



Investigating the Development of Persistent Contrails in Ice Supersaturated Regions with Cloudy Backgrounds Using ICON-LEM

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Abstract. Persistent contrails are a major contributor to aviation-induced non-CO₂ climate forcing, yet the extent to which their development depends on background cloud properties remains unclear. In this study, we aim to investigate persistent contrail development in various cloudy backgrounds. We use the high-resolution ICON-LEM model with a horizontal resolution of 156 m. Eight distinct ice-cloud scenarios are simulated as control runs, each initialized with realistic meteorological forcing. For each control case, a corresponding perturbation run is conducted by introducing an identical contrail, allowing us to assess its evolution within the same cloudy, ice-supersaturated environment. We find that persistent contrails embedded within natural cirrus clouds not only survive but can also alter the humidity field, cloud microphysics, and potentially the radiative properties of the host cloud. The evolution of persistent contrails is highly sensitive to the microphysical and thermodynamic properties of the background ice-supersaturated regions, particularly the combination of supersaturated layer thickness below flight level and the availability of excess water vapor, as the former alone is not sufficient to sustain contrail development. Although vertical growth through fall streaks is commonly expected, we suggest that in regions of high ice supersaturation and low atmospheric stability, contrails may also expand above the flight height due to latent heat release from deposition. Our findings indicate that mitigation strategies based solely on atmospheric thresholds are insufficient to reliably predict contrail evolution or their climate impact.

1 Introduction

Although near-global air traffic experienced an unprecedented reduction during the COVID-19 pandemic (Quaas et al., 2021), it has since resumed its rise. In 2023, air transportation nearly returned to its pre-pandemic levels, and by the first quarter of 2024, the aviation industry surpassed pre-pandemic traffic for the first time (International Air Transport Association, 2023, 2024). The aviation industry has grown significantly over the past decades, contributing not only to CO₂ emissions but also to various non-CO₂ effects that impact the Earth's climate. These non-CO₂ impacts, including emissions of nitrogen oxides (NO_x), water vapor, soot, sulfate aerosols, and the formation of contrails, account for approximately two-thirds of the net radiative forcing (RF) attributed to aviation (Lee et al., 2021). Among these, contrail cirrus, which includes both linear contrails and the



cloudiness that develops from them, represents the largest positive net effective radiative forcing (ERF) term, exceeding the contributions from CO₂ and NO_x emissions. Despite the substantial role of contrail cirrus in aviation-induced climate change, considerable uncertainty persists in accurately quantifying its overall impact.

Contrails, or condensation trails, are ice-laden clouds formed by aircraft exhaust that have been observed to form in the upper troposphere, leading to measurable changes in atmospheric conditions. Exhaust contrails form during the jet phase due to engine emissions of water vapor and soot particles, which result from the incomplete combustion of hydrocarbon fuels and act as cloud condensation nuclei (CCN) (Petzold et al., 1997; Heymsfield et al., 2010; Bond et al., 2013). For visible contrails to form—characterized by their distinct white cloud-like appearance—the aircraft exhaust plume must reach supersaturation with respect to water as it mixes with the surrounding ambient air (Schumann, 1996). Once this condition is met, extremely small supercooled water droplets rapidly condense onto soot particles and freeze almost instantly due to the low temperatures at cruising altitudes (Kärcher and Yu, 2009; Wong and Miake-Lye, 2010).

Contrail life can be divided into three main phases. First is the jet phase, lasting just a few seconds, where initial ice crystals form, heavily influenced by fuel emissions and ambient temperature (Kärcher et al., 2015). This is followed by the vortex phase, lasting a few minutes and characterized by significant ice crystal loss, influenced mainly by the number of crystals formed during the jet phase and the surrounding relative humidity (Unterstrasser, 2016). Finally, after a few minutes, once the vortices dissipate, the surviving ice crystals enter the dispersion phase, during which the contrail becomes more influenced by and fully integrated into the surrounding ambient air.

The dispersion phase of contrails is challenging to predict, as it is influenced by a broader range of atmospheric factors than the jet and vortex phases. In this stage, contrail spreading, mixing, survival, and total extinction are governed by ambient atmospheric processes, from small-scale diffusion to mesoscale wind shear and larger-scale dynamics like synoptic updrafts. These interactions create complex and often unpredictable patterns over time. Initially, contrail spreading is influenced by diffusion and turbulence intensity, but over time, the combined effects of wind shear and sedimentation become more dominant (Unterstrasser et al., 2017). The process becomes increasingly complex when ice sedimentation becomes significant, as contrail particles descend into air layers with varying humidity levels. Even within saturated layers, differences in supersaturation thickness can directly affect the vertical development of contrails (Bock and Burkhardt, 2016a).

The terminal fall speed of particles is influenced by their size and shape (Heymsfield and Wright, 2014). Larger particles tend to fall faster and separate from smaller ones, causing the upper part of the contrail to thin while still containing many small particles. Smaller ice particles may sublime more quickly than larger ones, under the influence of the Kelvin effect, leading to in situ particle losses (Lewellen, 2014). When larger particles fall into more humid air, they grow and fall even more quickly, forming fall streaks that can eventually lead to precipitation (Atlas et al., 2006; Unterstrasser et al., 2012). As individual contrails evolve, they expand and mix with natural cirrus clouds and other contrails (Schumann and Wendling, 1990). Merged contrails produce less total extinction compared to individual contrails due to competition for available humidity. This competition means that the climate impact of contrails does not increase linearly with traffic density (Unterstrasser and Sölch, 2012). “Contrail outbreaks”, which consist of both aged and young contrails that have spread over large areas, further illustrate the complexity of contrail evolution (Duda et al., 2001).



The prevalence and significance of cirrus clouds in the upper troposphere have been highlighted by various studies. Notably, research by Immler et al. (2008) found that cirrus clouds were present 55% of the time in their measurements, underscoring their frequent occurrence and importance in the atmosphere. These clouds play a crucial role in weather and climate systems due to their impact on radiative transfer (Chen et al., 2000). Cirrus clouds influence Earth's energy balance by reflecting incoming solar radiation, which cools the surface, and by absorbing and re-emitting outgoing terrestrial infrared radiation, which warms the atmosphere. Their net effect on surface temperature depends primarily on their optical properties (e.g., optical depth, ice-crystal size), cloud temperature, and the cloudiness of the underlying atmosphere (Stephens and Webster, 1981; Chen et al., 2000; Fauchez et al., 2015). Optically thick cirrus clouds tend to exert a cooling effect due to their high solar reflectance, whereas optically thin cirrus clouds typically contribute to atmospheric warming by trapping outgoing terrestrial radiation, similar to greenhouse gases (Hong et al., 2016; Campbell et al., 2016; IPCC, 2021).

Contrails, which typically form at altitudes where natural cirrus clouds are prevalent, can modify surrounding atmospheric conditions, subsequently influencing the development and properties of natural cloudiness. Using the global climate model ECHAM4, Burkhardt and Kärcher (2011) showed that contrail cirrus reduces natural cloudiness by absorbing water vapor, delaying the formation of natural cirrus clouds. Similarly, Schumann et al. (2015) demonstrated that contrail ice particles grow substantially by taking up moisture, which dehydrates the atmosphere at flight levels and redistributes humidity to lower altitudes.

The overlapping altitude ranges of contrails and cirrus clouds complicate their combined impact on the Earth's energy balance. Contrails can form in clear skies, within existing cirrus clouds, or merge with natural cirrus clouds through processes such as wind shear, sedimentation, and advection. Previous studies in the early 2010s (e.g., Kübbeler et al., 2011; Voigt et al., 2011) often characterized aircraft contrails as relatively thin or even subvisible under typical atmospheric conditions. Climate models up to around 2017 consequently tended to assume low contrail optical depths in their simulations. However, recent peer-reviewed studies from 2018 onward, utilizing satellite observations, in-situ measurements, and enhanced climate models, indicate that contrail-generated cirrus clouds can achieve significantly greater optical thicknesses and consequently larger radiative impacts than previously estimated (e.g., Bock and Burkhardt, 2019; Schumann et al., 2021; Wang et al., 2022; Zhang et al., 2024). Given that contrail and natural cirrus clouds frequently coexist and interact in the upper troposphere, accurately assessing their combined climate effects is crucial. These interactions can have dual climate impacts—either promoting the formation of new optically thin ice clouds, contributing to surface warming (Burkhardt and Kärcher, 2011; Boucher et al., 2013; Kärcher, 2018), or increasing the optical thickness of existing cirrus clouds, potentially enhancing their reflectivity and exerting a cooling effect (Tesche et al., 2016).

Verma and Burkhardt (2022) incorporated the influence of background cirrus ice crystals into the jet (Kärcher et al., 2015) and vortex phase (Unterstrasser, 2016) parameterizations. Using large eddy simulations over Germany, they estimated the number of contrail ice crystals remaining after the vortex phase, taking into account the surrounding cloudy region.

Gierens (2012) and Verma and Burkhardt (2022) estimated a slight increase in the threshold temperature for contrail formation in cloudy conditions as opposed to clear skies, attributed to the added humidity from the cirrus clouds' ice water content. However, their findings also indicate that these effects on the threshold temperature and ice crystal numbers are relatively



subtle, occurring significantly only under conditions of high ice water content and low supersaturation in cirrus clouds. This suggests that while the presence of cirrus can influence contrail formation, the overall impact might be limited under typical atmospheric conditions. Although the formation of contrails within cirrus clouds has a minimal immediate impact, they tend to mix over several hours through various processes. Gierens (2012) showed that contrails embedded in cirrus clouds decrease the average size of ice crystals while increasing their concentration.

Contrails not only affect the atmospheric potential for natural cloud formation, but also their growth, aging, survival, and dispersion are significantly affected by the characteristics of the existing background cloudy region. While contrails are typically transient, they can persist and grow for many hours in Ice-Supersaturated Regions (ISSRs) (Minnis et al., 1998; Schumann et al., 2017). This favorable atmospheric condition, often accompanied by natural cirrus clouds, as it is a prerequisite for their formation. Unterstrasser et al. (2017) used a Large-Eddy Simulation (LES) model with a Lagrangian ice microphysics module in an idealized setup. This study was the first to simulate the temporal evolution of both contrail-cirrus and naturally occurring cirrus clouds under different synoptic scenarios, enabling a direct comparison between them.

Current estimates of contrail cirrus radiative forcing do not fully account for the effects of contrails forming within natural clouds (Lee et al., 2021), partly due to the challenges in quantifying their interactions. As a result, the impacts of contrail formation within pre-existing cloud systems have remained underexplored. Recent studies using satellite observations have shed light on our understanding of the impacts of contrail-induced perturbations within cirrus clouds. For instance, Tesche et al. (2016) employed satellite-based lidar measurements, while Marjani et al. (2022) utilized combined radar–lidar retrievals from satellite observations. These studies have highlighted that contrails forming within natural cirrus clouds lead to measurable changes in cloud optical depth and increase ice crystal number concentration below flight altitude. This suggests that contrails embedded within cirrus clouds can modify the optical properties of these natural clouds. Observational studies, such as Gryspeerd et al. (2024), have also linked satellite data with air traffic records to identify contrails, using convolutional neural networks to detect linear cloud features. However, tracking contrails beyond their early stages remains a significant challenge. As contrails age, they lose their distinct linear structure, making it difficult to distinguish them from natural cirrus clouds and to fully evaluate the extent of anthropogenic cloud modification.

Despite recent advancements, significant gaps remain in understanding the spreading and aging stages of contrails under varying weather conditions (Kärcher, 2018). While prior studies have established the dynamics of contrail formation in different weather scenarios (Bier and Burkhardt, 2022) and their formation within cloudy regions (Verma and Burkhardt, 2022), uncertainties persist regarding their evolution and aging beyond the vortex phase, particularly within natural cloud systems.

This study addresses these gaps by investigating the evolution of young contrails from the post-vortex phase to about 3–4 hours after formation, with a particular focus on persistent contrails embedded within natural ice clouds. Using Large-Eddy Simulation (LES) with a horizontal resolution of 154 meters in weather forecasting mode, we incorporate realistic synoptic forcing to simulate contrail development under representative atmospheric conditions.



125 2 Methodology

This section outlines the modeling framework and procedures used to investigate the evolution of contrails within natural cirrus clouds. It details the configuration and setup of the model, the criterion used for contrail formation, and the method for initializing contrails within the model grid. Additionally, it describes the design of aircraft flight paths based on regions favorable for persistent contrail formation.

130 2.1 ICON Model Configuration

We utilize the ICOSahedral Non-hydrostatic (ICON) model, developed collaboratively by the German Meteorological Service and the Max Planck Institute for Meteorology (Zängl et al., 2015; Klocke et al., 2017; Costa-Surós et al., 2020). ICON operates on an unstructured triangular grid, refined successively from a spherical icosahedron, facilitating a range of applications from global climate simulations (Giorgetta et al., 2018) to high-resolution large-eddy simulations (Heinze et al., 2017). For this
135 research, we employ the ICON Large Eddy Model (ICON-LEM), an extension of the numerical weather prediction version of ICON (ICON-NWP). ICON-LEM integrates a physics package designed for Large Eddy Simulation (LES), enabling detailed atmospheric modeling on the unstructured grid. This setup captures both mean flow characteristics and turbulent statistics effectively, making it ideal for high-resolution atmospheric studies (Zängl et al., 2015; Dipankar et al., 2015).

The model's horizontal resolution is set at approximately 156 meters, utilizing the R2B14 triangular grid. Vertically, the
140 resolution decreases from the boundary layer to the top of the atmosphere. To target enhanced resolution in the upper troposphere—an area crucial for our study—we have set the number of vertical layers to 160. This adjustment yields a finer vertical resolution of about 150 meters at our focus altitude in the upper troposphere, enhancing our model's ability to accurately capture upper atmospheric dynamics.

The ICON model incorporates a comprehensive double-moment microphysical scheme for cloud liquid and ice by Seifert
145 and Beheng (2006). This scheme facilitates detailed simulation of microphysical processes across liquid, mixed-phase, and ice-phase clouds. It predicts both mass mixing ratios and number concentrations for six types of hydrometeors: cloud droplets, rain, ice, hail, snow, and graupel. Utilizing fine-resolution grid scales, the model is configured to resolve both deep and shallow convection, eliminating the need for separate parameterizations. Instead of using the default diagnostic cloud cover scheme, a straightforward all-or-nothing scheme is employed, where the cloud fraction within a grid box is set to either 1 or 0. This
150 approach simplifies the treatment of cloud cover, disregarding subgrid variability of total water content. Homogeneous and heterogeneous ice nucleation processes are parameterized following the methodologies of Köhler et al. (2006) and Phillips et al. (2008). The model explicitly accounts for the competition between heterogeneous and homogeneous ice nucleation. Homogeneous nucleation is primarily dependent on updraft velocity. The reduction of the supersaturation over ice by pre-existing ice particles due to heterogeneous nucleation is formulated in terms of a reduction of the updraft velocity. This results
155 in fewer homogeneously nucleated particles forming (Köhler et al., 2006).



2.2 ICON Model Setup

In this study, we defined our simulation domain following the observational approach of Marjani et al. (2022), who investigated individual contrails interacting with existing cirrus clouds, expanding upon previous analyses by Tesche et al. (2016). From the observed cases in Marjani et al. (2022), we selected 8 in which our model generated sufficiently upper-tropospheric cloud coverage for our analysis. For each case, we conducted simulations in both control and perturbation setups. Figure 1a shows the geographical center location of the LES simulation domains for the eight selected cases (red dots), which span the midlatitude Pacific Ocean from the west coast of the United States to Hawaii.

Our simulation process is divided into two distinct phases. First, we ran ICON-NWP at kilometer-scale resolution, using initial and boundary conditions from the ECMWF IFS operational analysis, updated every six hours starting at 0000 UTC. In this phase, the model was run in three nested domains with resolutions of 5 km, 2.5 km, and 1.25 km, respectively. Building on the output from this setup, we then performed a second run with ICON-LEM, initialized directly from the output of the finest nest (1.25 km resolution) obtained in the previous kilometer-scale simulation. ICON-LEM was configured to operate at a high spatial resolution of 156 meters, using a two-second time step and hourly boundary condition updates. This second run constitutes our main, high-resolution simulation of contrail evolution.

This approach ensures a smooth transition to higher resolution, effectively minimizing large-scale discrepancies between the boundary and the main domain, while also reducing initialization shocks. To allow adequate spin-up time, the high-resolution simulation was started at least four hours prior to contrail implementation. Figure 1 further illustrates the two-stage simulation domains for one representative case, highlighting the spatial coverage and nested resolution approach employed in this study. This initial extensive domain coverage ensures the accurate representation of atmospheric and synoptic-scale conditions, which is essential for realistic cloud dynamics analyses.

2.3 Contrail Formation Criterion

We use the Schmidt–Appleman Criterion (SAC; Schumann 1996) to determine whether aircraft exhaust mixes with ambient air and exceeds the threshold for visible contrail formation. For persistent contrails, ambient conditions must be at or above ice saturation. Additional details, including a schematic illustration of the mixing lines, can be found in Appendix B, providing further background on the Schmidt–Appleman Criterion.

For convenience, we display in Figure 2 the resultant *critical temperature* for contrail formation as a function of atmospheric pressure and relative humidity with respect to ice. This figure shows that, for a given atmospheric pressure, higher relative humidity corresponds to a higher temperature threshold for contrail formation. Conversely, at a fixed relative humidity, lower atmospheric pressure (i.e., higher altitude) reduces the contrail formation temperature.

2.4 Contrail Initialization in ICON Grid

In this study, contrails are initialized at a stage that corresponds to approximately 450 seconds of age, marking the post-vortex phase when atmospheric conditions begin to play a dominant role in their evolution (Bier and Burkhardt, 2022). They are

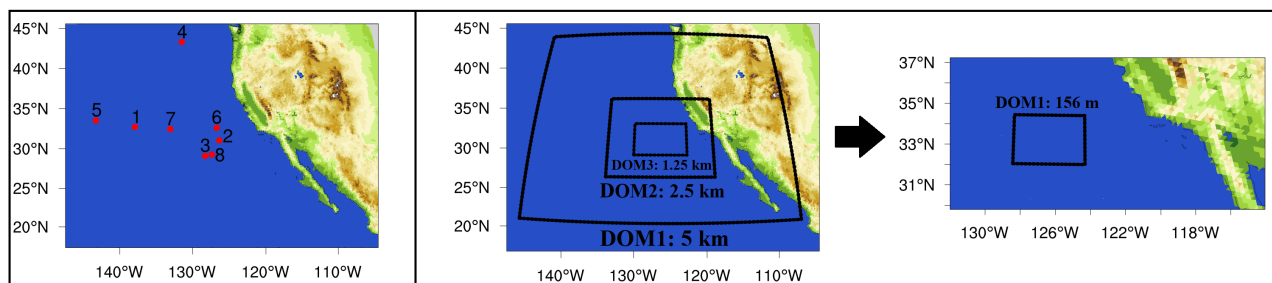


Figure 1. Left panel: Geographic center locations of the LES simulation domains for the eight contrail cases, spanning the midlatitude Pacific Ocean off the west coast of the United States. Numbers indicate the case identifiers (1–8), corresponding to the simulations analyzed in this study. Middle panel: Three nested domains used in the initial ICON-NWP simulations, progressively refined from 5 km (40° longitude $\times$ 24° latitude) to 2.5 km (16° longitude $\times$ 10° latitude), and finally to 1.25 km (8° longitude $\times$ 4° latitude). Right panel: The subsequent high-resolution ICON-LEM domain at 156 m resolution (4.2° longitude $\times$ 2.4° latitude), initialized directly from the finest domain of the initial simulation. Note that the middle and right panels show the domain configuration for Case 2, which is representative of the configurations used in all simulations.

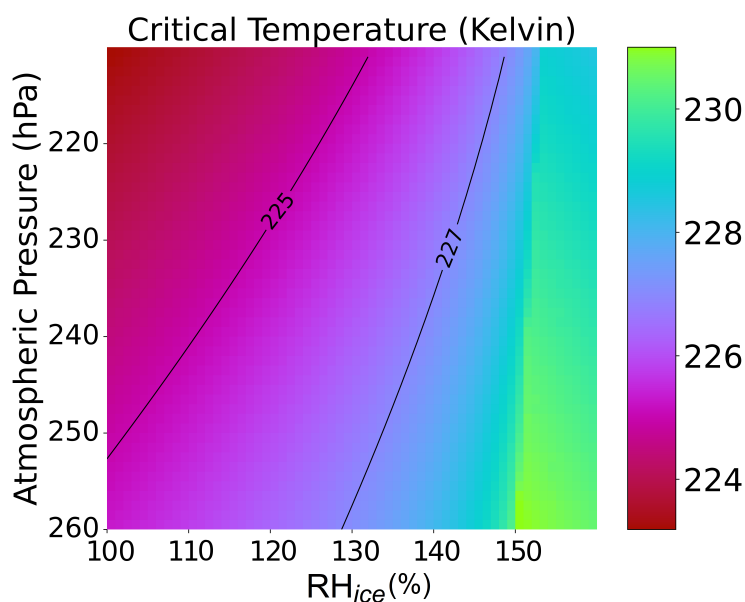


Figure 2. Heatmap showing the critical temperature (K) for contrail formation as a function of relative humidity w.r.t ice (%) and atmospheric pressure (hPa).

assigned a fixed ice crystal number concentration of about 150 cm^{-3} and an initial cross-sectional area of approximately $154 \times 150 \text{ m}^2$. These dimensions are inherently constrained by the model's horizontal and vertical resolution, ensuring consistency with the simulation grid.



This approach aligns with methodologies used in previous studies. Bock and Burkhardt (2016b) initialized contrail cirrus with a similar fixed ice crystal number concentration of 150 cm^{-3} , based on observations over Europe. In situ aircraft sampling of young contrails in the post-vortex phase, as reported by Schröder et al. (2000), Febvre et al. (2009), and Voigt et al. (2011), further supports this choice. Similarly, Unterstrasser et al. (2017) examined contrail-cirrus evolution using a Large-
195 Eddy Simulation model with a Lagrangian ice microphysics module in an idealized environment. Their simulations initialized all contrails at five minutes of age, with an average ice crystal concentration of about 20 cm^{-3} and local concentrations reaching up to 200 cm^{-3} . The contrails were approximately 500 meters deep and 200 meters wide, ensuring a consistent starting perturbation.

Additionally, Bier and Burkhardt (2022) incorporated parameterizations for contrail ice nucleation (Kärcher et al., 2015)
200 and ice crystal loss during the vortex phase (Unterstrasser, 2016) within the contrail cirrus scheme CCMoD of the global climate model ECHAM5. This approach enables a dynamic initialization of contrail ice crystal numbers based on atmospheric conditions and soot number emissions. According to their study, an ice crystal concentration of 150 cm^{-3} corresponds to a soot number emission of $1.5 \times 10^{15} \text{ kg}^{-1}$, a value considered representative of present-day soot emissions. This selection aligns with reported values for the west coast of the United States—our focal region—and reflects the atmospheric conditions of the area,
205 as outlined in their global distribution of annual mean contrail ice crystal number concentrations and contrail cross-sectional areas.

In our model, water vapor emissions equivalent to the aircraft's fuel burn are introduced along the flight path as either water vapor or ice crystals. We consider aircraft models such as the B767 and A300, which have a wingspan of approximately 50 meters and emit around 7.26 g of water vapor per meter of flight (Unterstrasser, 2016). The initialization process is governed
210 by the Schmidt–Appleman criteria and the ambient relative humidity, which together determine whether contrails persist. In our model, contrails form only if the ambient temperature is below the Schmidt–Appleman threshold and the relative humidity exceeds ice saturation (discussed in more detail in the next subsection). Along the flight path, each grid box is evaluated for these conditions to determine persistent contrail formation. If the conditions are met, water vapor emissions are converted into ice mass with a corresponding ice crystal number concentration; otherwise, they are introduced as water vapor.
215 This initialization occurs within a single time step, after which the contrail interacts with the surrounding environment and undergoes further evolution. Table A1 in Appendix A summarizes the simulation cases, including the dates, flight heights, flight temperatures, and the geographical center (latitude and longitude) of the simulated domain for each case.

2.5 Designing Aircraft Flight Paths Considering Persistent Contrail Formation Zones

In this study, we focus on the evolution of persistent contrails due to their substantial climate impacts. Teoh et al. (2024) found
220 that while fewer than a quarter of global flights produce persistent contrails, these contrails contribute the majority of contrail-induced radiative forcing. Consequently, identifying regions favorable for persistent contrail formation is essential, enabling us to initialize and position contrail tracks at optimal altitudes and locations. This requires target regions to have temperatures below the contrail formation threshold and ice supersaturation to sustain persistent contrail growth in the simulation. To achieve this, within our simulation domain, we analyzed the height levels around the desired flight altitude, using control run results



to verify suitability for contrail persistence. We then deliberately selected the contrail height and location to guarantee an environment conducive to persistent contrail formation (as opposed to mitigation strategies).

Figure 3 presents representative sample maps of temperature differences from the Schmidt–Appleman criterion within ice-saturated regions at three consecutive height levels, based on our model results. The top row panels show that while the lower altitude levels contain ice supersaturation regions, they are not cold enough for contrail formation, as they are warmer than the threshold temperature. This highlights that flying aircraft within saturated regions alone does not necessarily lead to formation of contrail (at least based on our current definition of contrail formation). In the bottom row panels, all three consecutive layers meet the temperature criterion for contrail formation. The temperature difference from the threshold increases with altitude, while the extent of the saturated region also varies. This suggests that for aircraft operating at higher altitudes, as is typical for modern aviation, the temperature criterion is rarely a limiting factor for contrail formation.

While contrail formation does not require atmospheric saturation, their persistence—which is our primary focus due to its significant climate impact—relies on ice supersaturation. Persistent contrails commonly develop in regions favorable for natural cirrus cloud formation, where they can either contribute to cloud development (Tesche et al., 2016; Marjani et al., 2022) or disrupt existing cloud processes (Burkhardt and Kärcher, 2011).

3 Result and Discussion

3.1 Contrail Ice Crystals Spreading in Ice Supersaturation Regions with Cloudy Background

Contrail evolution is influenced by atmospheric conditions, including temperature, humidity, and background cloud properties. Their persistence and spreading depend on environmental interactions, shaping their microphysics and radiative effects. To explore this, we first examine key characteristics of the simulated contrails in Ice Supersaturation Regions (ISSRs). Figure 4 presents ice crystal number concentration (N_i) snapshots for four different cases at various stages of contrail development at flight altitude. Initially, in younger ages, all cases exhibit a narrow, well-defined contrail core with high ice crystal concentrations. As contrails evolve, lateral spreading becomes more evident, though the extent and pattern of dispersion vary across simulations. In all cases, the highest N_i remains concentrated in the core at each time step, while N_i gradually decreases toward the outer edges as the contrail expands. Although N_i in the core declines over time, this high-concentration pattern persists even at two hours of age.

The differences in how these initially linear contrails spread over time are primarily driven by variations in horizontal wind shear—changes in wind speed and direction across the contrail—as well as atmospheric turbulence. When wind shear is strong, the contrail stretches, becomes wavy, or develops filament-like structures, as different segments experience varying wind forces. In contrast, when shear is weak, the contrail retains a more uniform, linear shape. Additionally, atmospheric turbulence plays a role in disrupting contrail symmetry, leading to irregular dispersion. This effect is particularly evident along the contrail edges, where regions of strongly differing ice crystal concentrations of contrail and natural ice clouds interact, resulting in a more chaotic spreading pattern. In highly turbulent conditions, the contrail may appear more fragmented, whereas in calmer conditions, it maintains a more coherent structure over time. The evolution of simulated contrail ice crystal concentration for

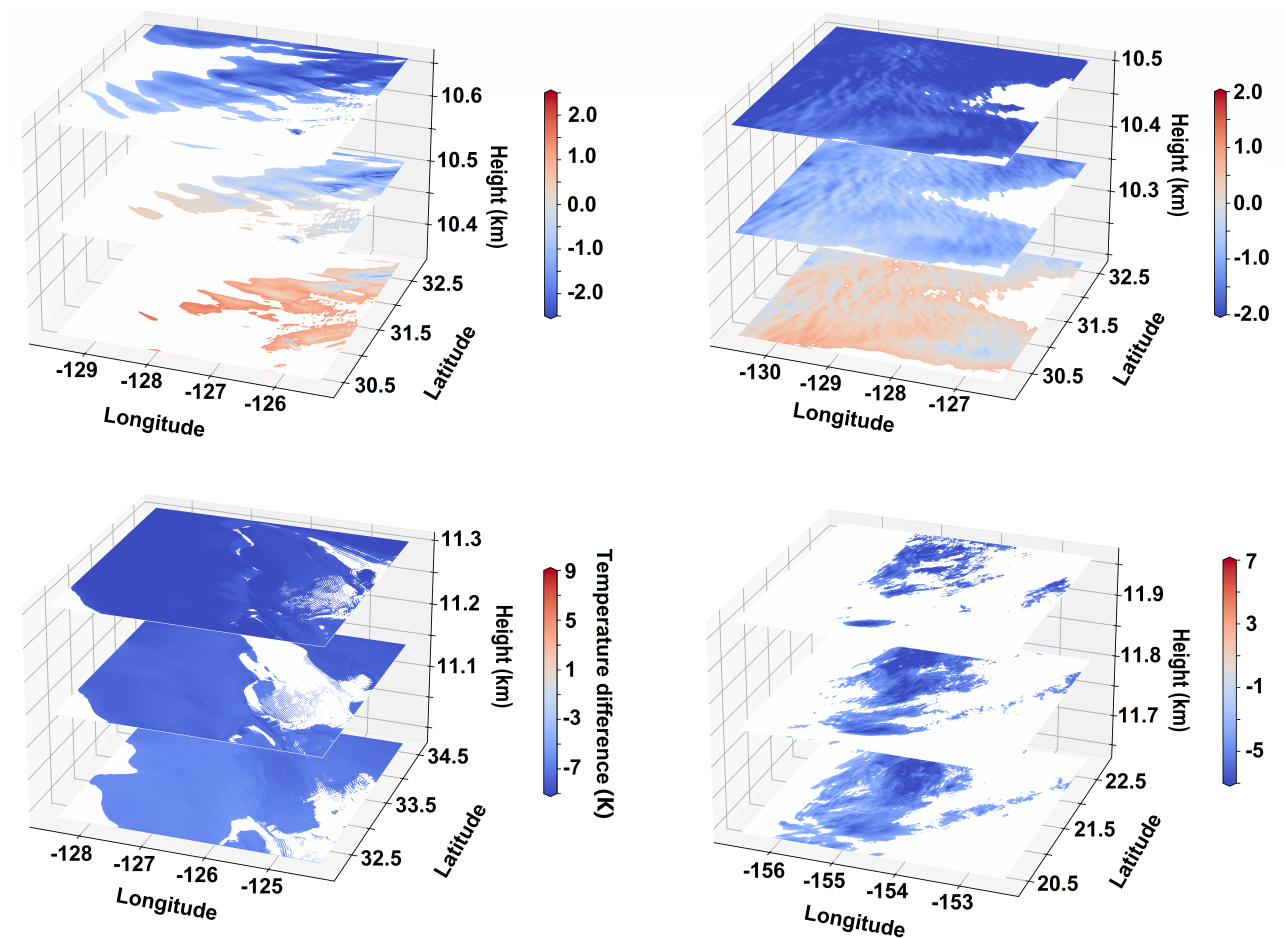


Figure 3. Temperature difference from the contrail formation threshold within saturated regions for four representative simulations. These examples illustrate the variability of conditions favorable for persistent contrail formation at three consecutive height levels and were used to guide contrail initialization in the perturbation runs. Please note the differing values in the color bar.

all eight cases is available as animations at the original model grid resolution. The link to these animations are provided in Appendix Video A1.

260 3.2 Contrail-Induced Changes in Relative Humidity within Ice Supersaturation Regions

Although relative humidity over ice (RH_{ice}) is a thermodynamic atmospheric parameter rather than a direct contrail variable like N_i , it is still influenced by contrail processes over short timescales. Figure 5 shows the RH_{ice} across multiple simulations, where the linear structure of contrails is clearly distinguishable, leaving a visible fingerprint within the atmospheric background.

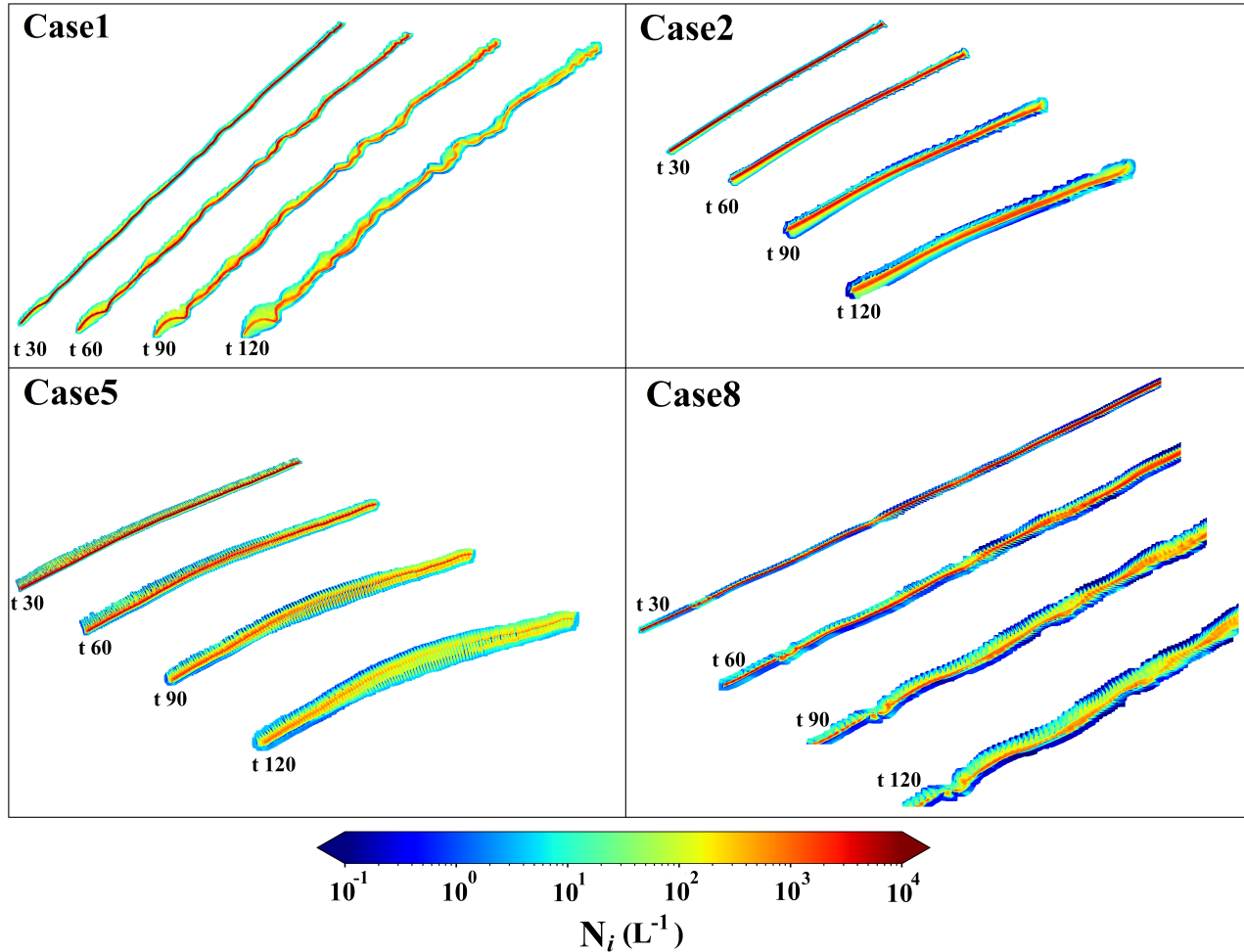


Figure 4. Horizontal spatial distribution of contrail ice crystal number concentration (N_i) at flight altitude for four selected cases, shown at 30, 60, 90, and 120 minutes after contrail initialization.

A common feature across all cases is that contrail regions stand out distinctly, exhibiting RH_{ice} values near 100%. This near-saturation condition is especially prominent in younger contrails, where ice crystals rapidly alter local humidity. Due to their exceptionally high N_i , young contrails quickly deplete atmospheric supersaturation, particularly within the core, where abundant small ice crystals effectively reduce humidity to saturation. Their high surface-area-to-volume ratio results in shorter deposition and sublimation timescales, making contrail cores highly efficient moisture sinks in ISSRs. In other words, contrails forming in such conditions can be described as “water vapor-thirsty,” rapidly depleting available atmospheric moisture.

This behavior is a key characteristic of persistent contrails in ISSRs and should be considered when analyzing their evolution. Unterstrasser et al. (2017) explained that if excess water vapor is not continuously supplied to the contrail core via updraft as



the contrail ages, local relative humidity easily falls below saturation. This drop in humidity leads to the in situ loss of smaller ice crystals due to sublimation.

Another feature, albeit confined, is the presence of elevated RH_{ice} values along the lateral edges of the contrail, particularly at the boundary between the contrail and the background ice-supersaturated cloudy region. This localized increase in RH_{ice} is likely driven by mixing and turbulence, resulting from the sharp contrast between the high ice crystal concentration of the contrail and the comparatively lower ice crystal concentration of the surrounding cloud.

These turbulent interactions modify ice crystal growth dynamics along the contrail edges. In these interfaces, N_i tends to drop sharply, likely due to turbulence-induced dispersion. However, the persistent availability of excess water vapor in these highly supersaturated zones allows ice crystals to grow significantly larger—often exceeding those in the contrail core and, in many cases, surpassing the ice crystal sizes in the surrounding background cloud. While we did not explicitly analyze sedimentation rates, the presence of these larger ice crystals at the contrail edges suggests enhanced sedimentation in this localized region, which could influence the overall contrail evolution.

Figure 6 presents a representative example of the ice crystal effective radius of a contrail within a natural cloudy region at flight altitude, highlighting typical patterns found in the simulations. A sharp increase in ice crystal size at the contrail edges indicates enhanced growth due to the continuous supply of excess water vapor from the surrounding ISSRs. In contrast, within the contrail core, ice crystals remain very small, even 90 minutes after contrail initialization.

This extremely small effective radius in the contrail core is a defining characteristic, driven by the initially very high number concentration of small ice crystals. This high concentration rapidly depletes initial available water vapor, ultimately limiting the potential for further crystal growth as the contrail ages.

While our model captures the common characteristics of linear contrails in ISSRs, including contrail morphology, turbulence effects, and small-scale variations during expansion, these aspects are not the primary focus of this study. Instead, the following sections take a broader perspective, analyzing how contrail evolution in ISSRs influences ice crystal number concentration (N_i) and ice water content (IWC) under varying atmospheric weather conditions. The goal is to identify key factors governing persistent contrail development in cloudy, ice-supersaturated regions.

3.3 Contrail Evolution within Ice Supersaturation Cloudy region: Differences Between Perturbation and Control Runs

Cold and humid conditions that meet the Schmidt–Appleman criterion and support persistent contrails are well recognized as key factors in identifying flight avoidance regions for planning mitigation strategies. However, in this section, we go beyond these criteria by comparing persistent contrail development under varying background conditions, providing a deeper understanding of the factors influencing their evolution and atmospheric impact.

This section examines the temporal evolution of contrails across eight different simulations, comparing the perturbation runs (with contrails) to the control runs (natural cloudy background). The duration of each simulation varies, as contrails exit the domain at different times.

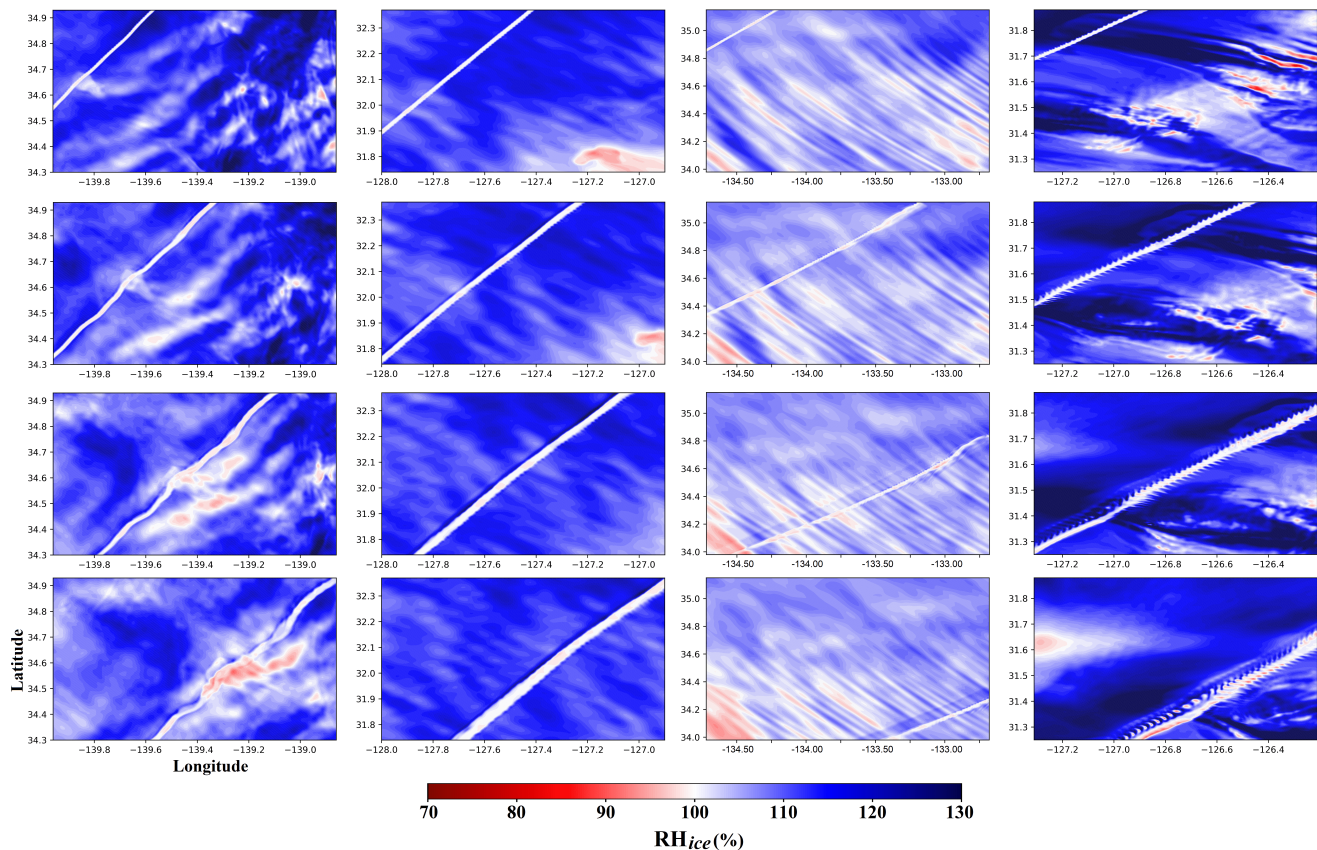


Figure 5. Horizontal spatial distribution of relative humidity with respect to ice (RH_{ice}) at flight altitude in cloudy ice-supersaturated background regions across multiple simulations (Cases 1, 3, 7, and 8 from left to right). The snapshots represent different contrail ages (10, 30, 50, and 70 minutes after contrail initialization). A distinct reduction in RH_{ice} to approximately 100% is simulated within the contrail region, often accompanied by a narrow and localized zone of elevated ice supersaturation at the interface between the contrail and the surrounding ice-supersaturated environment.

As will be shown in Figures 7 and 11, we use Time-Height Figures to investigate the differences between the perturbation and control runs, focusing exclusively on the contrail region (as shown in Figure 4). In these figures, the x-axis represents the elapsed time since contrail initialization, while the y-axis indicates vertical model level differences relative to the original contrail height. The zero height level corresponds to flight altitude, with positive values indicating levels below it. Each grid cell displays the anomaly of the average at a given time step and height level. However, horizontal variability is not captured, as values are averaged over the entire horizontal extent of the contrail. Since contrail width evolves over time, each grid value corresponds to a different spatial coverage accordingly.

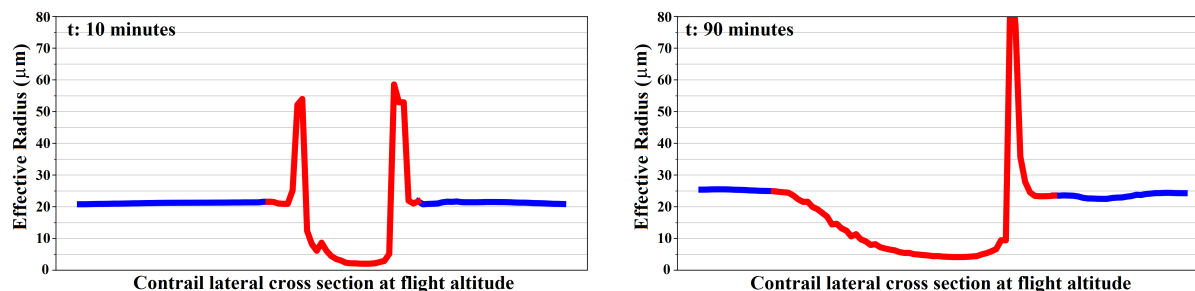


Figure 6. Lateral cross-section of the ice crystal effective radius at flight altitude. These samples illustrate a general pattern observed in our simulations; however, this structure is not uniformly present along the entire contrail flight track. The red curve represents the contrail region, while the blue curve corresponds to the surrounding cloudy background.

This approach enables the analysis of contrail-induced atmospheric modifications, providing insights into their vertical growth and temporal evolution. By doing so, we aim to identify key factors influencing contrail development under varying atmospheric conditions within ISSRs.

3.3.1 Contrail induced anomalies in Ice Crystal Number Concentration Under Various Weather Conditions

Ice crystal number concentration (N_i) anomaly is shown in Figure 7. At flight altitude in Case 1, the N_i remains above 1000 L^{-1} for up to 60 minutes after initialization, with more than 20% of the contrail area still exceeding this threshold at that time. By 90 minutes, N_i remains above 500 L^{-1} across most of the contrail, while 15% of the area still exhibits N_i values exceeding 1000 L^{-1} . At 120 minutes, N_i decreases further, with values remaining above 200 L^{-1} , though a small fraction (0.5%) of the area continues to exceed 1000 L^{-1} . By 150 minutes, N_i exceeds 100 L^{-1} in approximately 30% of the area, with 0.5% maintaining values above 500 L^{-1} .

At flight altitude in Case 2, N_i anomaly remains above 1000 L^{-1} for up to 60 minutes after initialization, with over 30% of the contrail area exceeding this threshold at that time. By 100 minutes, N_i decreases to values above 500 L^{-1} , while 20% of the area still retains N_i values exceeding 1000 L^{-1} . At 150 minutes, N_i remains above 200 L^{-1} , with 0.5% of the area still maintaining values above 1000 L^{-1} . By 180 minutes, N_i remains above 100 L^{-1} , with 25% of the area exceeding this value, and 0.5% of the area still exhibiting N_i values greater than 500 L^{-1} . These results demonstrate a gradual decline in N_i over time, while the contrail persists with a still substantial N_i for over 2 to 3 hours, albeit at progressively lower concentrations.

In Case 6, N_i remains elevated at flight altitude for an extended period, with values exceeding 500 L^{-1} up to 90 minutes and remaining above 200 L^{-1} until 140 minutes. Among all eight simulations, these three cases exhibit the most prolonged presence of high N_i at flight altitude. This suggests a delicate balance where ice crystals are neither too small nor the air too dry to induce rapid sublimation, while also preventing excessive humidity and rapid crystal growth that would accelerate sedimentation.



Comparing the contours of Case 1 and Case 2 reveals distinct differences in their vertical evolution. In Case 1, the contrail initially expands downward more rapidly, with a higher crystal concentration. For example, the 200 L^{-1} contour extends up to four layers below the flight altitude, whereas in Case 2, it reaches only two layers below. However, despite this stronger fall streak development, Case 1 does not ultimately exhibit greater vertical expansion. Over time, Case 2 develops a larger vertical extent, as indicated by the 30 L^{-1} and 10 L^{-1} contours. This difference is primarily attributed to the greater average ice-supersaturated (ISS) thickness below the flight altitude in Case 2, which supports sustained contrail growth and facilitates continued vertical development.

Evaluating the vertical development of Case 6 and Case 7 reveals that their growth is more restricted and shallower than in other cases. This limitation stems from the thin ISS layer below the flight altitude, which constrains the contrail's vertical extent. Not only is the vertical development of Case 6 and Case 7 restricted, but small negative N_i anomalies also emerge at lower altitudes beneath the ISSRs. Natural ice clouds, which generally contain fewer but larger ice crystals, can persist longer after moving beyond the supersaturated layer. In these cases, the flight altitude was near the lower boundary of the ice-supersaturated layer, which limited the potential for contrail ice crystals to grow as they sedimented into fresher saturated air below the flight level. As a result, these smaller ice crystals sublimated much faster than those in natural clouds upon entering subsaturated air, leading to the negative N_i anomalies observed at lower height levels in the perturbation run compared to the control run.

In all cases except 6 and 7, the N_i anomaly extends well below the saturated layer, reinforcing that contrail ice crystals had more opportunity to grow while sedimenting in saturated air. As a result, by the time they reached the subsaturated layer, they were large enough to persist, enabling the contrail to develop beyond the saturated region, as evident in Cases 1, 3, and 5. Therefore, although contrail passage through ISSRs generally increases N_i , these results suggest that under certain conditions, it may also cause a slight N_i reduction in small, localized regions that are less dominant than the areas of increase (recalling Figure 4, where localized zones of very small N_i are visible, appearing in dark blue shading in Cases 1 and 2).

It is worth mentioning that the vertical development of Case 7 is relatively larger than that of Case 6, with N_i contours decreasing more gradually and without a sharp reduction upon entering the subsaturated region. This difference is likely due to the rate at which relative humidity drops below the saturation threshold—gradual in Case 7 but sharp and abrupt in Case 6. Observational studies, such as Li et al. (2022), show that contrail cirrus can persist in slightly ice-subaturated air, rather than being limited to exclusively ice-saturated or supersaturated conditions. Regarding contrail persistence in slightly subsaturated air, the 80% relative humidity contours in Case 1 exhibit a more gradual decline after 100 minutes. This indicates that the transition from saturation to 80% relative humidity occurs much more slowly compared to earlier in the simulation. This slow decrease in saturation reduction is also reflected in the N_i anomaly patterns, particularly in the 30 and 10 L^{-1} contours. This further reinforces the idea that the rate at which relative humidity decreases in subsaturated air plays a crucial role in contrail development and contrail ice crystal survival.

Beyond these N_i variations, a broader implication is that the thickness of the supersaturated layer below flight altitude influences contrail vertical development in two related yet distinct manners:



(1) A thicker supersaturated layer allows sedimenting ice crystals to grow further in fresh supersaturated air, and (2) A deeper supersaturated layer enables ice crystals to grow large enough to persist in slightly subsaturated air, allowing contrail extension well beyond the saturation layer.

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The relative humidity contours in the control run for Case 4 indicate that the atmosphere remains near saturation across a considerable vertical depth (Figure 7). Looking at the vertical cross-section of IWC in the background weather condition of this case, relatively high values are evident (Appendix Figure A1). This elevated IWC spans a deep atmospheric layer, extending from lower altitudes upward, suggesting that cloud formation was influenced by strong vertical transport. Later in this study, we will show that the natural cloud in Case 4 has a strong greenhouse effect, related to a high cloud optical thickness. These characteristics suggest the presence of a liquid-origin ice cloud (Krämer et al., 2016), making Case 4 a clear example of this cloud type.

In this case, the contrail is initialized in a deep but only slightly supersaturated layer. Ideally, this should allow unrestricted vertical extension through fall streak development, as there is no ISS layer thickness restriction. However, the 30 and 10 L^{-1} contours of N_i in Figure 7 show a vertical extent comparable to cases with a more limited supersaturated layer (e.g., Cases 3, 5, and 8), suggesting that other factors may be constraining the contrail's vertical growth.

It seems that while ISSRs are essential for the formation of a persistent contrail, they may not be the main governing factor in contrail development. In the following sections, we will explore additional key atmospheric variables that influence contrail development and their subsequent radiative effects.

In Case 4, N_i at flight altitude decreases more rapidly than in other cases, as seen in the 1000, 500, and 200 L^{-1} contours. While part of this reduction results from horizontal spreading, dilution, and vertical extension through fall streak development, the comparatively higher rate of decrease suggests that a larger fraction of ice crystals undergo *in-situ* sublimation at flight altitude.

An initially weak supersaturation means that the initial available excess water vapor is very limited, preventing contrail ice crystals from growing larger at flight altitude. In contrast to other cases with high initial relative humidity, where rapid initial growth occurs (Unterstrasser, 2016), ice crystals in this case do not really experience such a phase. Additionally, the relative humidity contours from the control run show a decrease in RH_{ice} , indicating that no additional water vapor is being supplied in situ through updrafts. As a result, contrail ice crystals remain very small, making them more susceptible to complete sublimation under these conditions. With limited growth potential initially and no sustained water vapor source later, a significant fraction of ice crystals sublimates before they can develop further.

Moreover, in this case, part of the contrail was initialized within a fine-scale gravity wave-induced ice cloud and remained within the simulation domain for up to 60 minutes (Figure 8). Beyond this time, the contrail segment influenced by gravity wave dynamics mostly advects out of the simulation domain. Therefore, it is also worth noting that part of this ice crystal sublimation may be influenced by fine-scale gravity wave dynamics, which generate small-scale fluctuations and lead to lo-

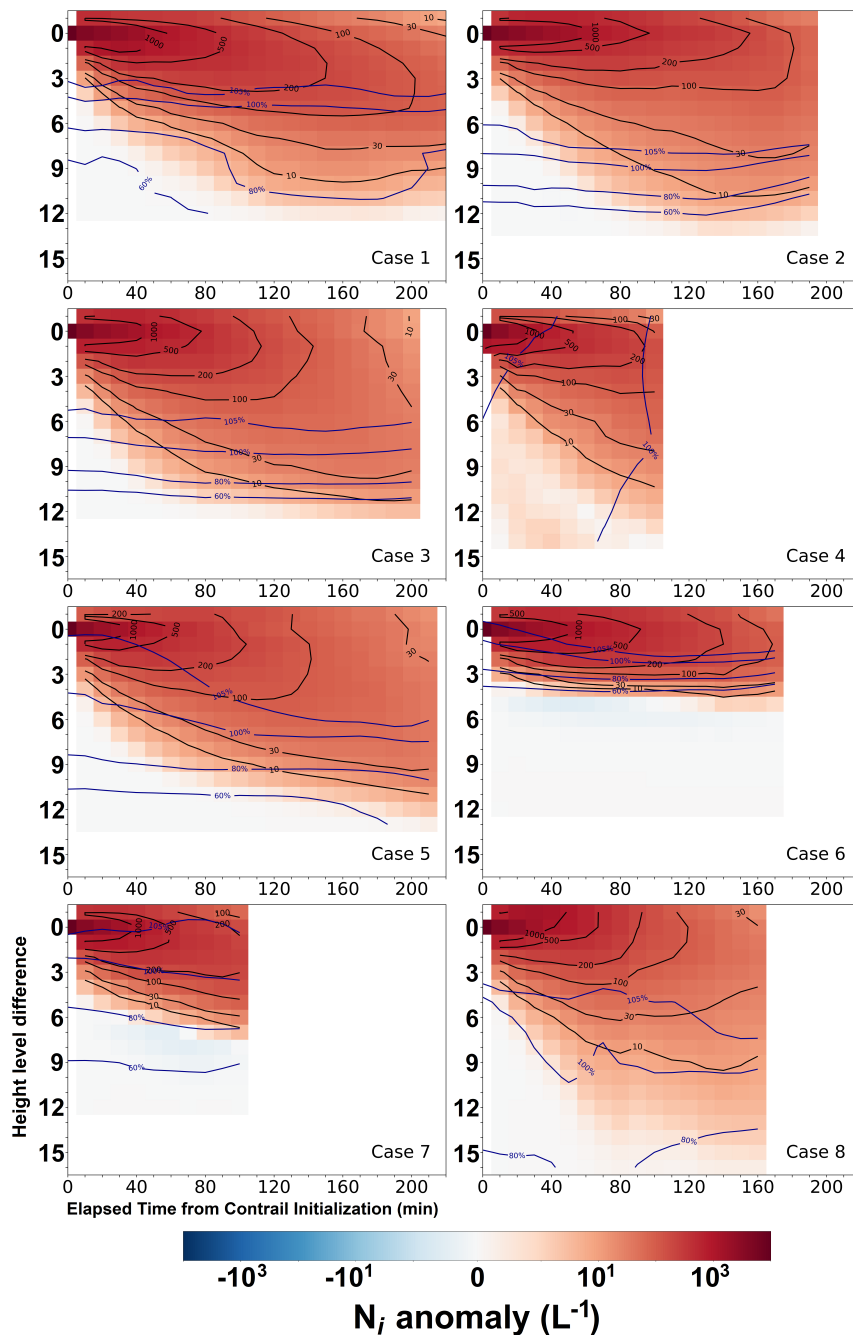


Figure 7. Time–height evolution of contrail ice crystal number concentration (N_i) anomalies for different cases, defined as the difference between the perturbation (contrail) and control (natural cloud) runs over the same region. The x-axis shows time since initialization; the y-axis shows height level differences from flight height. Black contours denote N_i anomalies; blue contours show RH_{ice} (%) from the control run. Warm colors indicate positive N_i anomalies; cool colors indicate negative ones.

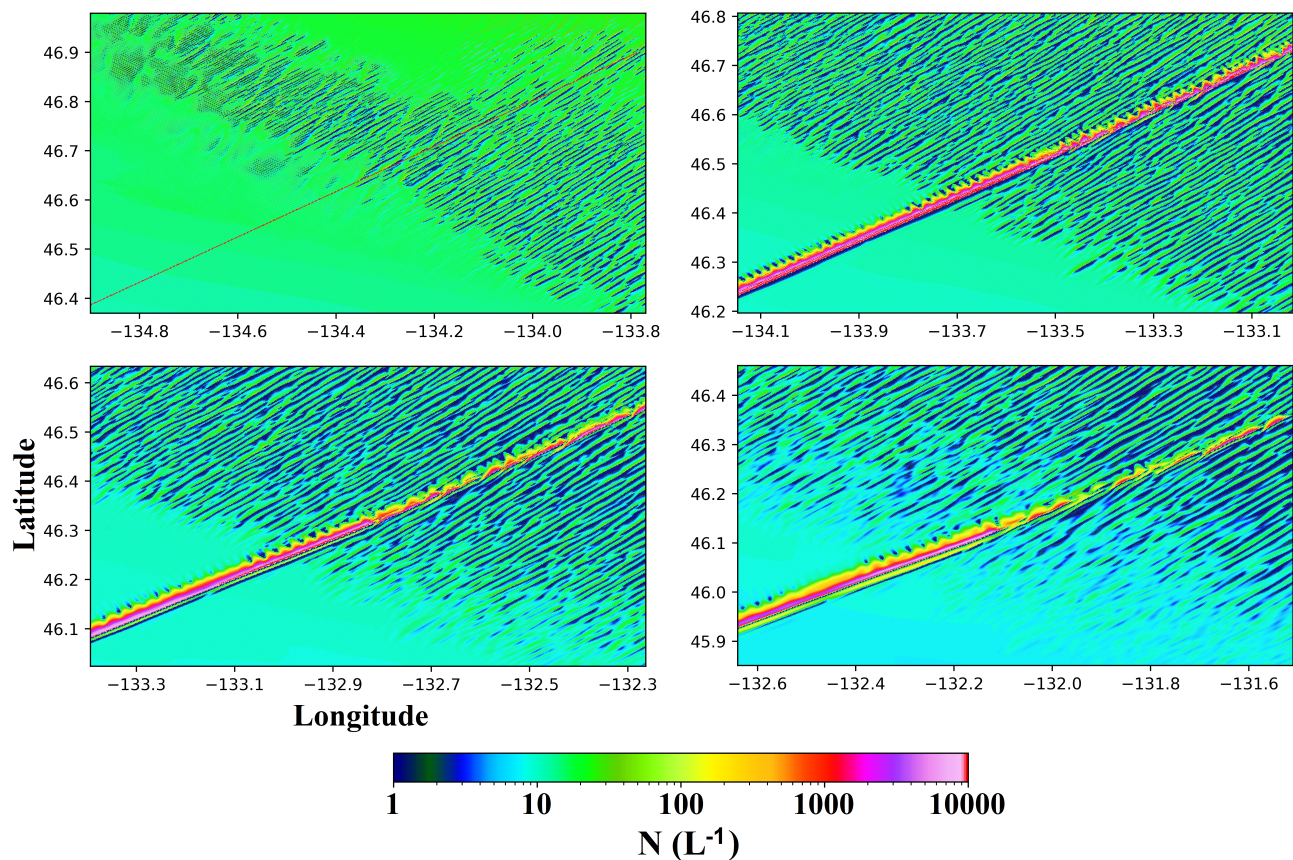


Figure 8. Horizontal spatial distribution of contrail ice crystal number concentration at flight altitude within a thick supersaturated layer in Case 4, alongside the evolution of fine-scale gravity wave-induced ice clouds. The panels correspond to contrail ages of 0, 20, 40, and 60 minutes (from top left to bottom right), respectively, representing the moment of contrail initialization and subsequent times. The figure is shown on the original triangular ICON model grid.

calized subsaturated regions. Additionally, these dynamics may limit the contrail's ability to mix and spread freely with the surrounding supersaturated environment. While the initial supersaturation is quickly depleted at flight height, contrails in other cases can sustain growth partly by drawing in water vapor from the edges through mixing with the surrounding ISSRs. In this case, however, gravity wave-induced restrictions on spreading may further contribute to ice crystal loss.

Atmospheric Stability and Contrail Ice Crystal vertical Growth

In Case 8, contrail ice crystals exhibit a distinct upward vertical development above flight altitude (Figure 7). While some upward extension occurs in all cases, primarily due to turbulent diffusion, vertical mixing, and wind shear, in this case, the N_i 1000, 500, and 200 L^{-1} contours extend upward more prominently. As previously discussed, young contrails are highly water vapor-thirsty, meaning that their development in ISSRs results in a high rate of deposition. This effect is clearly seen



in the map of RH_{ice} shown in Figure 5. However, high deposition not only reduces relative humidity to near saturation but also releases latent heat, creating a localized positive temperature anomaly (Appendix A2). As a result, the temperature in the contrail region becomes slightly higher than in the surrounding cloudy environment. In practice, however, this temperature difference is typically very small—only a few tenths of a degree or even less. As a result, its effect on buoyancy is minimal and is easily overshadowed by the background wind shear, mixing, turbulence of the surrounding environment, and the overall large-scale stability of the upper troposphere.

Time series of the atmospheric Brunt–Väisälä frequency at flight altitude during the control run is illustrated in Figure 9. Case 8 exhibits a distinctly lower frequency compared to the other cases, indicating weaker atmospheric stability. In a less stable atmosphere, even a minor temperature perturbation or buoyancy difference can induce a relatively large vertical displacement. Since the restoring force is weak, the contrail may ascend due to latent heat release. The evolution of this case suggests that contrails may also develop upward due to latent heat release, depending on atmospheric stability and the magnitude of temperature perturbations. These perturbations, in turn, are influenced by the mass mixing ratio of water vapor deposited onto young contrails. Studies of young contrail development during the vortex phase have shown that atmospheric stability influences the contrail’s cross-sectional area (Unterstrasser et al., 2017). However, we suggest that atmospheric stability may also influence the vertical expansion of contrail cirrus as it develops and ages—indicating that its role extends beyond the initial vortex phase.

Another distinct characteristic of this case is that the contrail’s vertical growth is significantly greater than in other cases. However, this is not very apparent in the N_i anomaly. Even so, positive N_i values extend well below flight altitude, indicating a significant downward development of the fall streak in this case (Later, you will see that this vertical extension becomes much clearer when analyzing the IWC anomaly.) This may be attributed to the relatively deep supersaturated layer, followed by a gradual decrease in subsaturation. Additionally, the stronger upward extension may be linked to the enhanced downward development of the contrail as well.

3.3.2 Contrail induced Ice Water Content anomalies Under Various Weather Conditions

Figure 10 is similar to Figure 7 but displays the anomaly in ice water content (IWC)—representing the changes in IWC within the contrail region compared to the same area in the background cloud. In contrast to N_i , the IWC anomaly increases as the contrail ages. With the exception of Case 4, the maximum IWC anomaly does not spatially or temporally coincide with the maximum N_i anomaly. In fact, in all simulations aside from Case 4, the highest IWC anomaly occurs during the final stages of the simulation and distinctly below flight altitude. This pattern indicates that the thickness of the ice-supersaturated layer beneath the contrail strongly influences both the position and magnitude of the peak IWC anomaly, with the maximum anomaly contour located just above the subsaturated layer. These simulations suggest that contrails formed in ISSRs typically reach their peak IWC anomaly around 2.5 hours after formation. It is important to note that this timing refers specifically to the IWC anomaly and not the ice water path.

Therefore, when studying contrails in ISSRs, it is not sufficient to focus only on the flight altitude. Observations should also consider the region below, as the maximum IWC anomaly in mature contrails (contrail cirrus) typically occurs at lower

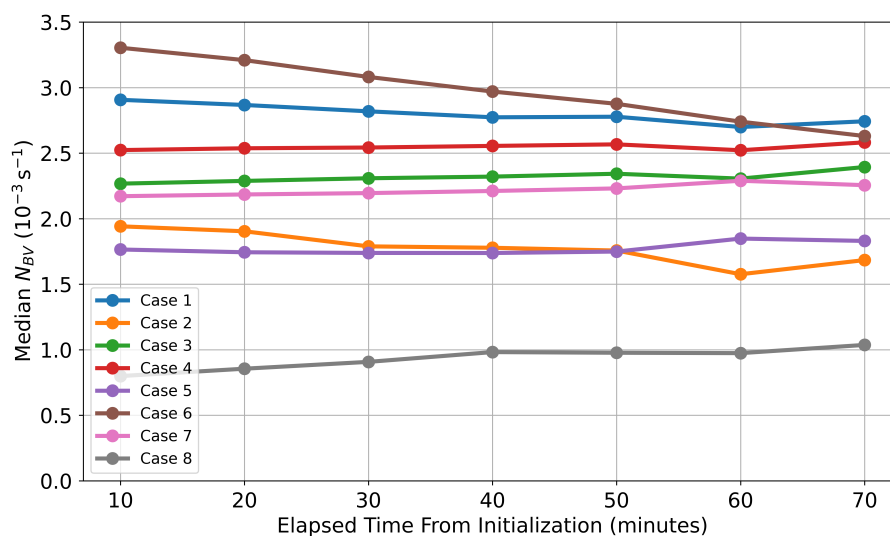


Figure 9. Time series of the median Brunt–Väisälä frequency for different cases. The values are computed over a broad region perpendicular to the flight path, representing the overall atmospheric conditions rather than only the immediate contrail environment.

altitudes, closer to the base of the supersaturated layer (however, the maximum N_i anomaly is probably still around the flight altitude). Analyzing the vertical structure of the ISSRs beneath flight altitude is crucial for fully understanding contrail evolution. This aligns with the study of Marjani et al. (2022), which investigated contrail impacts within cloudy regions using satellite-based assessments and detected the contrail signal hundreds of meters below the flight altitude.

When comparing the cases, the largest IWC anomaly is simulated for Case 5, where growth starts gradually at low values and peaks around 160 minutes after contrail initialization. The maximum anomaly, averaging approximately $6 \text{ mg} \cdot \text{m}^{-3}$, occurs just above the saturation contour. Case 3 follows a similar growth pattern, albeit with slightly lower peak values. Case 8 reaches a comparable maximum value to Case 3 but exhibits a different evolution. The anomaly grows relatively quickly at first, reaching $2 \text{ mg} \cdot \text{m}^{-3}$ and $3 \text{ mg} \cdot \text{m}^{-3}$ much earlier, after which IWC growth slows and remains relatively constant.

In contrast, aviation-induced IWC is weakest in Cases 1, 2, and 4. Case 7 was excluded as it quickly moved out of the simulation domain, limiting its development. The control simulations for Cases 1 and 2 (Appendix A3) reveal that both cases also exhibit very low background IWC, particularly around flight altitude. These are the two cases where contrails were initialized at higher altitudes (Case 1 at 12,138 m and Case 2 at 11,800 m) under extremely low ambient temperatures ($T < 215 \text{ K}$). These conditions may explain the weaker contrail-induced IWC anomalies in these cases. A more detailed discussion of the underlying reasons for this behavior will be provided in the next section.

Case 4 also recorded a low IWC anomaly but under different background weather conditions. In this scenario, the contrail formed at an altitude of 10,664 meters, with an average temperature of approximately 221 K—about 10 K warmer than Cases 1 and 2—within a deep ISSR. Furthermore, the control run exhibits relatively high IWC—especially compared to the



other simulations—suggesting that the background environment was already favorable for substantial ice content formation (Appendix A3).

3.3.3 Excess Water Vapor, Contrail Lifetime and Growth Potential

Even though both contrails and natural ice clouds are composed of ice crystals, their microphysical properties differ significantly. Young persistent contrails are characterized by exceptionally high ice crystal number concentrations, consisting of extremely small ice crystals—a feature not typically observed in natural clouds. Due to their high surface-area-to-volume ratio, these abundant small ice crystals have very short deposition and sublimation timescales. Consequently, young persistent contrails are highly efficient at consuming available moisture in ISSRs, rapidly depleting excess water vapor. This rapid moisture depletion creates a near-saturated environment at contrail flight altitude (as shown in Figure 5).

However, natural ice clouds do not necessarily deplete all available excess water vapor rapidly upon their formation. Observational studies have documented the frequent persistence of highly supersaturated conditions within natural cirrus clouds (Krämer et al., 2009; Diao et al., 2014), highlighting a fundamental distinction from contrails.

Therefore, the excess water vapor mass—defined as the mass of water vapor exceeding the saturation threshold at a given temperature and pressure (Eq. 1)—plays a critical role in contrail evolution within ISSRs. Specifically, this variable significantly affects contrail-induced ice water content (IWC) anomalies, a point thoroughly examined by Unterstrasser (2016).

$$\rho_v - \rho_{vs} \quad \text{when} \quad \rho_v > \rho_{vs} \quad (1)$$

ρ_v : Water vapor density ($\text{mg}\cdot\text{m}^{-3}$)

ρ_{vs} : Saturation water vapor density ($\text{mg}\cdot\text{m}^{-3}$)

Role of Excess Water Vapor in Contrail Evolution and Microphysical Properties

Figure 11 illustrates the temporal vertical distribution of excess water vapor density ($\text{mg}\cdot\text{m}^{-3}$), averaged within the contrail area only in the control simulations (natural cloud only). This representation reflects the moisture availability in the contrail region prior to its formation. The largest IWC anomalies were simulated for Cases 5, 3, and 8, respectively, while the weakest anomalies occurred in Cases 1 and 2. Meanwhile, Case 4 exhibited a distinct pattern, with a more pronounced initial increase in IWC followed by a slower rate of change over time.

Case 1 and Case 2 formed at higher altitudes (approximately 12 km) with significantly lower temperatures ($T < 215$ K). Despite their initially high relative humidity, the absolute amount of excess water vapor available is noticeably limited due to the low temperatures. This limited excess water vapor directly affects contrail ice crystal growth, resulting in their prolonged presence at flight altitude. This aligns with our earlier findings that these two cases exhibited prolonged N_i anomalies at flight altitude while also showing minimal growth in IWC anomalies. Looking at satellite-detectable contrails, Gryspeerdt et al. (2024) found that higher flight altitudes are associated with longer contrail lifetimes and increased persistence.

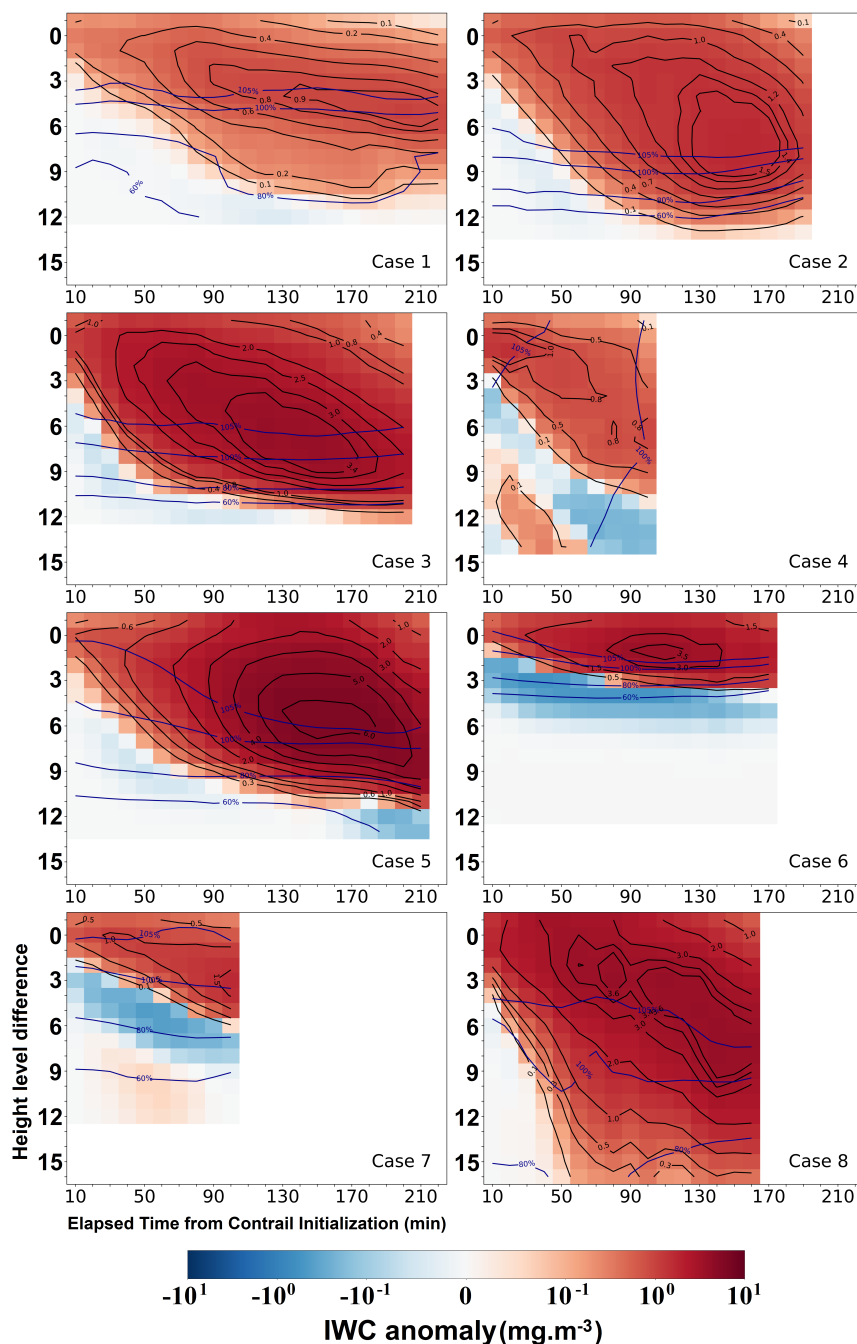


Figure 10. Time–height evolution of contrail ice water content (IWC) anomalies for different cases, defined as the difference between the perturbation (contrail) and control (natural cloud) runs over the same region. The x-axis shows time since contrail initialization; the y-axis shows height level differences from flight height. Black contours denote IWC anomalies ($\text{mg}\cdot\text{m}^{-3}$), and blue contours indicate RH_{ice} (%) from the control run. Warm colors indicate positive anomalies; cool colors indicate negative ones.



Although both Cases 1 and 2 had limited excess water vapor, Case 2 exhibited slightly higher values and, additionally,
490 its temporal pattern differed, with a gradual and constant increase in excess water vapor, indicating a sustained moisture
supply to the contrail region throughout its development. This pattern aligns with findings by Unterstrasser et al. (2017), who
emphasized the importance of sustained moisture availability—associated with prolonged but weaker updrafts—in supporting
contrail persistence. Consequently, Case 2 maintained high ice crystal number concentration and exhibited a longer lifetime
and slightly higher IWC anomaly compared to Case 1. However, the thickness of the underlying supersaturated layer also likely
495 influenced this outcome.

A similar trend was observed at flight level in Case 6, where excess water vapor initially remained low (below $1 \text{ mg} \cdot \text{m}^{-3}$)
but gradually and steadily increased over time, supporting its relatively longer ice crystal persistence at flight altitude compared
to other cases with similar altitudes and temperatures.

In Cases 5 and 3, the contours similarly exhibit a gradual increase, with Case 5 starting at lower values but gradually reaching
500 higher levels over time. Moreover, since these cases occur at lower altitudes, they benefit from a greater availability of excess
water vapor. This excess water vapor availability is clearly reflected in the contrail-induced IWC anomalies, though it may not
be readily apparent when examining relative humidity alone.

In contrast, Case 8, despite initially having high values of excess water vapor (values up to $4\text{--}5 \text{ mg} \cdot \text{m}^{-3}$), did not reach
comparable maximum IWC anomalies. Its excess moisture was rapidly consumed initially, accelerating ice crystal growth and
505 sedimentation. As a result, the IWC anomaly quickly reached intermediate values ($\sim 3 \text{ mg} \cdot \text{m}^{-3}$) but did not further mature or
intensify to levels observed in Cases 3 and 5.

As discussed previously, Case 4 exhibits unique behavior in both N_i and IWC anomalies. It is the only simulation where
the maximum IWC anomaly aligns spatially and temporally with the peak N_i anomaly. This case, characterized by deep
supersaturated layers with weak ice supersaturation, resembles conditions typically associated with liquid-origin ice clouds.

510 The comparison of the median time series of excess water vapor density in the natural ice cloud (control run) and the contrail-
affected region (perturbation run) is shown in Figure 12. The control run reveals a gradual decline in available moisture,
suggesting a weakening or cessation of mesoscale upward motions. While excess water vapor is steadily consumed by natural
clouds, its depletion is significantly accelerated in the presence of the contrail. In the perturbation run, excess water vapor
initially decreases sharply and then stabilizes as values approach zero. This behavior explains the rapid initial increase in
515 the IWC anomaly, followed by stalled growth—and even a decline—as additional sublimation is required to maintain near-
saturated conditions.

To summarize, these findings emphasize that persistent contrail development and growth are not only determined by the
presence of supersaturation conditions but also critically depend on the quantity and temporal availability of excess water
vapor within ISSRs.

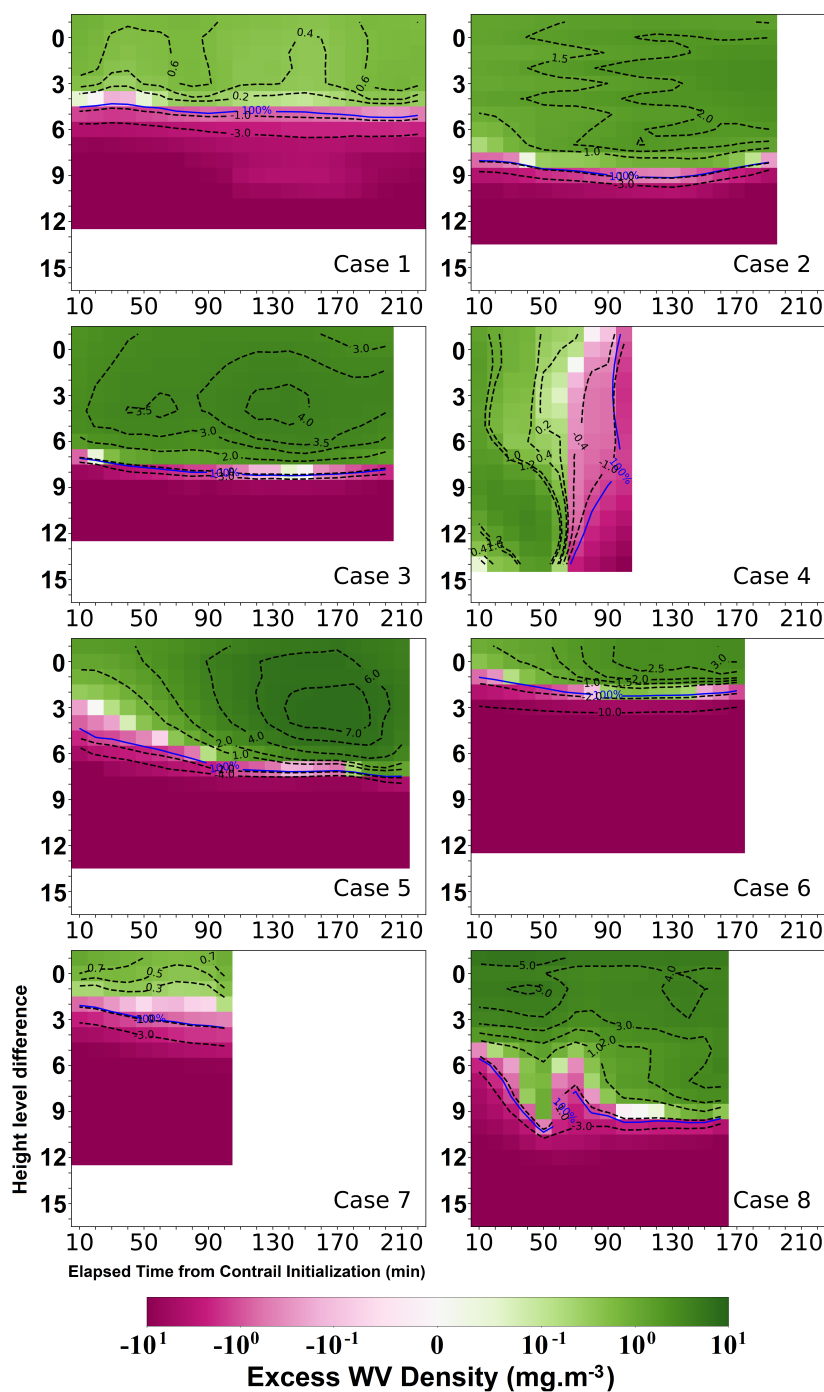


Figure 11. Time–height evolution of excess water vapor density ($\text{mg}\cdot\text{m}^{-3}$) in the contrail area for different cases in the control runs. The x-axis shows elapsed time after contrail initialization, while the y-axis represents height differences relative to flight level.

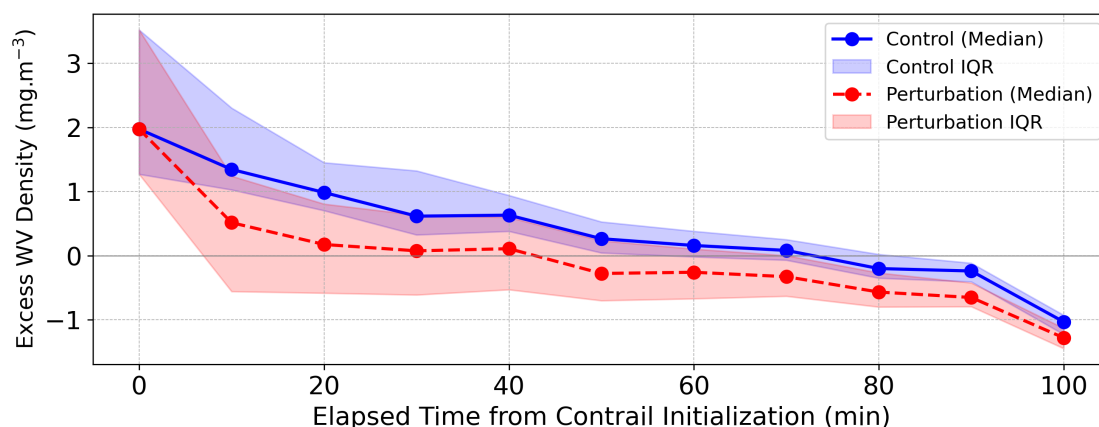


Figure 12. Time series of excess water vapor for the control (blue) and perturbation (red) runs in Case 4, at flight altitude. The blue line represents the evolution in the natural cloudy region, where excess water vapor remains positive until approximately 70 minutes, followed by a gradual decline, indicating the absence of strong upward motion. In the perturbation run, the contrail accelerates moisture depletion, leading to a more rapid decline in excess water vapor. Shaded regions indicate the interquartile range (IQR).

520 3.4 Radiative Effects of Individual Contrail Evolution in Ice-Supersaturated Regions

This section analyzes the radiative impacts—both longwave and shortwave—by comparing perturbation runs (with contrails) to control runs, focusing exclusively on the subregion directly affected by the contrail. This ensures that the comparison isolates contrail-induced effects from the broader atmospheric variability present in the full simulation domain.

3.4.1 Contrail-induced Thermal Radiative Effects

525 Figure 13 presents the time series of terrestrial infrared, or longwave (LW), radiative flux at the top of the atmosphere (TOA). Negative values indicate outgoing radiation and energy loss to space. Less negative values correspond to reduced outgoing radiation, signifying increased greenhouse effects and greater energy retention.

The smallest contrail-induced radiative impact is simulated for Case 4. This case features relatively high thermal flux in the control run, consistent with the presence of optically thick, liquid-origin ice clouds. Such clouds typically exhibit stronger
530 radiative effect than in situ-origin cirrus clouds due to their higher optical thickness (Krämer et al., 2016).

The strongest contrail-induced radiative impacts occur in Cases 5, 8, and 3, respectively, with Case 5 showing the highest anomaly of 24 W m^{-2} at 140 minutes. Case 5 exemplifies contrail growth under near-optimal conditions: it is situated at an altitude not too high to limit excess water vapor availability (unlike Case 2), and it benefits from a steady, gradual moisture supply. Additionally, it has sufficiently deep ISSRs below flight altitude—unlike Case 6, which had almost the same conditions
535 except that contrail growth was restricted by a very thin supersaturated layer beneath the contrail flight level.



Case 8 exhibits a significant radiative impact, ranking second after Case 5. The largest change in this case, 23 W m^{-2} , occurs as early as 60 minutes after initialization, highlighting its early-onset development. This rapid evolution was already observed in the IWC anomaly.

540 Interestingly, the radiative impact of Case 2, which represents contrails forming at high altitude, is not among the lowest. As expected, it increases gradually, reaching 18 W m^{-2} after 150 minutes—a value comparable to other cases with greater available water vapor.

Relationship between Thermal Radiative Effects and Ice Water Path

Figure 13 also includes the time evolution of IWP. As expected, Case 4 has the largest values in the natural cloudy region (control). However, the contrail-induced change in IWP remains minimal in this case, though a slight increase is still noticeable. 545 A potential relationship between changes in thermal net flux at the top of the atmosphere and IWP anomalies is evident from the analysis. We computed the pointwise distance correlation between contrail-induced changes in IWP and thermal net flux. The coefficient, as shown in Appendix A4, indicates a positive association between these variables—suggesting that larger increases in IWP correspond to greater reductions in outgoing longwave flux. Notably, while this correlation is observed in most cases, in Case 4 the pre-existing high IWP likely overshadows any contrail-induced effects.

550 3.4.2 Contrail-induced Solar Radiative Effects

To assess solar, or shortwave (SW), radiative effects, all cases were normalized to a standardized reference irradiance corresponding to 1st March at a latitude of 34° . This normalization enables direct comparison of net solar flux across cases, based on a reference value of $S_{\text{ref}} = 231 \text{ W, m}^{-2}$. Figure 14 presents the time series of solar net flux at the top of the atmosphere for all cases, together with the corresponding albedo time series.

555 Although the perturbation and control runs show similar overall temporal evolution, the presence of contrails consistently enhances local atmospheric reflectivity, thereby reducing the incoming solar radiation. The largest reductions in solar net flux are observed in Cases 3, 5, and 8, while Cases 1, 4, and 7 exhibit comparatively smaller effects (note that Case 7 exits the simulation domain prematurely).

In our study, although contrails exhibit a cooling effect from the shortwave (solar) perspective, their warming impact due to 560 the trapping of outgoing longwave radiation (greenhouse effect) remains dominant. A version of Figure 14, normalized using a standardized reference irradiance corresponding to June 21st—when solar irradiance typically reaches its annual maximum—is provided in Appendix A5. Even under these peak solar conditions, the cooling effect from reduced solar flux cannot fully compensate the warming caused by longwave radiation trapping.

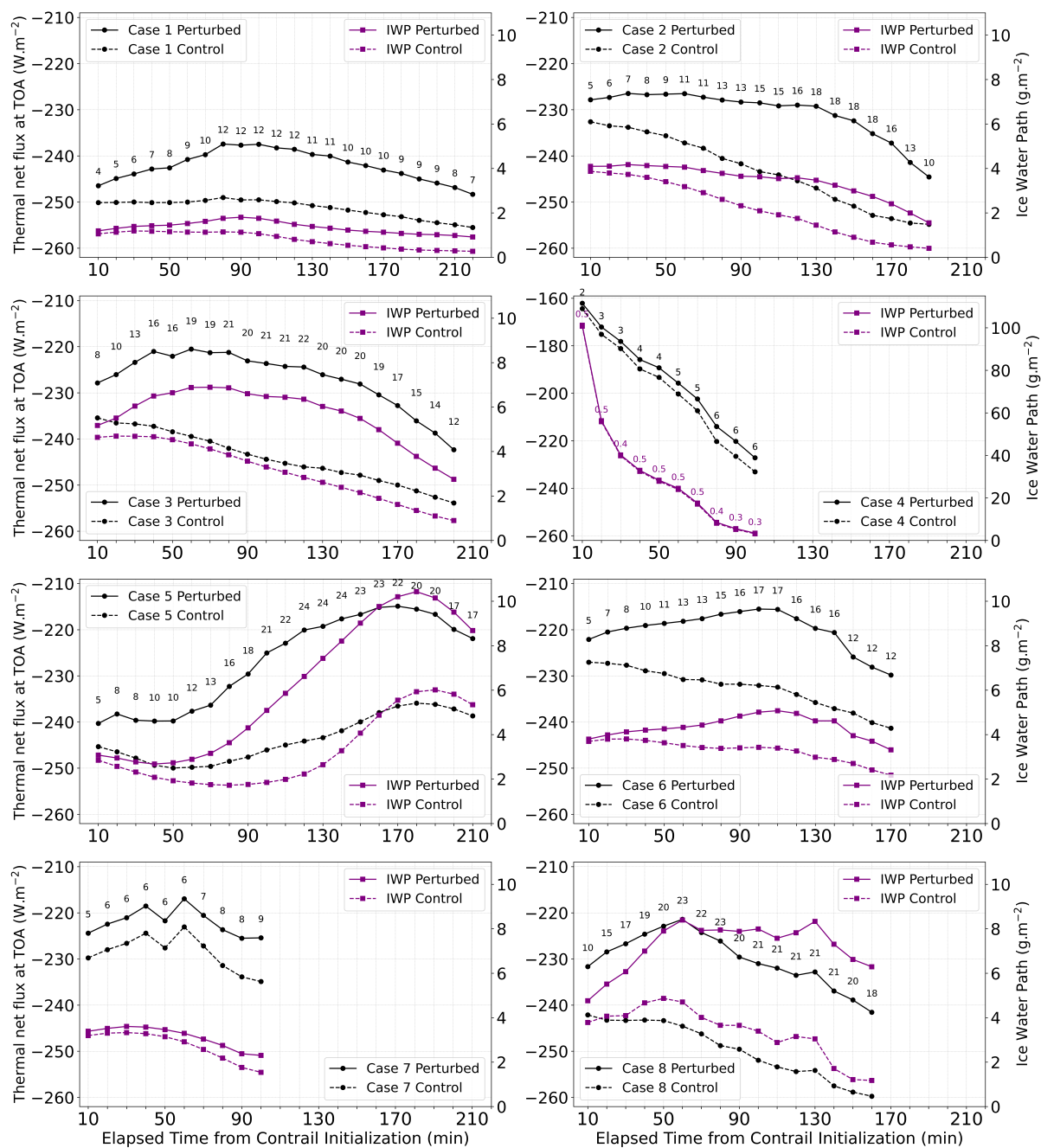


Figure 13. Time series of thermal net flux at the top of the atmosphere (left y-axis) and ice water path (IWP, right y-axis) for control and perturbation simulations across eight cases. Differences between control and perturbed runs quantify the localized thermal radiative impact of contrails.

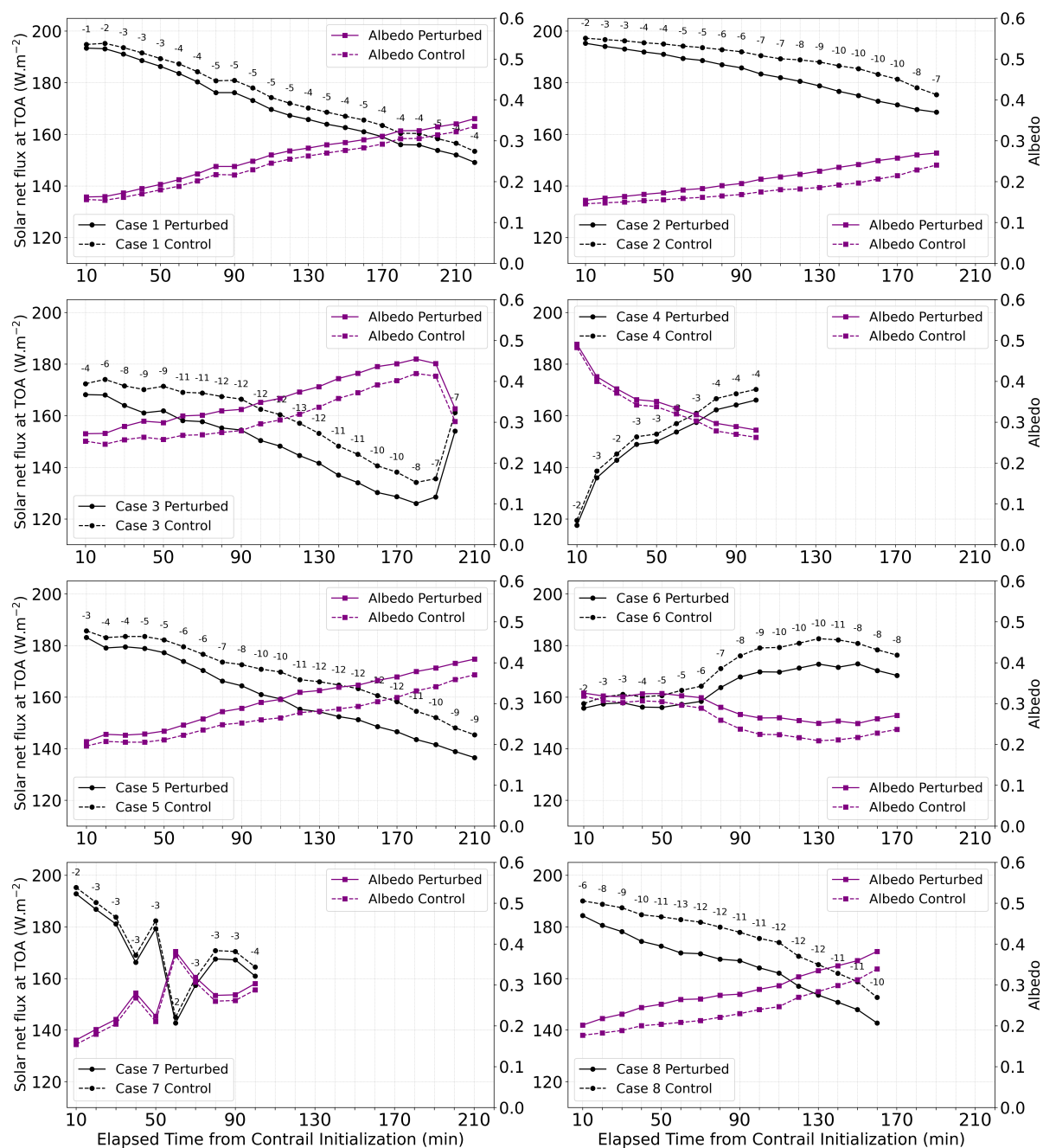


Figure 14. Time series of solar net flux at the top of the atmosphere for control and perturbation simulations across eight cases (left axis). Flux values are standardized using a reference irradiance ($S_{\text{ref}} = 231 \text{ W} \cdot \text{m}^{-2}$), corresponding to March 1st at latitude 34° , allowing direct comparison across cases. The right axis shows albedo (perturbed and control), plotted with purple square markers.



4 Conclusion

565 This study aimed to investigate how persistent contrails evolve within varying ice-supersaturated environments—typically associated with cloudy backgrounds—and to address the question: what atmospheric constraints govern contrail development and persistence?

To capture contrail evolution under realistic weather conditions, we employed a two-stage modeling framework. First, kilometer-scale simulations using ICON-NWP were performed with nested domains to provide synoptically consistent initial and boundary conditions for our main simulations. The output from the finest nest then initialized high-resolution ICON-LEM simulations at 156 m horizontal resolution. In these simulations, we introduced an identical perturbation—a fixed ice crystal number concentration of 150 cm^{-3} —along targeted flight tracks that satisfied the Schmidt–Appleman criterion throughout the perturbed region. This two-stage modeling framework ensured a smooth scale transition and provided physically consistent background cloud environments for large-eddy simulation (LES) of contrail evolution. By comparing the evolution of identical initial contrail perturbations across diverse cloudy, ice-supersaturated backgrounds—and against corresponding control runs featuring only natural cirrus clouds—we assessed how environmental variability governs persistent contrail development.

Our high-resolution simulations emphasize that contrail persistence and microphysical development are strongly shaped by the surrounding atmospheric environment—particularly the interplay between the vertical extent of ice supersaturation and the availability of excess water vapor. A thick supersaturated layer alone does not guarantee contrail growth unless sufficient water vapor is available to sustain deposition. Notably, contrails developing within liquid-origin ice clouds—despite deep vertical extent—exhibit limited growth when ice supersaturation is marginal. Our findings also reveal that in the cold upper troposphere, contrail ice water content may be constrained by the atmosphere’s limited water vapor holding capacity, even under strong supersaturation.

While vertical spreading through fall streaks is well established, our results suggest that in environments with high ice supersaturation and low atmospheric stability, contrails may also expand above the flight altitude due to latent heat release from rapid deposition. Consistent across cases, we find that the net radiative effect of contrails remains dominated by longwave warming, with shortwave cooling from increased albedo insufficient to offset it—even under summer solstice conditions. These results suggest that simplistic threshold-based mitigation strategies, such as those relying solely on the Schmidt–Appleman criterion or RH values, may be insufficient to accurately predict or mitigate contrail climate effects.

590 Future studies may explore the sensitivity of our findings to perturbations in ice crystal number concentration (N_i), by systematically increasing or decreasing the initial values. This would help assess how changes in N_i influence the evolution of the ice water path and better quantify the microphysical feedbacks. In our LES simulations, the model resolution of 156 meters was chosen to fully resolve the initial vertical cross-sectional area of the contrail within a single grid box. As a result, we were not able to investigate the effects of smaller aircraft or narrower initial cross-sections without moving to a finer resolution, such as 78 meters. This study focuses exclusively on the evolution of individual contrails in ice supersaturated cloudy backgrounds. While this allows for detailed process-level understanding, we acknowledge that the results may not be directly generalizable to conditions involving contrail outbreaks or interactions between multiple contrails. Lastly, the microphysical schemes used



in this study are based on the parameterizations of Seifert and Beheng (2006). These parameterizations may require further tuning, especially regarding the growth rates and sedimentation behavior of contrail ice particles, which can differ from those of natural cirrus clouds—particularly if one aims to accurately interpret the extent of vertical development.

Appendix A: Supplementary Tables and Figures

This appendix provides additional tables, animations, and figures that support the analysis presented in the main text.

Table A1. Summary of simulation cases, including simulation dates, flight altitudes, average temperatures at flight level, and simulated domain centers.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Dates of Simulation	2011-02-10	2011-03-15	2010-12-23	2010-10-11	2010-11-15	2011-03-15	2010-04-04	2010-11-07
Domain Center (Lat, Long)	34.4, -139.6	33.4, -126.4	31.4, -128.5	45.9, -133.4	34.4, -146	35, -126.8	34.6, -134	31.6, -127.5
Flight Height (m)	12138	11801	10664	10664	10664	10664	10664	11143
Flight Temperature (K)	211	211	222	221	223	220	220	219

Video A1. Contrail Ice Crystal Concentration Development Within a Cloudy Background

The evolution of contrail ice crystal concentration within a cloudy background is presented for all eight simulation cases as individual animations. Each animation corresponds to a specific case and shows contrail development at flight altitude. The simulations were performed using ICON-LEM with a horizontal resolution of approximately 156 meters, based on the R2B14 triangular grid. Snapshots are taken every 10 minutes to capture the temporal progression of contrail behavior.

The animations are available at Zenodo: <https://doi.org/10.5281/zenodo.15106425>

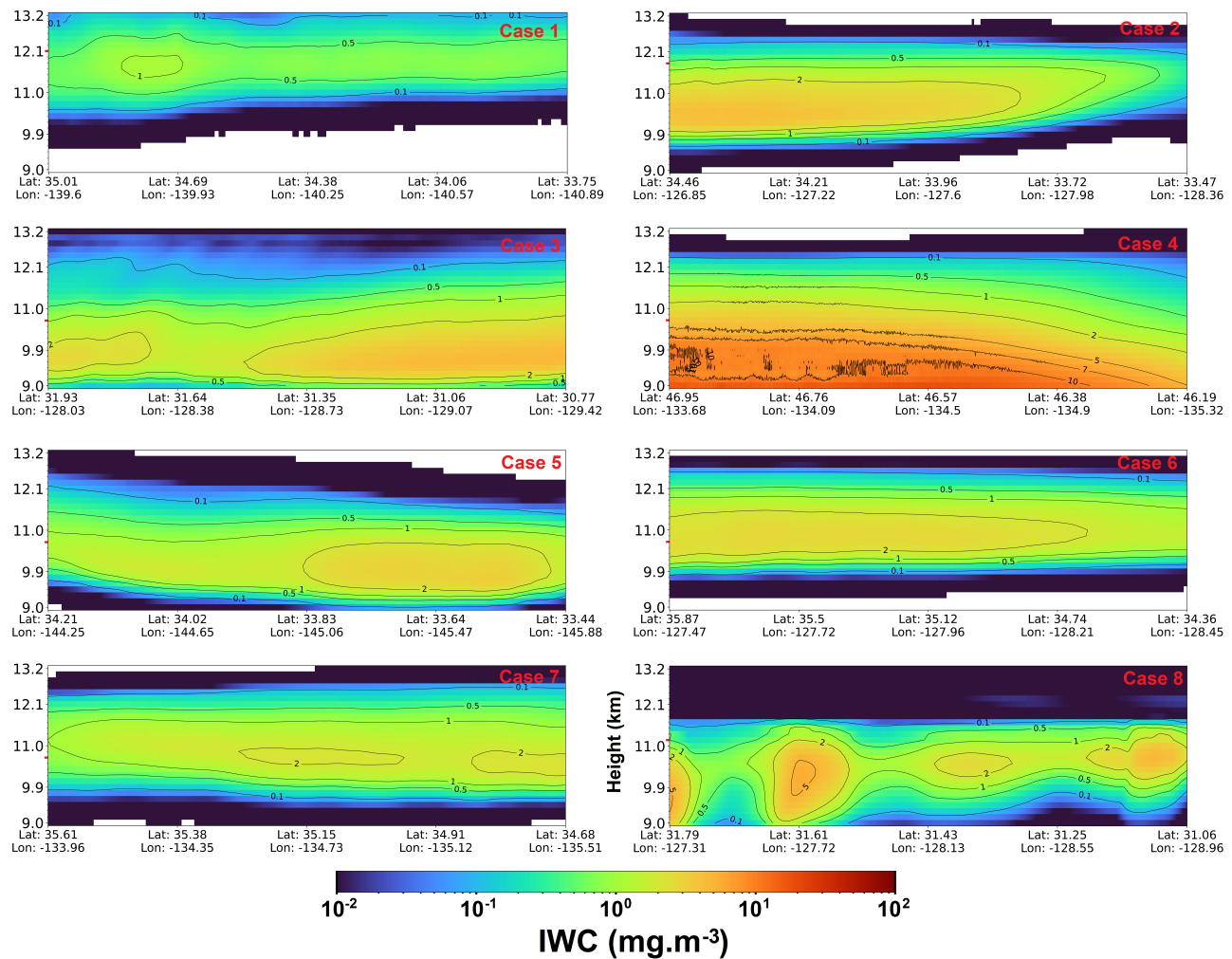


Figure A1. Vertical cross-sections of background ice water content (IWC) along the flight track for all eight cases at the moment of contrail initialization, based on the control simulations. The data are averaged over a broad region perpendicular to the flight path, representing the overall mean atmospheric conditions rather than just the immediate contrail environment. The altitudes at which contrails are initialized are indicated by red tick marks.

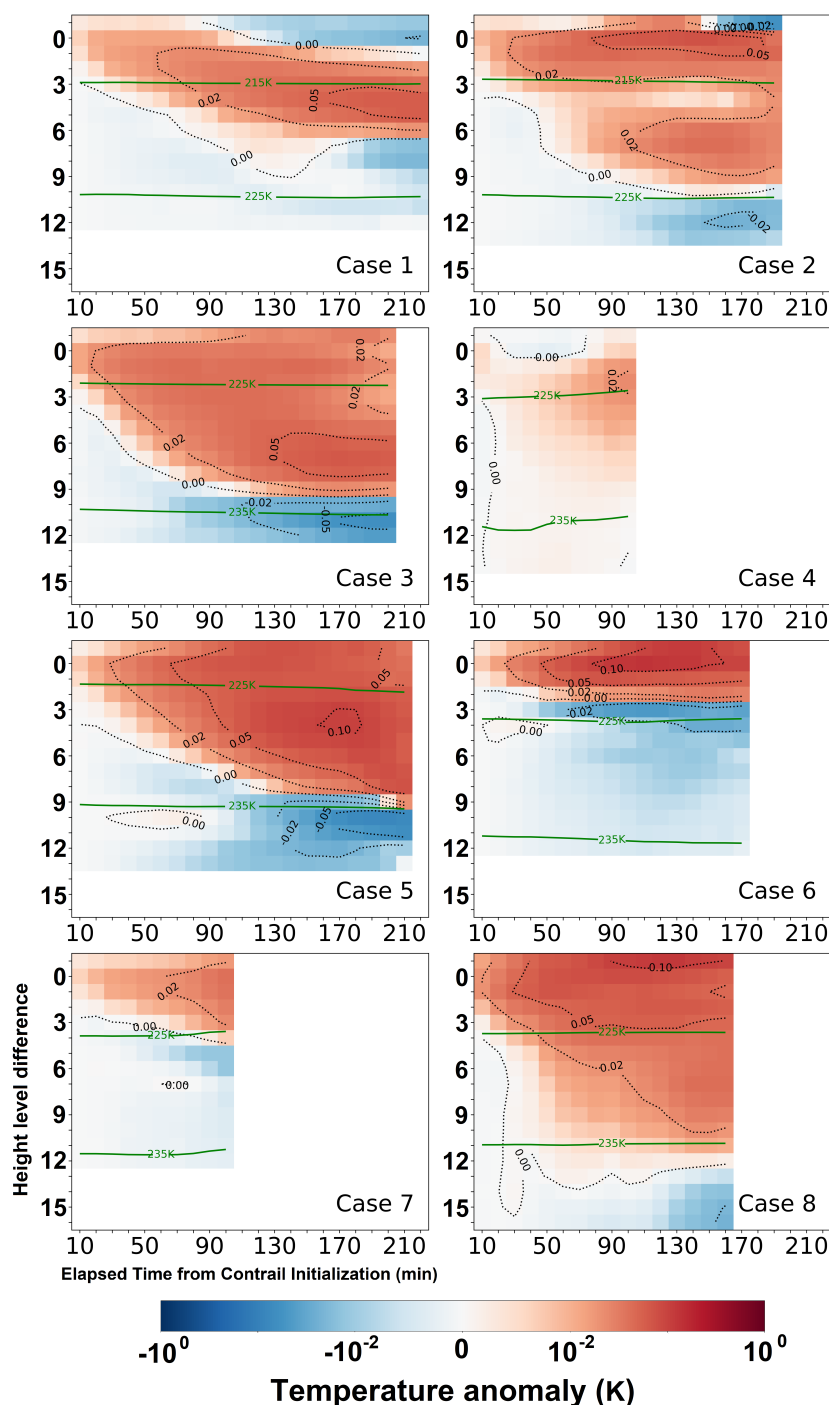


Figure A2. Time–height evolution of temperature anomalies for different cases, defined as the difference between the perturbation (contrail) and control (natural cloud) runs. The x-axis shows time since contrail initialization; the y-axis shows altitude. Green contours mark 215, 225, and 235 K from the control run. Warm colors indicate positive anomalies; cool colors indicate negative ones.

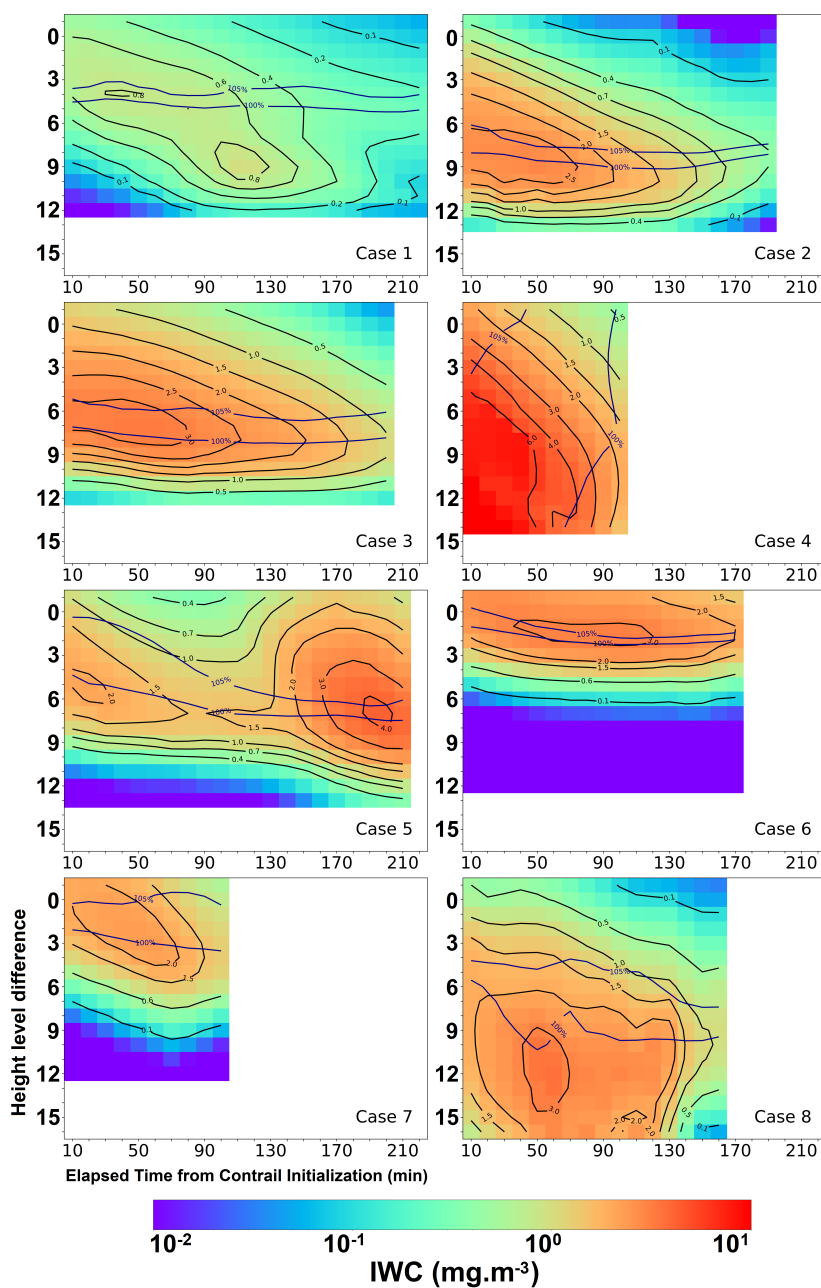


Figure A3. Time–height evolution of IWC anomalies for different cases, defined as the difference between the perturbation (contrail) and control (natural cloud) runs. The x-axis shows time since contrail initialization; the y-axis shows altitude. Black contours denote IWC anomalies (mg.m⁻³), while blue contours indicate relative humidity over ice (RH_{ice}, %) from the control run.

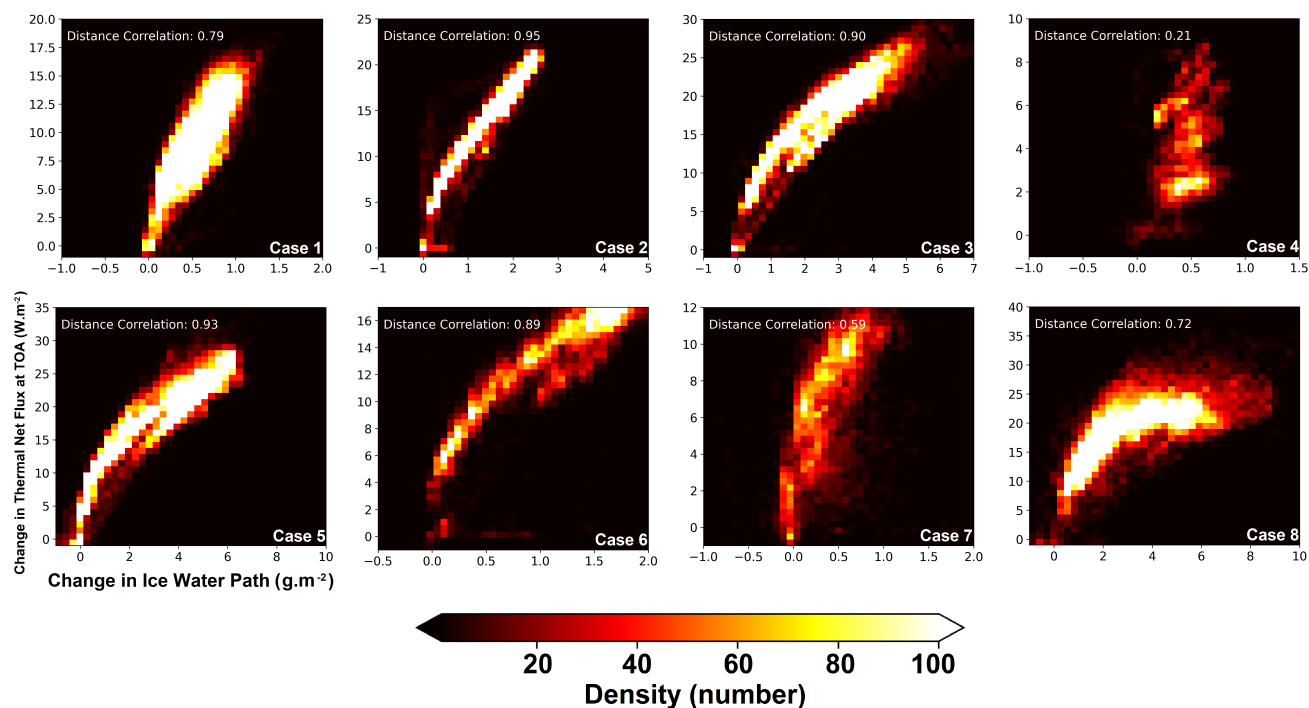


Figure A4. Overall 2D histogram of pointwise contrail-induced changes in ice water path (IWP) and changes in thermal net flux at the top of the atmosphere for all eight cases. The computed distance correlation coefficient indicates a positive association between these variables, suggesting that larger pointwise increases in IWP are related to greater reductions in outgoing longwave flux.

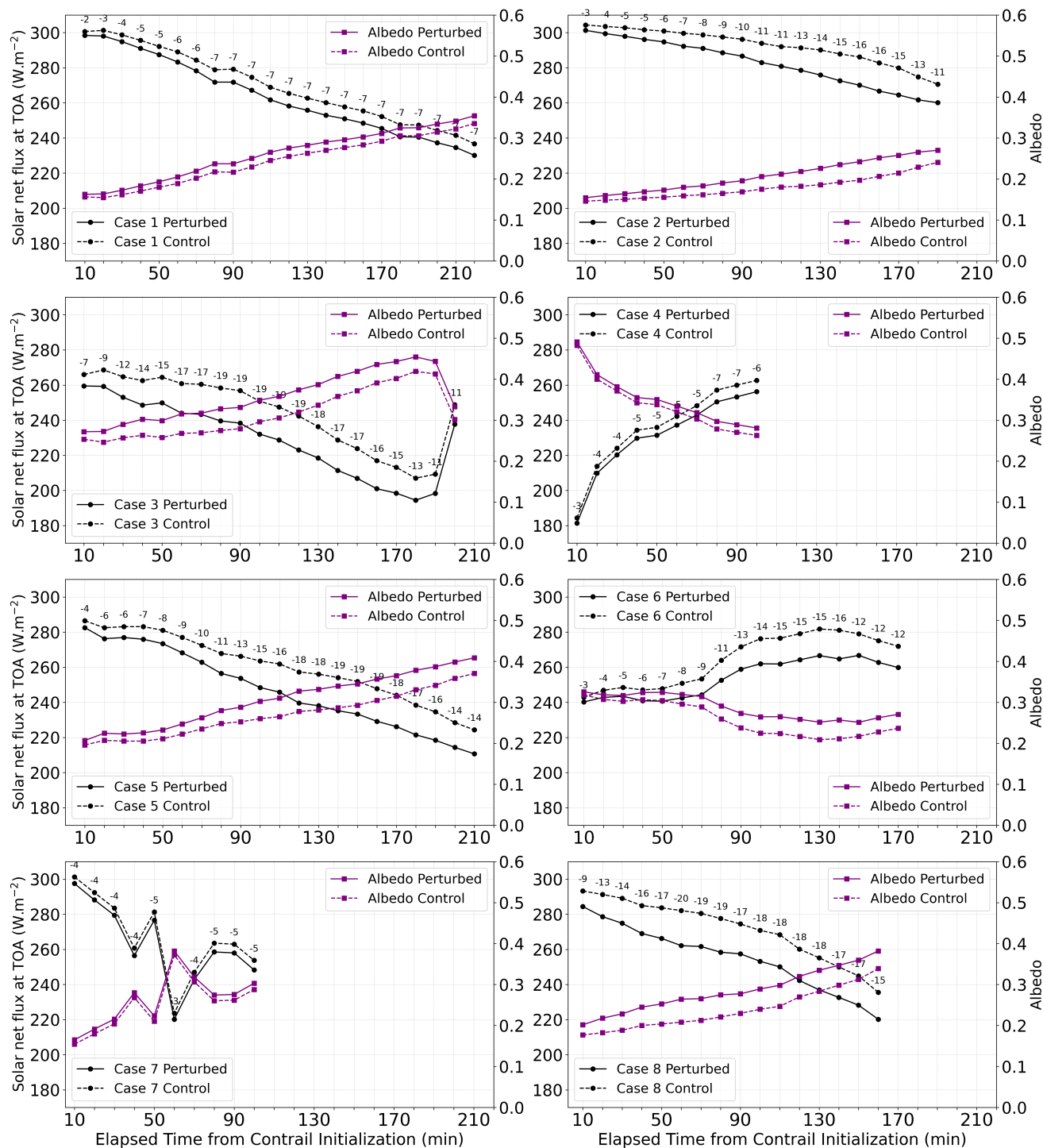


Figure A5. Same as Figure 14, but standardized using a reference irradiance of $S_{\text{ref}} = 365 \text{ W} \cdot \text{m}^{-2}$, corresponding to June 21st at latitude 34° , when solar irradiance is at its annual maximum in the Northern Hemisphere.



Appendix B: Contrail Formation Conditions - A Closer Look

610 The Physics of Contrail Formation: The Schmidt–Appleman Criterion

Aircraft contrails form when hot, moist engine exhaust mixes with the colder ambient air at cruising altitudes. This mixing process follows a linear trajectory in temperature–vapor pressure space, known as a mixing line. The Schmidt–Appleman Criterion (SAC; Schumann (1996)) provides an analytical framework for contrail formation by defining the conditions under which this mixing line intersects the saturation vapor pressure curve over liquid water. Such an intersection indicates that
615 the exhaust plume has reached water saturation, allowing exhaust particles—predominantly composed of soot, as observed in typical commercial flight operations— act as cloud condensation nuclei (CCN).

As a result, supercooled water droplets quickly form and freeze, generating a visible contrail. Numerous flight experiments have confirmed that contrails only form when this water saturation is exceeded (Busen and Schumann, 1995; Schumann, 1996; Jensen et al., 1998; Schumann, 2000). For contrails to persist, however, the surrounding atmosphere must also be at least
620 saturated with respect to ice; otherwise, the ice particles sublime and the contrail dissipates shortly after formation.

Slope of the Mixing Line and the Threshold Temperature θ_{100}

The slope of the mixing line, denoted by G , depends on atmospheric pressure and several aircraft-specific parameters and is calculated using Equation (B1). This formulation incorporates the mass emission index of water vapor (M_w), the specific heat capacity of air (c_p), atmospheric pressure (P_a), specific combustion heat (Q), and propulsion efficiency (η). For our analysis,
625 we adopt values of $M_w = 1.25 \text{ kg}_{\text{wv}} \text{ kg}_{\text{fuel}}^{-1}$, $c_p = 1005 \text{ J kg}^{-1} \text{ K}^{-1}$, $Q = 43.2 \text{ MJ kg-fuel}^{-1}$, and $\eta = 0.3$, following Bock and Burkhardt (2019).

$$G = \frac{c_p M_w P_a}{0.622 Q (1 - \eta)} \quad (\text{B1})$$

To determine the Schmidt–Appleman threshold temperature—the maximum ambient temperature at which contrails can form—a threshold mixing line must be derived using the specified aircraft parameters and atmospheric pressure. The point of
630 tangency between this mixing line and the saturation vapor pressure curve over liquid water defines θ_{100} —the threshold temperature at water saturation within the mixing plume. This value, which varies with pressure, provides the basis for calculating the complete threshold mixing line.

Figure B1 (left) displays θ_{100} across different atmospheric pressures, illustrating that lower atmospheric pressures correlate with lower θ_{100} , thereby indicating the cooler conditions the plume must reach for contrail formation to occur.

635 Atmospheric Temperature and Humidity in Contrail Formation

Along the threshold mixing line, each atmospheric vapor pressure corresponds to a specific temperature—the Schmidt–Appleman threshold temperature (θ_G)—which represents the highest ambient temperature at which contrail formation can occur under

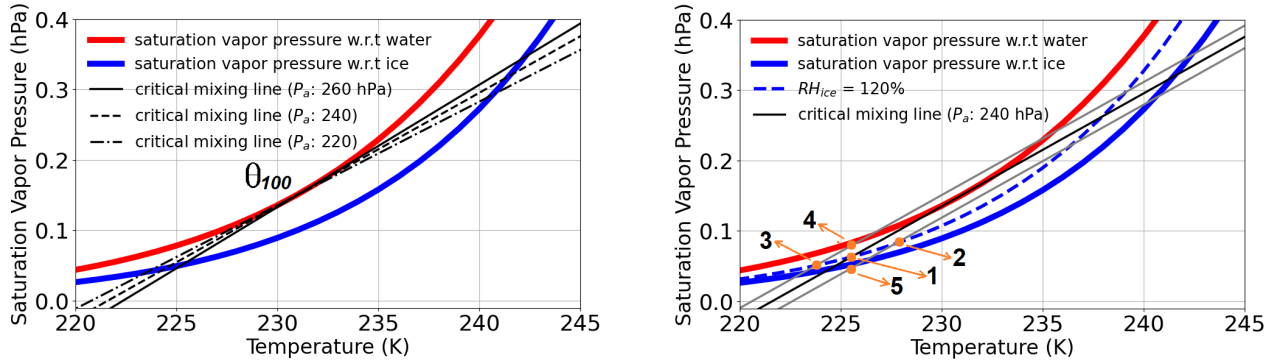


Figure B1. (Left) Threshold mixing lines are shown for three different atmospheric pressures. The tangent point between each mixing line and the water saturation curve indicates the threshold temperature at water saturation. It is evident that at higher ambient pressures, the tangent occurs at warmer temperatures, indicating a higher threshold temperature for contrail formation. (Right) The dashed blue line represents the saturation vapor pressure curve at a relative humidity with respect to ice (RH_{ice}) of 120%. The three diagonal lines, which have identical slopes, represent mixing lines for a fixed atmospheric pressure and aircraft characteristics, but varying ambient temperatures and humidities. This illustrates how the critical mixing line delineates atmospheric conditions that are favorable for contrail formation from those that are not.

given conditions. Conversely, for a given ambient temperature along the mixing line, one can compute the threshold vapor pressure (e_G), which is the minimum required for contrail formation at that atmospheric temperature and pressure.

Figure B1 (right) illustrates the intersection between the critical mixing line at an atmospheric pressure of 240 hPa and the saturation vapor pressure curve corresponding to RH_{ice} of 120% (point 1).

We used the Goff–Gratch empirical formula to calculate saturation vapor pressure, owing to its high accuracy across a broad range of cold temperatures. If the ambient temperature, given a specific atmospheric pressure (P_a) and relative humidity, is below θ_G , contrail formation is likely; conversely, if it exceeds θ_G , contrails will not form. The critical temperature for this particular atmospheric pressure and relative humidity is indicated by point 1. For these conditions, the critical temperature is $\theta_G = 225.5$ K.

When the ambient temperature exceeds the critical temperature (moving from point 1 to point 2), the mixing line no longer intersects the water saturation vapor pressure curve (the gray line aligned parallel to the black line on its right side), indicating that contrail formation will not occur. Conversely, when the ambient temperature falls below this critical threshold (moving from point 1 toward point 3), the mixing line intersects the saturation curve, ensuring contrail formation (represented by the gray line aligned parallel to the black line on its left side).

From another perspective, ambient humidity also plays a critical role: at a given atmospheric pressure and temperature, contrails form only when ambient humidity exceeds a critical value. When the atmospheric pressure is 240 hPa and the temperature is 225.5 K, contrail formation requires an ambient vapor pressure corresponding to RH_{ice} of 120% (point 1). If the ambient humidity is any higher (moving from point 1 to point 4), the mixing plume surpasses saturation with respect to water,



guaranteeing contrail formation. Conversely, lower humidity (moving from point 1 to point 5) falls short of liquid saturation, and no contrail will form.

Summary of Appendix B and Context for Figure 2 In brief, both fuel/engine properties and ambient atmospheric conditions (temperature, pressure, and humidity) determine contrail formation. A *look-up table* of these threshold temperatures, as a
660 function of RH_{ice} and P_a , is included in the main text (Figure 2). This heatmap more compactly visualizes how higher relative humidity and higher pressure both raise the contrail formation temperature threshold.

Data availability. The ICON model outputs used in this study are stored at the German Climate Computing Center (DKRZ) and are available upon request to the corresponding author.

Author contributions. SM conceived the study, developed the methodology, performed the model simulations, carried out the data analysis,
665 and wrote the manuscript. SM also conducted the ICON model setup and technical implementations. JQ supervised the project and provided scientific guidance throughout, contributing to the interpretation of the results and manuscript development. SME contributed through discussions and feedback during the study. All authors reviewed and edited the final manuscript. This work forms part of SM's doctoral dissertation.

Competing interests. J. Quaas serves on the editorial board of *Atmospheric Chemistry and Physics*. The authors declare that they have no
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