to 1000 m resulted in a strongly positive sensitivity (Table 1 and Table 3 in Lewellen, 2014). In this study, varying d along the same range also results in a positive sensitivity for EULAG-LCM, APCEMM, and CoCiP (Fig. 11) – indicating uncontested agreement with the Lewellen (2014) findings. Finally, in Lewellen (2014) the sensitivities to RH_{i0} , $T_{CA,0}$, and s
660 had differing signs in different regions of the meteorological space. In this study, the only variable yet to be discussed with sensitivities of differing signs in different locations of the meteorological space is $T_{CA,0}$, which has ambiguous signs for EULAG-LCM and APCEMM, but is strongly negative in CoCiP (Fig. 11).

We now compare the sensitivities obtained in this study to those obtained by Akhtar Martínez et al. (2025). The CoCiP and APCEMM sensitivities to d and s from this study agree in sign with the corresponding sensitivities in Akhtar Martínez et al. (2025). However, the CoCiP sensitivity to RH_{i0} and the APCEMM sensitivity to $T_{CA,0}$ disagree in sign with those in Akhtar
665 Martínez et al. (2025).

The disagreement in the CoCiP sensitivity to RH_{i0} likely arises from the different meteorology space explored and the diffusion regime initialisations. In Akhtar Martínez et al. (2025) the CoCiP N_{tot} at 5 min increased from 2.39×10^{12} at 110 % RH_{i0} to 2.86×10^{12} at 120 % RH_{i0} (20 % increase), but it only increased to 3.03×10^{12} when increasing the RH_{i0} to 140 % (a further 7 %
670 increase compared to the 110 % RH_{i0} case). This illustrates that there are diminishing returns regarding the vortex-phase survival fraction as RH_{i0} is increased (as seen in Lottermoser and Unterstrasser, 2025 and in Unterstrasser, 2016). In this study, post-vortex N_{tot} increases by at least 129 % when going from 110 % to 120 % RH_{i0} (Table 2). Simultaneously, the RH_i at the end of the parametrised updraught increases from 140 % to 153 % - corresponding to a smaller relative increase in the available water vapour above saturation (33 %) when compared to the cases without updraught (50 % increase in the available water
675 vapour above saturation). All else being equal, increases in the initial ice crystal number are correlated with higher total extinction through a higher ice crystal surface area and a lower sedimentation speed (e.g. Lottermoser and Unterstrasser, 2026), whereas increases in diffusion regime RH_{i0} are correlated with heavier ice crystals which sediment out of the ISSR faster. The increased sedimentation affects the entire CoCiP plume equally due to its monodisperse and 0D assumptions. Hence, in Akhtar Martínez et al. (2025) the effects from the small increase in vortex-phase survival fraction (27 % at 5 min) are unable to
680 compensate for the increased ice crystal mass when jumping from 110 % to 140 %, resulting in a negative sensitivity. However, in this study the effects due to the larger increase of the survival fraction (at least 129 % at 0 min) compensate for the increased sedimentation speed, resulting in a positive sensitivity. This compounds with a relatively smaller increase of available water



vapour for the cases in which $w_{\text{syn}} > 0.00 \text{ m s}^{-1}$. Since APCEMM has a PSD capable of representing multiple ice crystal sizes, the increased ice mass does not affect the entire contrail equally, allowing for the increase in total extinction to dominate over the decrease in lifetime in both the previous and current studies.

The disagreement in the APCEMM sensitivity to $T_{\text{CA},0}$ may appear because of three reasons: the use of a different diffusion regime initialisation between the studies, the different meteorological space spanned, and the integration time horizon. In the study by Akhtar Martínez et al. (2025) increasing the $T_{\text{CA},0}$ from 208.15 K to 223.15 K whilst maintaining RH_{i0} at 125 % resulted in a decrease in initial N_{tot} from 8.85×10^{12} to 8.31×10^{12} (~6 % decrease). In this study increasing the $T_{\text{CA},0}$ from 217 K to 225 K whilst maintaining RH_{i0} at 120 % results in a decrease in initial from 2.17×10^{12} to 1.51×10^{12} (~30 % decrease). In both studies, increasing the temperature increases the available water vapour above saturation per ice crystal, and hence the mean ice crystal mass. By considering the effect of the integral time horizon in Appendix D, we can see that decreasing the time horizon increases the sensitivity to temperature from near zero to 0.38 in APCEMM and from 0.26 to 0.73 in EULAG-LCM. Hence, it is likely that the 24 h time horizon used in Akhtar Martínez et al. (2025) caused the negative sensitivity. This is because the effect of the temperature is not uniform throughout the contrail lifespan: increasing the temperature increases the instantaneous total extinction but reduces the contrail lifetime. Hence, if the time horizon is low enough, only the increased total extinction will be apparent. If the time horizon is large enough, the shorter lifetime may outweigh the higher instantaneous total extinction.

4.2 Discussion

4.2.1 Parity

The parity plots of the lifetime total extinction indicate that APCEMM and EULAG-LCM are more strongly correlated than CoCiP and EULAG-LCM (Pearson correlation coefficient of 0.93 vs 0.50). The APCEMM/EULAG-LCM linear fit has a gradient of 1.29, compared to the CoCiP/EULAG-LCM gradient of 0.31. This indicates that the simplifications made in CoCiP, although providing a substantial increase in computational speed, may cause it to be unable to appropriately represent key functional relations present in the contrail physics.

Nevertheless, normalising the lifetime total extinction of each run by the median value for each model improves both the histogram agreement and the CoCiP/EULAG-LCM fit gradient (0.59). Given the lack of ground truth for model validation, using normalised model outputs may lead to better avoidance decisions. If two models disagreed on average by a large amount, targeting the contrails with the most warming as predicted by each model rather than the contrails responsible for an absolute amount of warming might eliminate some biases in the results of each model, given that an appropriate normalisation is used.

4.2.2 Sensitivity

The results of the sensitivity analysis highlight that differences in the model sensitivities are attributable to the differences in simplifying choices made by each model. We find that the four most important modelling choices are the model dimensionality



(0D vs 2D), the model PSD representation (monodisperse vs polydisperse), the local-scale meteorology feedbacks, and the inclusion of turbulence.

The 0D plume assumption in CoCiP causes the entire plume to be affected by changes that otherwise affect each part of the contrail differently. This makes the functional relations in the CoCiP contrails fundamentally different to the functional relations of the 2D models. Consequently, the sensitivities to all parameters in CoCiP are the furthest from the corresponding EULAG-LCM sensitivities, including disagreements in signs for the variations of temperature and updraught velocity.

Differences in the sensitivities of EULAG-LCM and APCEMM to temperature and layer depth are not attributable to a single component alone. Furthermore, we identify some instances where the sign of the secondary effects of the temperature disagreed between EULAG-LCM and APCEMM. This illustrates the complexity of intercomparison for complex models, particularly when more than one modelling choice may contribute to certain behaviours. This also demonstrates the need for a ground truth dataset for validation.

Differences with the prior studies by Lewellen (2014) and Akhtar Martínez et al. (2025) are attributed to three possible sources: differences in the meteorological parameter range explored by each study, differences in the diffusion regime initialisation, and differences in the integration time horizon. Hence, if we are to isolate the modelling uncertainties in future intercomparisons, the development of a common set of meteorological and aircraft-related scenarios is imperative.

Overall, we identify some of the modelling components that drive differences in the sensitivities across models. We also show that the three models disagree in sign of some secondary sensitivities and, in the case of CoCiP, in the primary sensitivity to temperature. This renders the case-by-case predictions of contrail warming irreconcilable, even amongst the higher-fidelity models. However, alternative approaches that are robust to these case-by-case disagreements may, on average, be able to nullify some of the model-based uncertainties identified in this study.

5 Exploring the effect of the model configuration on the geometric and optical properties of the simulated contrail

Although the differences between CoCiP and the 2D models have been accounted for by exploring the consequences of the modelling choices made by CoCiP, the differences between APCEMM and EULAG-LCM are yet to be fully explained. While EULAG-LCM and APCEMM exhibit qualitatively similar contrail-cirrus life cycles, the quantitative differences—such as those in total extinction—are substantial. To isolate the physical processes driving the differences between APCEMM and EULAG-LCM, this section performs a sensitivity analysis in which the EULAG-LCM configuration is changed in different simulations (summarised in Table 4). We perform these simulations in both the baseline meteorology (Sect. 5.1) and in meteorology with a single perturbed meteorological variable (Sect. 5.2). The simulations in Sect. 5.2 provide both robustness to our findings and additional insights, the implications of which are discussed in Sect. 5.3.

We categorize the configuration modifications into either initialisation changes or changes to the contrail-cirrus physics. Changes to the initialisation affect only the initial background fields of wind, temperature, and water vapour. Changes to the



745 contrail-cirrus physics affect either how the contrail evolves (**NoKelvin**) or how the optical properties of the contrail are
calculated (**SpheresOutput**).

The changes to the initialisation of the contrail are aimed at identifying the crucial aspects of both the turbulence representation
used and the coupling between the vortex regime and the diffusion regime. To analyse the effect of the different turbulent
schemes, a simulation with no initial turbulence is produced (**NoTurb**). Compared to the reference EULAG-LCM simulation
750 (**REF**), this simulation excludes the initial turbulent fluctuations in the water vapour, temperature, and wind fields, but
maintains the corresponding perturbations produced in the vortex regime. This configuration more closely resembles the
APCEMM diffusion regime initialisation, which lacks these initial perturbations. Nevertheless, APCEMM does include
random turbulent temperature fluctuations at all grid-cells throughout the simulation (Sect. 1.1.2). Hence, inclusion of the
NoTurb simulations also facilitates the comparison of the turbulence representations in APCEMM and EULAG-LCM.
755 Conversely, the **NoVortex** simulations exclude the vortex-phase perturbations of the water vapour, temperature, and wind
whilst maintaining their perturbations due to the background turbulence. Since APCEMM only includes the vortex-phase water
vapour deficit in the diffusion regime initialisation, the **NoVortex** simulations allow for the comparison between the EULAG-
LCM and APCEMM initialisation strategies. Finally, the **NoTurbVortex** simulations exclude all perturbations in the wind,
temperature and water vapour fields except for the vortex-phase water vapour deficit. This configuration is the closest to the
760 APCEMM initialisation and hence allows us to identify whether the APCEMM behaviour can be recovered in EULAG-LCM
simply by matching the initialisations as much as possible.

The changes to the contrail cirrus physics aim to determine the relative importance of the habits used by each model, and the
Kelvin effect in the diffusion regime. Since EULAG-LCM does not have a built-in way to employ spherical habits for ice
growth and sedimentation, the **SpheresOutput** simulations treat the habits as spheres when computing the optical properties
765 – namely extinction and total extinction. APCEMM also employs spherical habits, so the **SpheresOutput** simulations aim to
identify whether the habit used for optical property calculations accounts for the qualitative differences between APCEMM
and EULAG-LCM. Finally, since we identified a discrepancy between APCEMM and EULAG-LCM in the time evolution of
the number of ice crystals, we perform EULAG-LCM simulations with the Kelvin effect disabled to attempt to identify whether
the implementation of the ice growth equations may be partially responsible for some of the aforementioned differences.

770 **Table 4: List of EULAG-LCM contrail-cirrus simulations analysing the effect of simplifications/assumptions in model setup or
model physics. This serves as the legend for Figs. 15 and 16.**

Category	Label	Line style	Modifications in EULAG-LCM contrail-cirrus simulation setup
N/A	REF		Uses the default settings that were used to produce the main dataset.
Initialisation	NoTurb		No initial turbulent fluctuations are present in the fields of water vapour, temperature, and wind. Vortex-phase perturbations in these fields are included.



Contrail- cirrus physics	NoVortex		No vortex phase field perturbations of water vapour, temperature, and wind are included. Initial turbulent fluctuations of those quantities are included.
	NoTurbVortex		No initial turbulent fluctuations are present in the fields of water vapour, temperature, and wind. No vortex phase field perturbations of temperature, and wind are included either.
	SpheresOutput		Spherical ice crystals are assumed only in the computation of the extinction during post-processing.
	NoKelvin		The Kelvin effect in the ice crystal growth equation is disabled.

5.1 Baseline meteorology simulations using different EULAG-LCM configurations

Fig. 14 displays time series of microphysical and geometric contrail-cirrus properties for a single meteorological scenario
($T_{CA,0} = 217\text{K}$, $RH_i = 120\%$, $w_{syn} = 0.00\text{ m s}^{-1}$, $s = 0.002\text{ s}^{-1}$, $d = 1\text{ km}$). We first focus on the **NoTurb** and **NoTurbVortex**
simulations since they display the closest geometrical properties to APCEMM (see panels e, f, and h in Fig. 15).

Comparing the **REF** simulations with the **NoTurb** and **NoTurbVortex** simulations reveals that turbulence introduces a source
of stochasticity to the contrail evolution. Turbulent fluctuations in temperature and humidity increase the loss of smaller ice
crystals (panel b): by $t = 2\text{ h}$, **REF** contains $1.2 \times 10^{11}\text{ m}^{-3}$ fewer ice crystals than the **NoTurb** simulations. This difference
grows to $4.1 \times 10^{11}\text{ m}^{-3}$ by $t = 7\text{ h}$. When discarding the turbulent perturbations alongside the vortex-phase field perturbations,
the ice crystal loss in the **REF** simulation is further enhanced: by $t = 2\text{ h}$. The **REF** simulation contains $2.8 \times 10^{11}\text{ m}^{-3}$ fewer ice
crystals than the **NoTurbVortex** simulation, and $5.0 \times 10^{11}\text{ m}^{-3}$ fewer ice crystals by $t = 7\text{ h}$. , turbulence also mixes humid
ambient air into the contrail, enhancing water vapour uptake by the surviving ice crystals. Together, these processes eliminate
smaller crystals while promoting the growth of the larger surviving ones. Consequently, the centre of number shifts downward
(Fig. 15d), while the centre of mass remains largely unchanged (Fig. 15c). For $t > 4\text{ h}$, the **NoTurbVortex** simulation features
the largest ice crystal number values (closely followed by the **NoTurb** simulation), even exceeding those of the **NoKelvin**
simulation discussed below.

The changes in the vertical distribution of ice crystals caused by the different configurations also affect all other contrail
geometric properties due to shear. The initial increase in contrail thickness proceeds at nearly the same rate for all sensitivity
runs because it is driven by the differential sedimentation of the largest ice crystals. Hence this growth ceases once the contrail
has filled the moist layer below cruise altitude and ice crystals begin to fall into the subsaturated layer beneath. Contrail
broadening reaches a quasi-steady plateau after 4 h in all simulations except **NoTurb** and **NoTurbVortex**, where width
continues to increase over the full 8 hours. The contrail depth-to-width aspect ratio is also closest to APCEMM for the **NoTurb**
and **NoTurbVortex** simulations between 2 and 8 h (Fig. 15h). Nevertheless, the **NoVortex** simulation also affects the



795 geometrical properties of the contrail in a similar but less pronounced manner than the **NoTurb** and **NoTurbVortex** simulations in the baseline meteorology. The anomalous behaviour of the **NoTurb**, **NoVortex** and **NoTurbVortex** simulations is also evident in the evolution of ice mass and total extinction, where the time evolution of all other configurations align more closely with **REF** than **NoTurb** does.

In the **NoVortex** simulation, at initialisation, the ice crystals experience the prescribed background humidity instead of the depleted humidity from the ice formation in the jet and vortex regimes. This double-counting of the locally available water prevents in-situ sublimation, resulting in the growth of the small ice crystals that otherwise sublimate. As a result, the ice mass increase is stronger compared to the **REF** simulation, even exceeding the ice mass increase in APCEMM. Since sublimation in APCEMM is also reduced, this causes the time evolution of the ice crystal number in the **NoVortex** simulation to be qualitatively closer to that in APCEMM throughout the entire contrail lifetime. Furthermore, slight perturbations to the temperature field are also disregarded in the **NoVortex** case, which may allow for the increased survival of small ice crystals. Similarly, when the Kelvin effect is disabled (**NoKelvin**) the ice crystal number time evolution is closest to the APCEMM results throughout the contrail lifetime due to decreased sublimation of small ice crystals. Yet, the differences in ice mass and total extinction between **REF** and **NoKelvin** simulations remain small. Following the explanations in Unterstrasser (2017b), the smallest ice crystals — which only survive in the **NoKelvin** simulation — do not significantly contribute to the higher moments of the size distribution. The small ice crystals do affect the ice mass and total extinction in the **NoVortex** simulation because the additionally available water and the removal of vortex-phase temperature fluctuations allow the small ice crystals to grow to a larger size, increasing the number of ice crystals that do affect the contrail ice and geometric properties.

Finally, by construction, the **SpheresOutput** and **REF** results agree on all displayed quantities except total extinction. Given a fixed ice mass, spherical ice crystals have smaller surface area and projected cross-sectional area than hexagonal columns. Consequently, the total extinction of **SpheresOutput** is lower than that of **REF**.

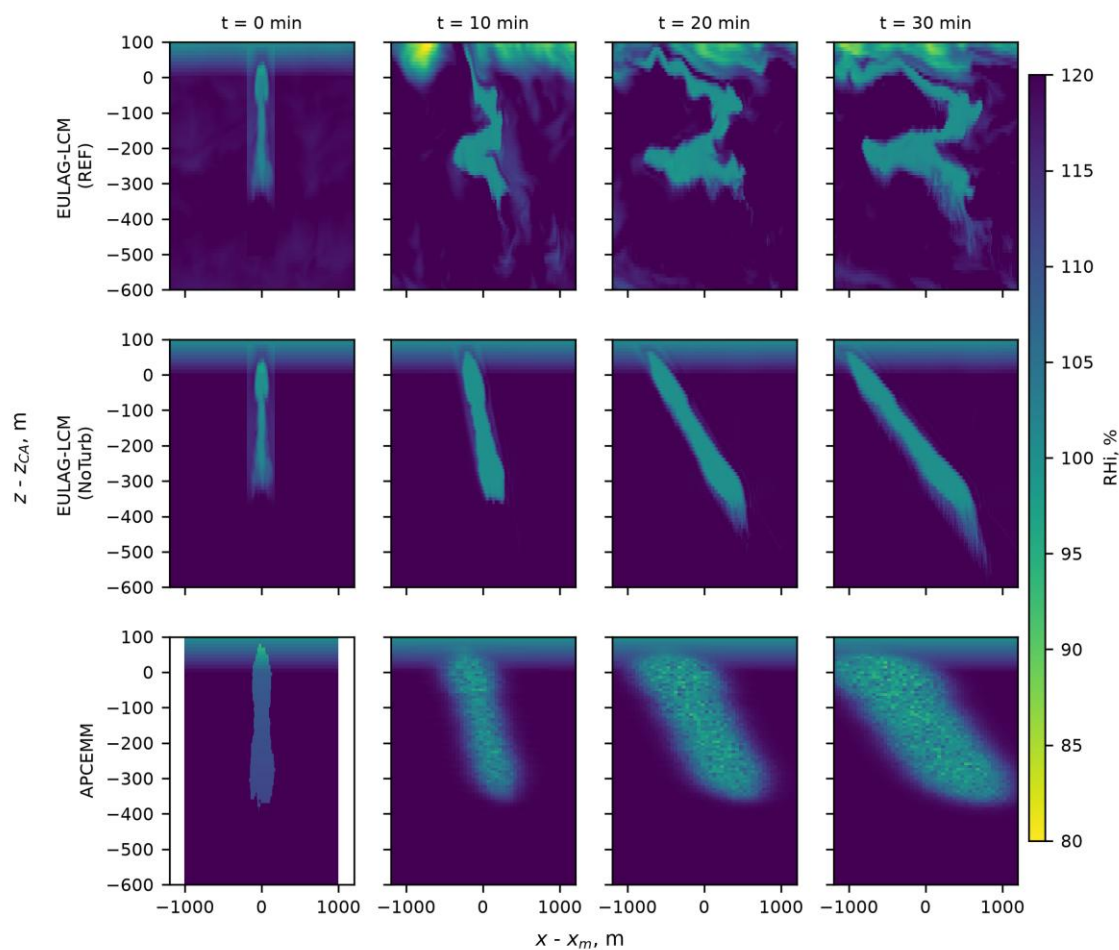


Figure 14: Evolution of the 2D RH_i field for EULAG-LCM with inherited turbulent disturbances (top row) and without the inherited disturbances (middle row) and for APCEMM (bottom row) for the simulations using the baseline meteorology.

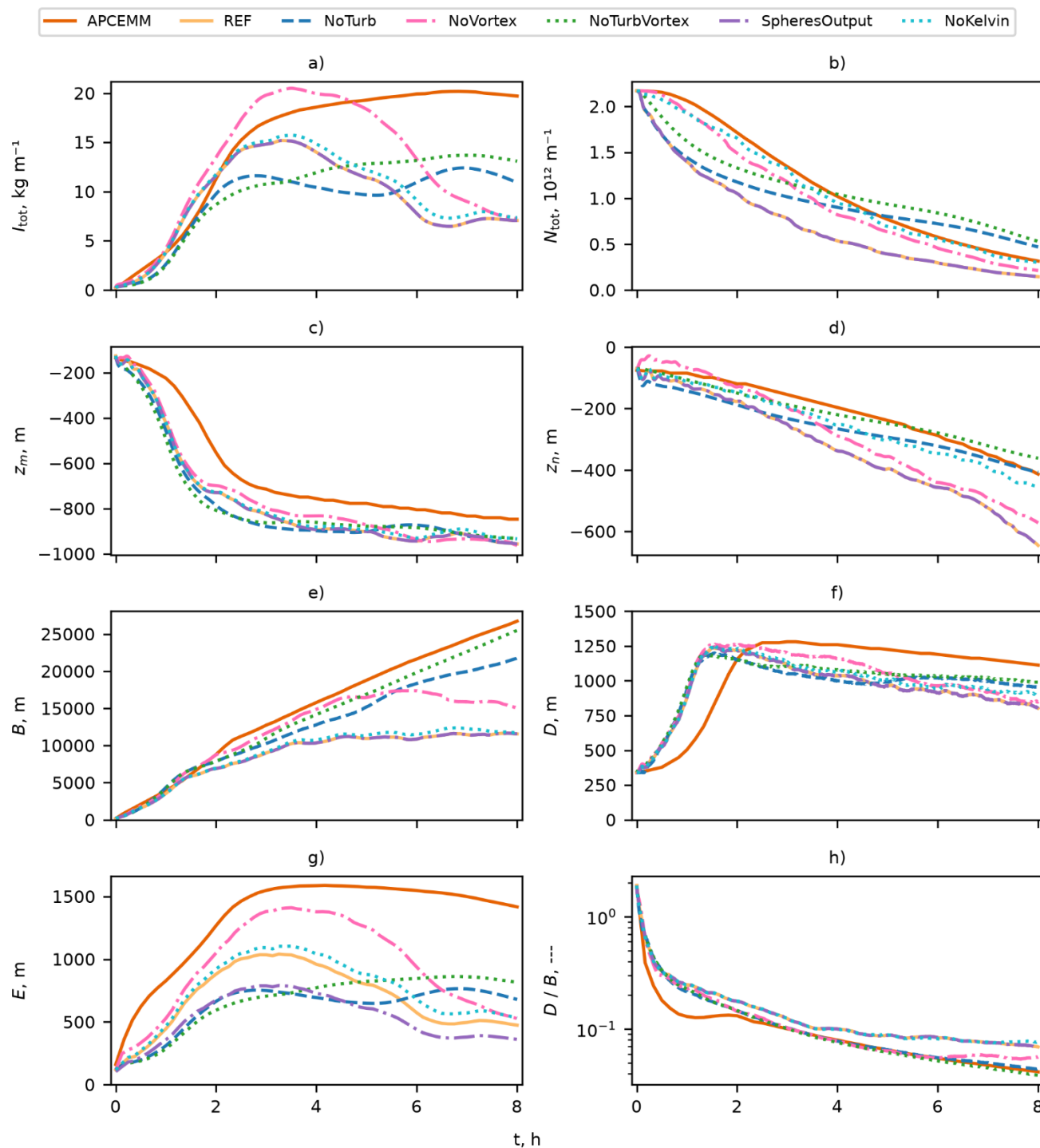


Figure 15: Time evolution of the total ice mass (I_{tot} ; a), total ice number (N_{tot} ; b), centre of mass vertical position (z_m ; c), centre of number vertical position (z_n ; d), width (B ; e), depth (D ; f), total extinction (E ; g), and the depth-to-width aspect ratio (D/B ; h) of



the contrail simulations using the baseline meteorology produced by APCEMM and different configurations of EULAG-LCM. Table 4 provides more details of the EULAG-LCM configurations used.

825 5.2 Perturbed meteorology simulations using different EULAG-LCM configurations

To better understand the effects of the changes in model configuration on the contrail properties, we now extend the analysis in Fig. 16 by including meteorological scenarios where one input parameter deviates from the baseline conditions ($T_{CA,0} = 217 \text{ K} \rightarrow 225 \text{ K}$, $RH_i = 120 \% \rightarrow 110 \%$, $w_{syn} = 0.00 \text{ m s}^{-1} \rightarrow 0.02 \text{ m s}^{-1}$, $s = 0.002 \text{ s}^{-1} \rightarrow 0.006 \text{ s}^{-1}$, $d = 1000 \text{ m} \rightarrow 500 \text{ m}$.

830 Fig. 16 provides the time evolution of the simulations performed when one meteorological variable is perturbed from the baseline value. We first explore the findings from Sect. 5.1 which remain valid for the perturbed meteorologies, and we then consider the findings that are not universally applicable across all meteorological conditions.

Across all meteorological conditions, we find that disabling the Kelvin effect has a negligible effect on the total extinction (first column of Fig. 16) and on the contrail depth-to-width aspect ratio (third column of Fig. 16). Similarly, using the spherical ice crystal assumption for post-processing only (**SpheresOutput**) decreases the instantaneous total extinction throughout all
 835 simulations.

The effects of removing the initial turbulence in EULAG-LCM vary depending on the perturbed meteorological variable. In all cases except in the case with the perturbed temperature, removing turbulence results in behaviour that is qualitatively more like APCEMM. In terms of the contrail geometry, the depth-to-width aspect ratio in both the **NoTurb** and **NoTurbVortex** simulations appears to be closest (along with the **NoVortex** simulations) to the values from the corresponding APCEMM
 840 simulation. Similarly, in all cases except the case with perturbed shear, **NoTurb** and **NoTurbVortex** simulations have a lower total extinction than the **REF** simulations until after the peak total extinction in the **REF** simulations. This slower decay in the total extinction seen in the **NoTurb** and **NoTurbVortex** simulations when compared to the **REF** simulations is also characteristic of some of the APCEMM simulations. The analysis presented earlier in this investigation suggests that this behaviour is caused by the high ice crystal number of the slow-falling contrail core in APCEMM. Hence, this suggests that the
 845 qualitatively similar behaviour from the **NoTurb** and **NoTurbVortex** simulations may be explainable across all meteorological conditions through the reduction of in-situ ice crystal losses throughout the contrail lifetime when compared to the **REF** simulations (see the second column in Fig. 16).

A special case worth highlighting which the above findings apply to is the simulation using a higher shear value (0.006 s^{-1}). For this case, all simulations (not just the **NoTurb** and **NoTurbVortex**) display the slower decline of their total extinction past
 850 the peak, and there is also more qualitative agreement in the magnitude of the total extinction between APCEMM and the other simulations. The fact that the width-to-depth aspect ratio values from all models and configurations are closest to each other in this meteorological condition suggests that shear dominates the contrail spreading, ice uptake, and lifetime of the contrail. This indicates that modelling differences (in 2D models) may be attenuated by higher shear.

The only meteorological condition that the above findings do not apply directly to involves the higher initial cruise temperature.
 855 For this case, the differences between the **NoTurb** and **NoTurbVortex** simulations are pronounced in all three quantities



shown in Fig. 16. This is because at such a high ambient temperature, the formation and persistence of ice crystals is unstable, meaning that the ice crystals are more susceptible to perturbations in the temperature. Since the only difference between the **NoTurb** and **NoTurbVortex** simulations is the exclusion of post-vortex temperature and wind perturbations in the **NoTurbVortex** simulations, this indicates that post-vortex perturbations can be as important as the turbulent temperature
860 fluctuations at higher ambient temperatures.

Finally, across all meteorologies except for the high temperature case, the **NoVortex** simulations have been the closest in the magnitude of the peak total extinction to the APCEMM simulations. Furthermore, they have also seen similar width-to-depth ratios as the **NoTurbVortex** and **NoTurb** simulations. However, the **NoVortex** simulations are unable to consistently replicate the slow decline of the total extinction after the peak that is seen in APCEMM simulations. This suggests that the lack of post-
865 vortex temperature disturbances may partially be responsible for the higher total extinction consistently seen in APCEMM. A likely mechanism for this is through the additional growth of the surviving ice crystals, suggesting that a more realistic diffusion regime initialisation may be required in APCEMM. Meanwhile, the fluctuations in temperature and humidity caused by the background and vortex-phase turbulence in EULAG-LCM help eliminate some of the ice crystals in the contrail core, boosting its fall rate and resulting in a lower contrail lifetime.

870 5.3 Discussion and implications

In this section, we now discuss the key findings from the model configuration analysis and their implications for contrail modelling.

First, we find that shear can either amplify or attenuate differences between 2D contrail models, depending on its magnitude relative to the amount of differential sedimentation. When the widening rate due to shear is comparable to the sedimentation
875 speed of the contrail core, the changes in the vertical distribution of ice crystals also affect all other contrail geometric properties, and by extension the contrail optical properties. However, when the widening rate due to shear dominates over the width shrinkage rate due to the contrail core sedimentation and the resulting contrail truncation at the lower saturation threshold (the altitude beneath which $RH_i < 100\%$), shear can attenuate the differences between models, as seen in Fig. 16. These findings do not apply to 0D models due to their inability to represent differential sedimentation and to partially sublimate a
880 contrail. From these findings, it is possible that regions of a parameter vector space associated with higher or lower uncertainty in the contrail properties may be identifiable through their values of vertical wind shear. However, this may only apply in limited circumstances since real meteorology differs from the idealised meteorological profiles we employ in this study.

Second, we also find that the initialisation conditions may have a lasting impact on the contrail behaviour, causing discrepancies in both the optical and geometric properties of the contrails. The main mechanism responsible for this is the
885 higher *in situ* ice crystal loss associated with both the vortex regime perturbations and the background turbulence perturbations to the wind, temperature, and water vapour fields. When comparing the diffusion regime initialisation in EULAG-LCM to that in APCEMM and CoCiP, the simplified initialisation approach used by APCEMM and CoCiP may fall short of meeting the requirements for a seamless transition between the vortex and diffusion regimes. In APCEMM, this is because only the water



vapour field is modified to account for the water uptake necessary to form the ice crystals provided by the vortex regime
890 (Fig. 14). In CoCiP, not even this initial water vapour deficit is accounted for in subsequent evolution steps due to its offline
implementation, so the contrail grows faster than it should. Hence, we encourage future work on better initialisation conditions
for the diffusion regime in simplified models. Similarly, both CoCiP and APCEMM include parametrisations for turbulence
which are usually not adjusted between model runs, regardless of the atmospheric state. This is because the parameters related
to turbulence (e.g. diffusivity) are not easily relatable to the atmospheric state the models will simulate the contrail evolution
895 in. Therefore, further work is also recommended on turbulence parametrisations that can be adjusted to replicate the
atmospheric state. Without this, case-by-case meteorological uncertainties may remain unbounded.

The **NoKelvin** simulations also revealed that the N_{tot} may not be an adequate diagnostic metric. This is because there exist
numerous ice crystals which do not contribute to the contrail optical and geometrical properties; as given by the initial ice
crystal number reduction present in the **REF** simulations but absent in the **NoKelvin** simulations in Figs. 15 and 16. Hence, a
900 filtered version of the N_{tot} that only accounts for those ice crystals contributing above a certain threshold to the optical and
geometric properties may be more appropriate.

Overall, although this sensitivity study provides insight into the potential importance of each modeling configuration, the
findings from this section are limited to a few idealised meteorological scenarios, and hence further work is required to obtain
more generalisable findings.

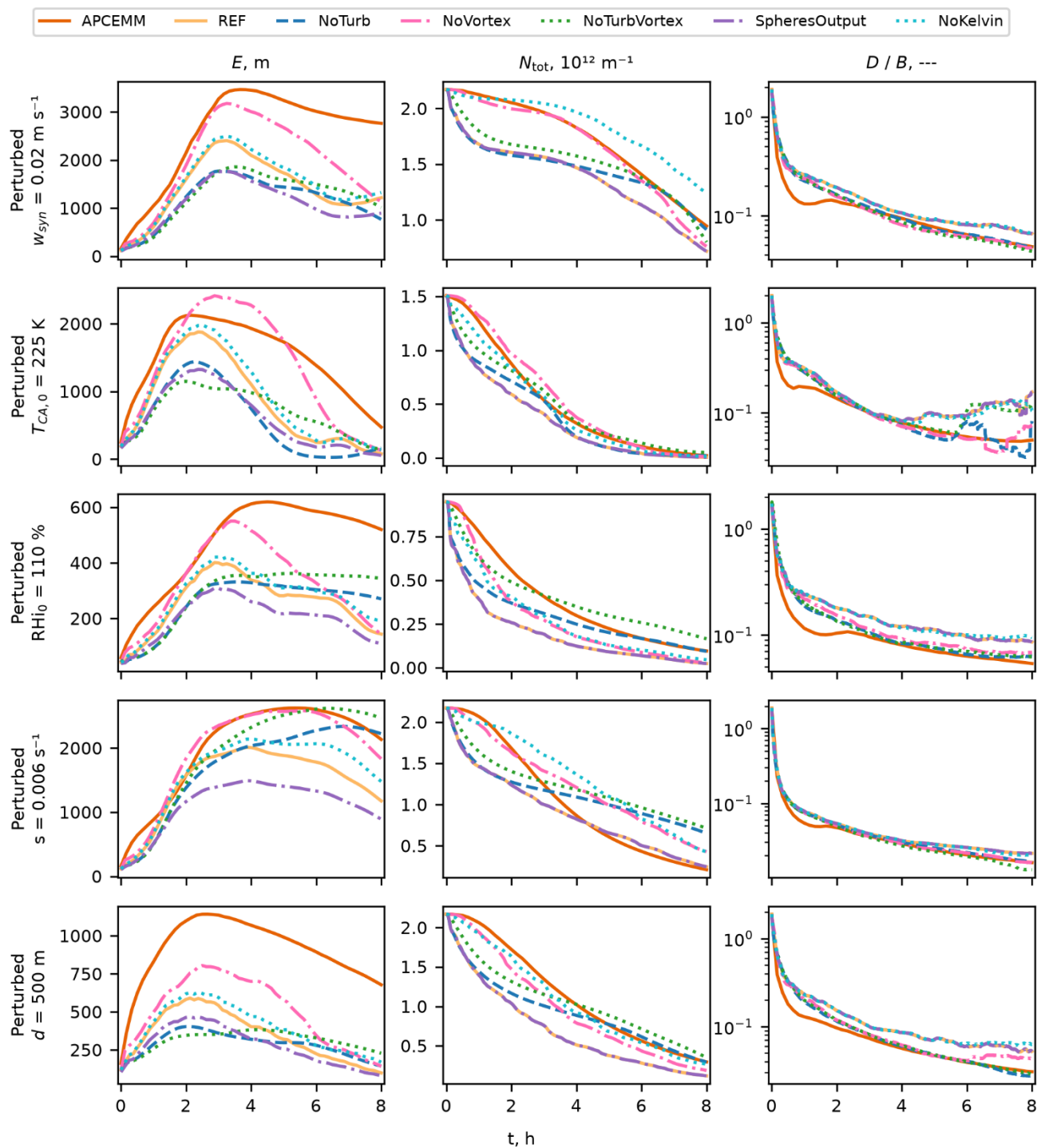




Figure 16: Effects of changing one meteorological parameter from the baseline meteorology on the relative differences in the total extinction (first column), ice crystal mass (second column) and the depth-to-width ratio (third column) for the same EULAG-LCM configurations as in Fig. 15. Table 4 provides more details of the EULAG-LCM configurations used.

6 Limitations and further work

910 Due to the high computational cost of EULAG-LCM runs, we consider a limited number of meteorological parameter setups with several idealisations (e.g. the trapezoidal humidity profile, uniform vertical wind shear), investigating a subset of the meteorological space. The sensitivity metric used in this study represents an average effect of increasing a variable within this subset of the meteorological space. As such, our study does not provide results which are generalisable to a global scale. Furthermore, we do not consider variations of aircraft/engine/fuel properties, although a limited comparison of CoCiP and

915 EULAG-LCM has been performed for evaluation of the effects of fuel choice (Lottermoser and Unterstrasser, 2026). We also do not include interactions between adjacent contrails, nor with surrounding or emerging natural cirrus in the vicinity. Nor do we prescribe changes of background relative humidity due to real-world vertical transport patterns. Moreover, the contrail initialisation in all three models is based on contrail data after vortex break-up as obtained by a priori EULAG-LCM vortex phase simulations. We deliberately disregard the effect of different contrail initialisation routines in each model on the overall

920 uncertainty of the contrail-cirrus predictions. This allows us to focus on the contrail physics during the diffusion phase. In typical applications of CoCiP and APCEMM, EULAG-LCM vortex-phase simulations would not be available to initialise these models. Therefore, the sensitivities to the meteorological variables from APCEMM and CoCiP (Fig. 11) may change if their corresponding early plume formulation had been used.

Finally, the intercomparison has been performed in the absence of feedbacks with a coupled weather model. Further work

925 should focus on evaluating the differences across different couplings of contrail and NWP models or GCMs under real air traffic data. Such an experiment will give better insights into the likely climate impact caused by contrails, and it will also better capture the true implications of modelling differences.

7 Conclusions

In this study, we present contrail-cirrus evolution as simulated by three different models with varying levels of complexity and

930 computational demand. Through this, we identify four of the likely crucial components of contrail models that maintain the fundamental physics in the contrail: the local-scale meteorological feedbacks (in particular the depletion of water vapour), the use of spatially heterogeneous contrail modelling, the ability to represent differential sedimentation, and the ability to represent turbulent fluctuations.

Differential sedimentation is responsible for the separation of the contrail core (comprising a high ice crystal concentration but

935 low ice mass) and the precipitation plume (comprising a low ice crystal concentration with a high ice mass). In APCEMM, since the ice phase is represented in a grid, differential sedimentation is enabled by using bins in the ice crystal radius space.



In EULAG-LCM, the use of simulation particles to represent ice crystals allows the ice crystals to fall at different rates. CoCiP uses a monodisperse 0D plume and hence lacks the ability to represent differential sedimentation. In our investigation, we find that the results from APCEMM are better correlated than the results from CoCiP with the EULAG-LCM results (with a Pearson correlation coefficient of 0.93 and 0.50 respectively). Furthermore, we find opposing sensitivities to ambient temperature when comparing CoCiP to either of the 2D models. We suggest that the disagreement found stems from differences in the physics between the models which include and the models which exclude differential sedimentation.

Although no model excluded ice loss processes, we found that in-situ ice losses are augmented by the grid-scale turbulence and by the meteorological perturbations from the vortex regime in EULAG-LCM. APCEMM simulations lose ice crystals more slowly than EULAG-LCM. In combination with some differences in formulations and numerics between APCEMM and EULAG-LCM, this leads to contrails that sediment more slowly and hence persist for longer. In APCEMM, this results in a higher lifetime total extinction in the baseline case and on average. To address the in-situ losses caused by turbulence, we recommend that future iterations of contrail models include these perturbations alongside an adjustable and interpretable turbulence representation to reduce the case-by-case meteorological uncertainties associated with turbulence. To address the *in situ* losses associated with the perturbations from the vortex regime, we also encourage the development of more robust coupling methods between the vortex and diffusion regimes. Another possibility would be to extend the simulation period of the vortex phase simulation to a point where perturbations no longer trigger long-lasting changes on the subsequent contrail-cirrus evolution.

Nevertheless, although we find that the different representations of turbulence partly explain the differences between the sensitivities of APCEMM and EULAG-LCM to shear and layer depth, we are unable to fully justify the differences in the sensitivity to the temperature and updraught velocity. We also identify opposing signs of some of the secondary sensitivities, implying that case-by-case warming predictions may not be reconcilable between these three models.

We find that normalising the results from each model leads to an improvement in the agreement between the parity plot gradient for the CoCiP/EULAG-LCM cases (from 0.31 to 0.59). This suggests that systematic errors with a consistent effect on lifetime total extinction may be mitigated through normalisation. Although our choice of the median as the normalising factor successfully highlighted the variability across the model simulations, we propose the development of a normalising factor from a dataset consisting of real meteorology and flight data so that it can be applied to deployed contrail avoidance schemes. We also recognise that modelling choices that result in competing effects may not be mitigated by normalisation, as is evidenced by the low Pearson correlation coefficient between CoCiP and EULAG-LCM.

Although the extent of model disagreement when including feedbacks with a coupled weather model is still unknown, our results suggest that strategies for contrail avoidance decision-making that are robust to the low correlation coefficient between models will be needed in the future – especially if ground truth validation data remains unavailable. In the meantime, neutral



avoidance strategies may provide a lower-risk alternative as they would be expected to yield a reduction in warming proportional to the number of contrails avoided without relying on modelling of contrail evolution.

970 **Appendix A: Harmonisation of diffusion regime initialisation conditions**

To ensure coherent diffusion regime initialisation across models, we use contrail cross-sections extracted from vortex-phase simulations obtained by EULAG-LCM. These data are not directly compatible with APCEMM nor CoCiP and must hence be harmonised.

975 For initialisation of the diffusion regime, APCEMM requires the PSD at each grid cell to replicate the desired ice mass and ice number spatial distributions. We reconstruct the APCEMM PSD by sorting the EULAG-LCM SIPs (keeping information on the discrete position, size and multiplicity of the represented ice crystals) into the ice crystal radius bins at each APCEMM grid cell. At the start of the diffusion regime, CoCiP requires the total ice crystal mass and number, plume centre position, and information of the elements of the Gaussian covariance matrix (Eq. 6 in Schumann, 2012), reproduced here and adapted for our coordinate system:

$$980 \quad \sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xz} \\ \sigma_{xz} & \sigma_{zz} \end{pmatrix}, \quad (\text{A1})$$

Obtaining the total ice crystal mass and number is straightforward, but representing the spatial distribution is not. Unlike in EULAG-LCM and APCEMM, the plume centre in CoCiP necessarily coincides with the centre of mass and centre of number. For simplicity, we define the CoCiP plume centre to have the same position as the EULAG-LCM ice mass profile centre of mass at initialisation. For the covariance matrix, we assume that σ_{xz} is zero (such that the major and minor axes are aligned with the horizontal and vertical directions) because shear is not considered during the vortex phase and the initial contrail is not yet tilted. We then perform optimisation in the $(\sigma_{xx}, \sigma_{zz})$ space using a grid search, minimising the squared difference between the ice mass concentrations of the EULAG-LCM contrail and the CoCiP Gaussian plume evaluated at the same grid points:

$$985 \quad \begin{bmatrix} \sigma_{xx}^* \\ \sigma_{zz}^* \end{bmatrix} = \arg \min_{\sigma_{xx}, \sigma_{zz}} \|I_{\text{EULAG-LCM}} - I_{\text{CoCiP}}(\sigma_{xx}, \sigma_{zz})\|_2^2, \quad (\text{A2})$$

990 where $I_{\text{EULAG-LCM}}$ and I_{CoCiP} are the 2D matrices containing the ice mass distributions for the corresponding model, both evaluated at the EULAG-LCM grid centres.

Appendix B: Computation of 1D distributions, contrail width, and contrail depth

In EULAG-LCM and APCEMM, we compute the 1D profiles for ice mass and ice number from the corresponding 2D cross-sections introduced in Section 2.2:



$$995 \quad I_X(x; t) = \sum_z I(x, z; t) dz, \quad (B1a)$$

$$I_Z(z; t) = \sum_x I(x, z; t) dx, \quad (B1b)$$

$$N_X(x; t) = \sum_z N(x, z; t) dz, \quad (B1c)$$

$$N_Z(z; t) = \sum_x N(x, z; t) dx, \quad (B1d)$$

Where dx is the grid cell horizontal length, and dz is the grid cell vertical length. We then calculate the width and depth of the
 1000 contrails by solving the following optimisation problems with a grid search at each timestep:

$$\begin{bmatrix} x_1^*(t) \\ x_2^*(t) \end{bmatrix} = \arg \min_{x_1, x_2} \left| \frac{1}{I_{\text{tot}}(t)} \sum_{x_1}^{x_2} I_X(x; t) - 0.95 \right| \text{ s. t. } x_2 > x_1, \quad (B2a)$$

$$\begin{bmatrix} z_1^*(t) \\ z_2^*(t) \end{bmatrix} = \arg \min_{z_1, z_2} \left| \frac{1}{I_{\text{tot}}(t)} \sum_{z_1}^{z_2} I_Z(z; t) - 0.95 \right| \text{ s. t. } z_2 > z_1, \quad (B2b)$$

$$B(t) = x_2^*(t) - x_1^*(t), \quad (B3a)$$

$$D(t) = z_2^*(t) - z_1^*(t), \quad (B3b)$$

1005 where B and D are the 95 % contrail width and depth respectively. In CoCiP, the width and depth are given by the following equations (adapted from Eq. 8 from Schumann, 2012):

$$B(t) = \sqrt{8\sigma_{xx}}, \quad (B4a)$$

$$D(t) = \sqrt{8\sigma_{zz}}, \quad (B4b)$$

where σ_{xx} and σ_{zz} are the horizontal and vertical terms of the covariance matrix associated with the Gaussian plume.



1010 Appendix C: Analysis of the effects of shear on geometry with different aspect ratios

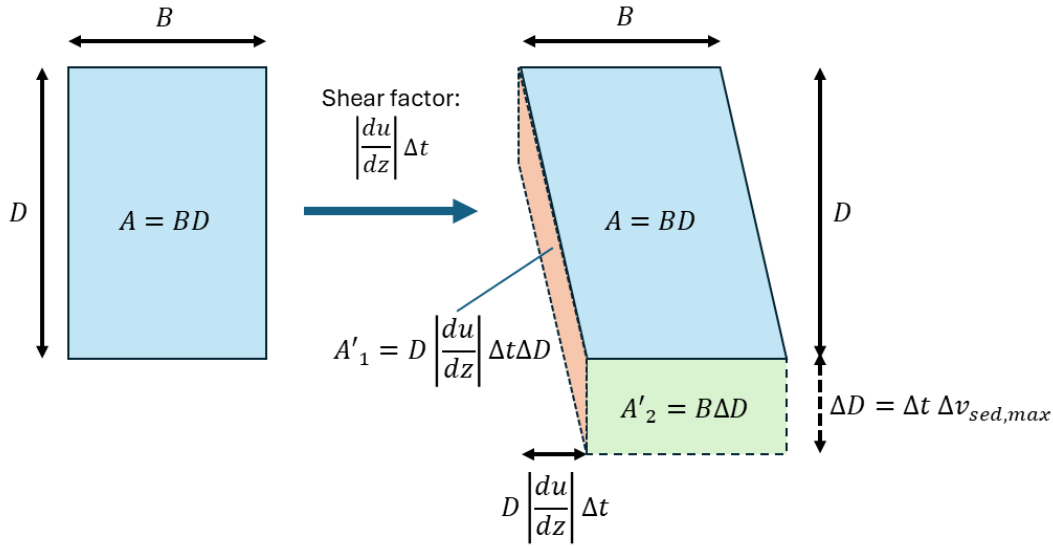


Figure C1: Diagram illustrating the effects of a shear factor on a simplified representation of a contrail. The spent air (air at 100 % RH) is given by the light blue, and the fresh air is given by the orange.

To understand how the effect of shear varies depending on the contrail geometry consider the effect of shear on a simplified
 1015 contrail with an initially rectangular cross-section in Fig. C1. Before applying shear, only the green area (denoted A'_2) provides fresh air after sedimentation occurs. Applying the shear transformation, additional fresh air becomes available for ice crystals to sediment into and take up water on the side of the control volume (given by the orange area, denoted A'_1). The ratio of fresh air available with and without shear in a sedimentation step is hence given by the following equation:

$$\frac{A'_1 + A'_2}{A'_2} = 1 + \frac{D}{B} \left| \frac{du}{dz} \right| \Delta t, \quad (C1)$$

1020 where $\left| \frac{du}{dz} \right|$ is the magnitude of the wind shear, and Δt is the time over which the shear has been applied.

It follows from Eq. C1 that the amount of shear-enabled new fresh air will be larger than the corresponding amount of shear-disabled new fresh air. For a single timestep, the effect of shear will be largest when the $\frac{D}{B}$ ratio is largest.

Appendix D: Effect of the time horizon

Fig. 11 analysed the lifetime total extinction. It is defined as the total extinction integrated over the complete simulation period
 1025 of 8 hours. Like in Unterstrasser (2020) and in Lottermoser and Unterstrasser (2026), we reduce the integration period as motivated in the latter study (see Sect. 3.2.3 in Lottermoser and Unterstrasser, 2026).

In short: the prescribed updraught patterns favour long contrail lifetimes, for which contrail-cirrus mainly dissolve by sedimentation (ice crystals fall out of the moist layer). In reality, ascending air masses may start to subside, and the contrail vanishes by sublimation. The lifetime is limited by sedimentation and/or subsidence (Bier et al., 2017). To mimic scenarios with subsidence-limited lifetimes, we simply reduce the integration period in our example to 4h.

Comparing Fig. 11 to Fig. D1, we can see that the changes in sensitivity are minor when reducing the integration time horizon of the lifetime total extinction from 8 h to 4 h (Eq. 6). The only sensitivities with major changes are the initial cruise temperature sensitivity, and the sensitivities to the updraught velocities.

When changing from the 8 h simulations to the 4 h simulations, both APCEMM and EULAG-LCM sensitivities to temperature increase: from near zero to 0.38 in APCEMM and from 0.26 to 0.73 in EULAG-LCM. This is because the balance between the higher total extinction and the higher sedimentation speed (and lower lifetime) of the ice crystals changes. When the time horizon is reduced, the difference in ice crystals that sublimate is smaller so the higher total extinction dominates, causing a rise in the sensitivity in the APCEMM and EULAG-LCM sensitivities to the initial cruise temperature.

Overall, changing the updraught velocity and the integral horizon causes no change in any conclusions of the main text for the meteorological scenarios tested.

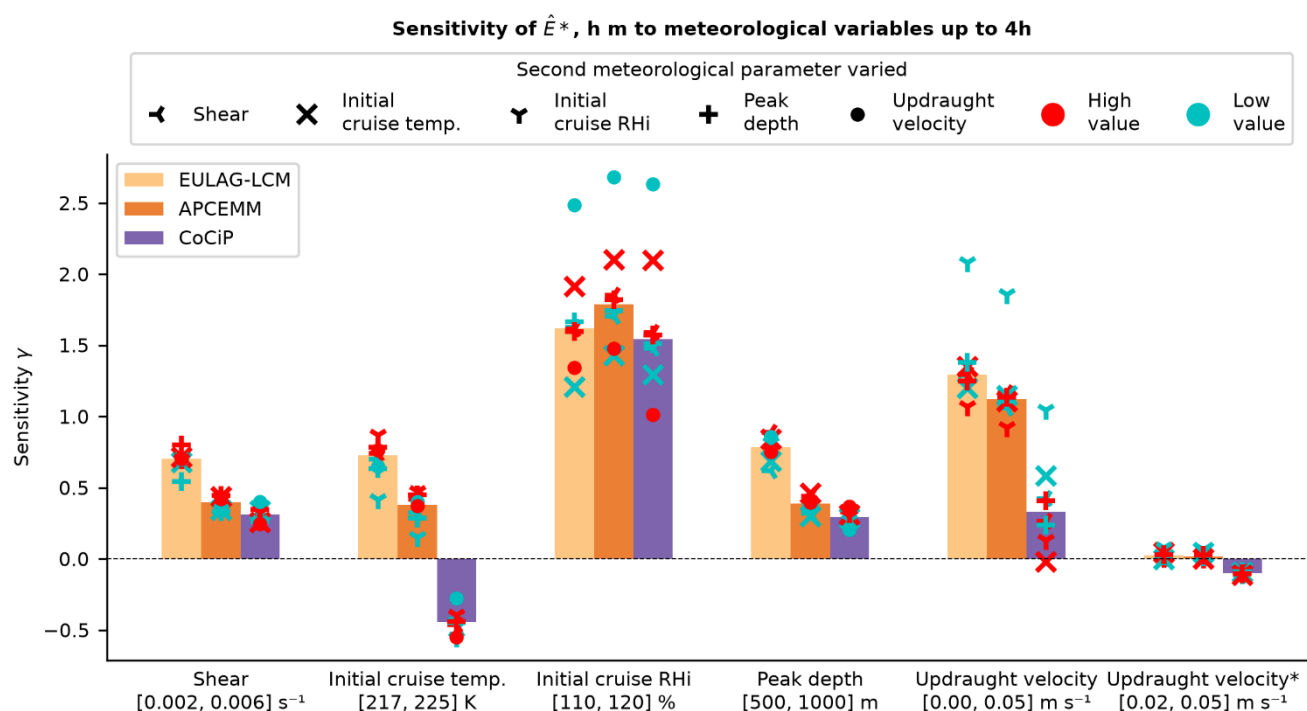


Figure D1: Like Fig. 11, but using a time horizon of 4 h instead of the 8 h used in Fig. 11.



Code availability

Pre-processing and graph-generating scripts are available at Akhtar Martínez et al. (2026b). The modified APCEMM code is
1045 available at Akhtar Martínez et al. (2026a). The modified CoCiP code is available at Akhtar Martínez et al. (2026c). EULAG-
LCM is a proprietary software owned by DLR and is therefore not publicly available.

Data availability

Processed output data from each contrail model are available alongside the pre-processing and graph-generating scripts at
(Akhtar Martínez et al., 2026b).

1050 Author contribution

All authors provided extensive technical and scientific contributions throughout the investigation. CAM modified the CoCiP
code and part of the APCEMM code, wrote the post-processing code for CoCiP and APCEMM, performed the simulations
using CoCiP and APCEMM, and wrote the code that generated the graphs. AL ran all the EULAG-LCM simulations and wrote
some of the EULAG-LCM post-processing code alongside SU. SDE and SU provided technical guidance, and SDE modified
1055 part of the APCEMM code. JPJ provided research guidance and reviewed the quality, importance, and validity of the arguments
raised. JPJ, SDE, and SU set the overall scope of the manuscript, and all authors contributed to the structure of the experimental
design. CAM prepared the manuscript with reviews and edits from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Use of artificial intelligence

CAM made use of “Claude Sonnet 4.5”, “Claude Sonnet 4.6”, “Claude Sonnet 5”, and “Claude Opus 4.6” by Anthropic through
GitHub Copilot in a purely assistive manner. Example use cases include retrieving code scaffolding of common patterns
(analogous to how tutorial websites and help forums are used), asking questions about functions (akin to using the code
documentation), assistance in the navigation of existing code bases, assistance with understanding some error messages,
checking for bugs in new code before compilation and running. Any artificial intelligence (AI) output was thoroughly checked
for correctness and, if presented with any unfamiliar functions, the official documentation was consulted and understood. The
code produced with AI assistance would be able to be produced by CAM without the AI if given access to help forums, tutorial
websites for unfamiliar packages, and code documentation. CAM also used artificial intelligence for English language and
typesetting assistance, but not for generation of new content in the manuscript. This mainly consisted of identifying spelling,
grammar, and typographical errors. CAM reviewed and refined the language suggestions made by these tools prior to their
inclusion in the manuscript.

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