

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 ~~1561~~154 m. Eight distinct ice-cloud scenarios are simulated as control runs, each initialized with realistic meteorological forcing.

5 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
10 the temporal 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~~relying solely on persistent-contrail threshold criteria is insufficient, as the time-varying background
15 conditions strongly influence how far contrails grow and develop.

1

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).

20 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 (Burkhardt and Kärcher, 2011; Schumann and Heymsfield, 2017). 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~~ In merged contrails, competition among ice crystals for the available humidity limits their growth, yielding

less total extinction ~~compared to individual contrails due to competition for available humidity~~ than in individual contrails (Singh et al., 2024). 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 ([Krämer et al., 2016, 2017](#)), which provide comprehensive overviews of cirrus microphysical characteristics, climatologies, and radiative effects. Notably, research by Immler et al. (2008) found that cirrus clouds were present 55% of the time in their measurements, while [Sun et al. \(2024\)](#) reported an occurrence frequency of approximately 48% in the tropical Western Pacific, 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., 2022a; 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.

95 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
100 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
105 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.

110 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
115 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 that of Gryspeerdt et al. (2024), have also linked satellite data successfully integrated satellite imagery with air traffic ~~records~~ data to identify contrails, ~~using~~ employing convolutional neural networks to detect their characteristic linear cloud features.
120 ~~However~~ Despite these advances, tracking contrails beyond their ~~early-initial~~ early-initial stages remains a ~~significant-major~~ significant-major challenge. As contrails evolve and age, they gradually lose their distinct linear structure, ~~making it difficult to distinguish them becoming increasingly difficult to differentiate~~ from natural cirrus clouds and ~~to fully evaluate the extent of anthropogenic cloud modification hindering a comprehensive evaluation of anthropogenic influences on cloud properties.~~

~~Despite recent advancements,~~ To complement these observational efforts and address the challenges in tracking aged contrails,
125 modeling studies have offered valuable insights into their dynamics, yet significant gaps remain in understanding the spreading and aging stages ~~of contrails~~ under varying weather conditions (Kärcher, 2018). While prior ~~studies have established the~~

research has explored the initial dynamics of contrail formation in ~~different diverse~~ 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 as they interact with and become indistinguishable from~~ natural cloud systems.

This Building on these foundations, this study addresses these gaps by ~~investigating employing high-resolution Large-Eddy Simulations (LES) to investigate~~ the evolution of young contrails from the post-vortex phase ~~to about 3–4 up to approximately 3~~ hours after formation, with a ~~particular focus special emphasis~~ on persistent contrails embedded within natural ice clouds. ~~Using Large-Eddy Simulation (LES) Operating in weather forecasting mode~~ with a horizontal resolution of 154 meters ~~in weather forecasting mode, we~~, our simulations incorporate realistic synoptic forcing to ~~simulate model~~ contrail development under representative atmospheric conditions. ~~By initializing identical ice crystal concentrations corresponding to a narrow, line-shaped post-vortex contrail, we isolate how background cloud conditions influence its subsequent growth, persistence, and radiative effects.~~

2 Methodology

This section ~~outlines describes~~ 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 used to simulate persistent contrails embedded in cloudy, ice-supersaturated regions, including the ICON setup, case selection, contrail initialization, and flight-path design.~~

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 and supports~~ applications from global climate simulations (Giorgetta et al., 2018) to high-resolution large-eddy simulations (Heinze et al., 2017). For this 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, allowing the simulation of 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 ~~156–154~~ meters, utilizing the R2B14 triangular grid. Vertically, the ~~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~~ model uses a stretched, height-based, terrain-following coordinate system, with finer resolution near

the surface that gradually coarsens with altitude, with the model top located at 22 km. To better resolve upper-tropospheric ice cloud dynamics, we configure 160 vertical levels, yielding an average spacing of 137 m across the full column and roughly 150 meters at our focus altitude in the upper troposphere, enhancing our model's ability to accurately capture upper atmospheric dynamics within the 8–12 km altitude range, corresponding to typical commercial flight levels. This configuration provides sufficient detail to capture upper-atmospheric processes while remaining computationally efficient.

The ICON model incorporates a comprehensive Microphysics follow the double-moment microphysical scheme scheme of Seifert and Beheng (2006) for cloud liquid and ice by Seifert and Beheng (2006). This scheme facilitates detailed simulation of microphysical processes across liquid, mixed-phase, and ice-phase clouds. It predicts, predicting both mass mixing ratios and number concentrations for six types of hydrometeors: hydrometeor categories (cloud droplets, rain, ice, hail, snow, and graupel. Utilizing fine-resolution). At fine grid scales, the model is configured to resolve both resolves deep and shallow convection, eliminating the need for separate parameterizations so no separate convective parameterization is used. Instead of using the default diagnostic cloud cover scheme, a straightforward all-or-nothing scheme is employed, where PDF-based cloud-cover scheme intended for coarser configurations, we use a binary scheme in which the cloud fraction within a grid box is set to either 1 or 0. This approach simplifies the treatment of cloud cover, disregarding subgrid variability of total water content when resolved hydrometeors are present and 0 otherwise—standard practice when clouds are explicitly resolved at grid scale. Homogeneous and heterogeneous ice nucleation processes are parameterized following the methodologies of Kärcher et al. (2006) and Phillips et al. (2008). The model explicitly accounts for the represents competition between heterogeneous and homogeneous ice nucleation. Homogeneous nucleation is primarily dependent nucleation: homogeneous nucleation depends primarily 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, and the reduction of supersaturation by heterogeneously formed ice crystals is implemented as an effective reduction of the updraft velocity. This results in fewer homogeneously nucleated particles forming, which in turn lowers homogeneous nucleation rates (Kärcher et al., 2006).

This ice nucleation configuration is the default for ICON-LEM and has been successfully applied and evaluated in previous high-resolution LES studies using comparable setups, including simulations at 625, 312, and 156 m resolutions over Germany that captured small to mesoscale variability in clouds and precipitation (Heinze et al., 2017). Additional studies have shown that the scheme adapts well to short time steps, with nucleation effectively captured through supersaturation adjustments applied at each model time step, without the need for substepping (Schemann and Ebell, 2020; Verma and Burkhardt, 2022).

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 km. Second, we perform a high-resolution ICON-LEM, initialized directly from the output of the finest nest (1.25 km resolution) obtained in the previous kilometer-scale simulation. The ICON-LEM was configured to operate at a high spatial resolution of 156 meters, using a horizontal grid spacing of 154 m (R2B14), a two-second time step and hourly boundary condition, and hourly boundary condition updates. This second run constitutes our main, high-resolution simulation of contrail evolution.

This two-stage approach ensures a smooth transition to higher resolution, effectively minimizing large-scale discrepancies between the boundary and the main domain, while also reducing initialization and reduces spin-up 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 domains for a representative case, highlighting including the spatial coverage and nested-resolution approach employed in this study. This the nested-resolution strategy. The initial extensive domain coverage ensures the accurate representation of up to 40° longitude by 24° latitude in the coarsest nest—helps ensure that atmospheric and synoptic-scale conditions are well represented, which is essential for a more realistic cloud dynamics analyses simulation.

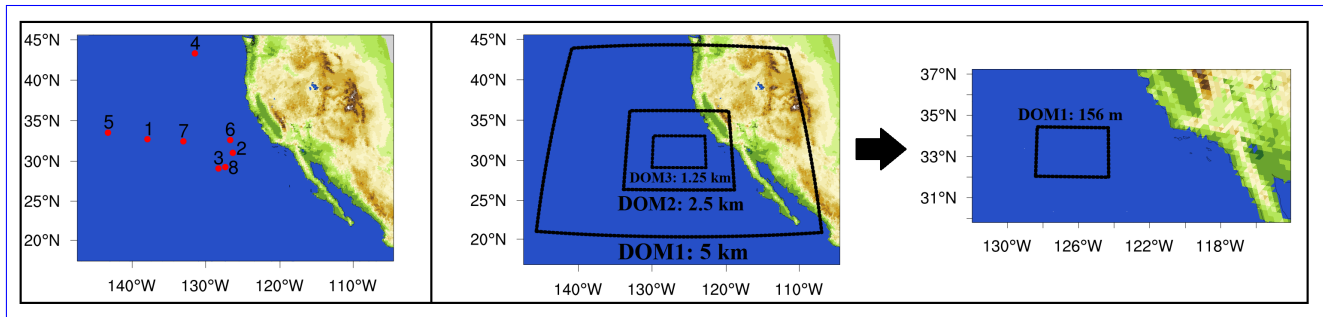


Figure 1. Left panel: Geographic center locations of the LES simulation domains for the eight contrail cases, spanning the midlatitude Pacific Ocean off the west coast of the United States. Numbers indicate the case identifiers (1–8), corresponding to the simulations analyzed in this study. Middle panel: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

2.3 Simulation Case Selection and Background Conditions

215 We conduct eight high-resolution LES simulations with ICON-LEM, each representing a distinct real-world scenario within the midlatitude Pacific Ocean between the U.S. west coast and Hawaii, with domain centers shown in Figure 1. The cases are selected from the satellite-based catalog of Marjani et al. (2022), which identified contrail-induced modifications to cirrus clouds using combined radar–lidar retrievals of ice crystal number concentrations along aircraft tracks intersecting thin cirrus. From this catalog, we selected events with extensive upper-tropospheric cloud cover and ice-supersaturated conditions favorable for persistent contrail formation. Together, the eight cases capture a representative range of background variability, enabling the study of contrail–cirrus interactions in non-idealized environments subject to realistic synoptic forcing. Key setup parameters for each simulation are listed in Table 1.

220 For each case, a control run of the natural cloudy background is paired with a perturbation run that is identical except for contrail initialization along a prescribed flight path (Section 2.5). The control simulations provide a baseline for quantifying contrail-induced changes and for characterizing the inherent variability of the background atmosphere.

225 Background weather characteristics are shown in Figure 2 as time series of median values for four parameters: (a) excess water vapor above ice saturation; (b) depth of ice-supersaturated layers (ISS) below flight altitude; (c) relative humidity over ice (RH_{ice}); and (d) vertical velocity. Notable trends and case-specific features derived from these time series, together with vertical cross-sections of ice water content (IWC) in Appendix A1, are summarized in Table 2 to facilitate comparison among cases.

Table 1. Summary of the simulation cases: simulation dates; domain centers; flight altitude, and background conditions at flight level—temperature, pressure, and static stability (Brunt–Väisälä frequency, N_{BV}).

	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, Lon)	34.4, -139.6	33.4, -126.4	31.4, -128.5	45.9, -133.4	34.4, -146.0	35.0, -126.8	34.6, -134.0	31.6, -127.5
Flight Height (m)	12 138	11 801	10 664	10 664	10 664	10 664	10 664	11 143
Temperature (K)	211	211	222	221	223	220	220	219
Pressure (hPa)	200	209	250	246	257	249	244	237
N_{BV} (10^{-3} s^{-1})	2.9	1.9	2.3	2.5	1.8	3.3	2.2	0.8

2.4 Contrail Formation and Initialization in ICON

230 We use the Schmidt–Appleman Criterion (SAC; Schumann 1996) to determine whether aircraft exhaust mixes and assess whether the mixing of aircraft exhaust with ambient air and exceeds the threshold for visible contrail formation. For persistent contrails, ambient conditions must also be at or above ice saturation. Additional details, ensuring that the ice crystals do not sublime

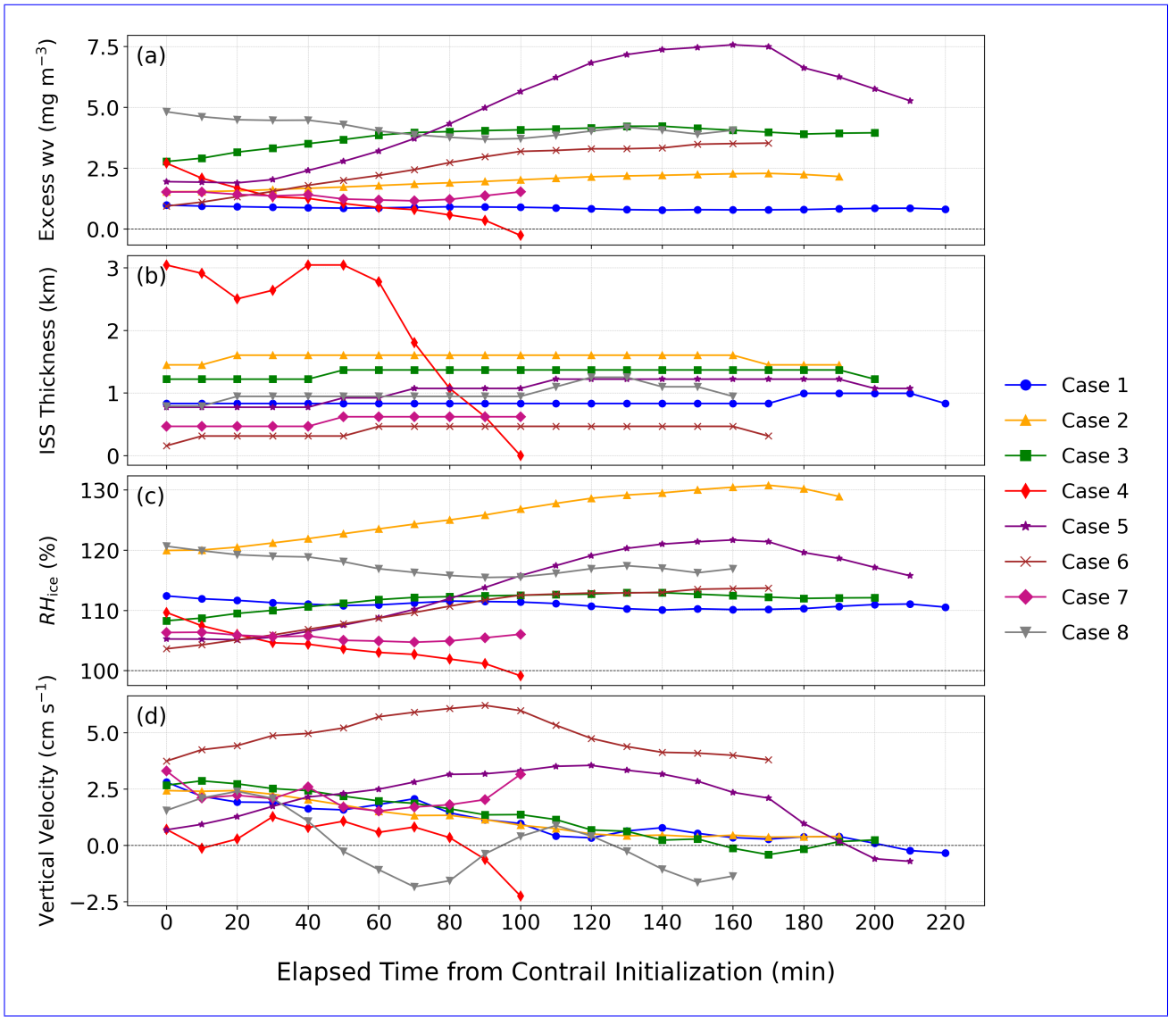


Figure 2. Time series of background atmospheric parameters from control simulations for the eight selected cases: (a) excess water vapor above ice saturation, (b) depth of ice-supersaturated layers (ISS) below flight altitude, (c) relative humidity over ice (RH_{ice}), and (d) vertical velocity. Cases were chosen following Marjani et al. (2022) to sample diverse cirrus environments favorable for persistent contrail formation. Values shown are median statistics over the analysis region at each time step. Conditions vary spatially and temporally in these non-idealized environments, influencing contrail development.

after formation. Further details on the SAC, including a schematic illustration of the of mixing lines, can be found are provided in Appendix B, providing further background on the Schmidt–Appleman Criterion.

Table 2. Overview of the eight cloudy background simulation cases, including key atmospheric conditions relevant for contrail persistence. Cases were selected from Marjani et al. (2022) based on the presence of sufficient upper-tropospheric cloud coverage in ice-supersaturated regions.

Case	Key Background Conditions
1	Characterized by Low excess water vapor; gradually weakening updraft; low background IWC ($\sim 0.1\text{--}1\text{ mg m}^{-3}$) at high altitude, consistent with thin in-situ cirrus.
2	Low initial excess water vapor with sustained moisture supply; moderate ISS thickness; very high RH_{ice} ($> 120\%$); gradually weakening updraft; low to moderate background IWC ($\sim 0.1\text{--}2.4\text{ mg m}^{-3}$).
3	Moderate initial excess water vapor increasing gradually; moderate ISS thickness; moderate ice supersaturation; updraft weakening to minor downdraft; moderate background IWC ($\sim 0.1\text{--}2.6\text{ mg m}^{-3}$).
4	Moderate excess water vapor decreasing to near zero; very thick ISS thickness ($\sim 3\text{ km}$) with weak supersaturation; high background IWC (more than 10 mg m^{-3}) resembling liquid-origin ice clouds.
5	Moderate initial excess water vapor with steady moisture supply (from 2 to above 7 mg m^{-3}); moderate ISS thickness below flight level; low initial RH_{ice} with steady increase; moderate and consistently strengthening updraft; moderate background IWC ($\sim 0.1\text{--}2.5\text{ mg m}^{-3}$).
6	Low initial excess water vapor with gradual moisture increase; very limited ISS thickness beneath the flight altitude; steady positive median updraft ($> 4\text{ cm s}^{-1}$).
7	Low excess water vapor; very thin ISSR beneath flight altitude; weak background IWC ($\sim 0.1\text{ mg m}^{-3}$).
8	Highest initial excess water vapor ($\sim 5\text{ mg m}^{-3}$); very low stability.

For convenience, we display in The critical temperature, i.e., the maximum ambient temperature at which contrail formation becomes thermodynamically possible, is computed using the following parameters: water vapor emission index $M_w = 1.25\text{ kg}_{wv}\text{ kg}_{fuel}^{-1}$, specific heat capacity of air $c_p = 1005\text{ J kg}^{-1}\text{ K}^{-1}$, combustion heat $Q = 43.2\text{ MJ kg}_{fuel}^{-1}$, and propulsion efficiency $\eta = 0.3$. These values are used in the standard SAC formulation, in which the slope of the mixing line (G) is given by

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

with P_a denoting the ambient pressure. These parameter choices follow previous contrail modeling studies (Kärcher et al., 2015; Bock and

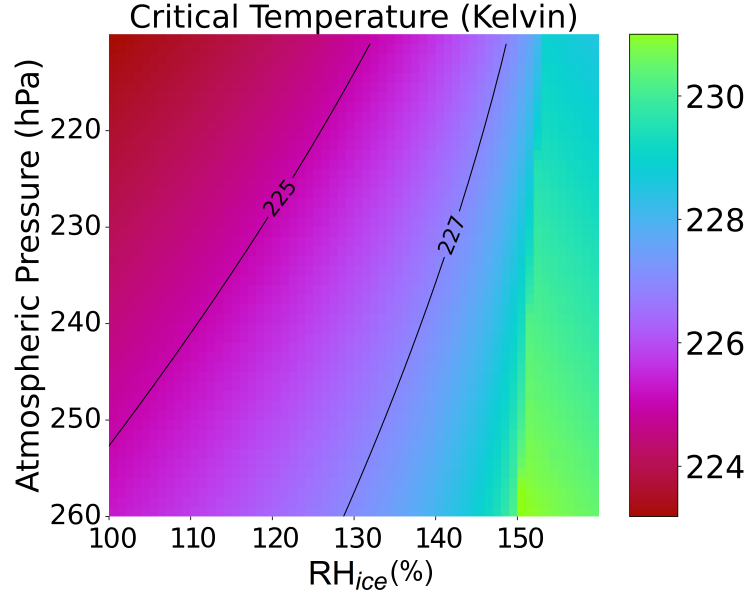


Figure 3. Heatmap showing the critical temperature (K) for contrail formation as a function of relative humidity w.r.t with respect to ice (%) and atmospheric pressure (hPa). The calculation assumes a water vapor emission index of $M_w = 1.25 \text{ kg}_{\text{wv}} \text{ kg}_{\text{fuel}}^{-1}$, specific heat capacity of air $c_p = 1005 \text{ J kg}^{-1} \text{ K}^{-1}$, combustion heat $Q = 43.2 \text{ MJ kg}_{\text{fuel}}^{-1}$, and propulsion efficiency $\eta = 0.3$.

Figure 3 the resultant shows the 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 over ice using the above parameters. For a given pressure, higher relative humidity corresponds to a higher temperature threshold for contrail formation. Conversely, at increases the threshold, while for a fixed relative humidity, lower atmospheric pressure (i.e., pressure (higher altitude) reduces the contrail formation temperature critical temperature.

2.5 Contrail Initialization in ICON Grid

In this study, contrails are initialized at a stage that corresponds to approximately 450 seconds of age, marking the In ICON, these formation criteria are evaluated along the simulated flight paths to initialize contrails. We consider the B767 and A300 as representative aircraft, with a wingspan of roughly 50 m and a water vapor emission of about 7.26 g per meter of flight (Unterstrasser, 2016). Each grid box along the flight path is evaluated against the SAC temperature threshold and ice saturation condition: if both are met, water vapor emissions are introduced as ice mass with a corresponding ice crystal number concentration; otherwise, they are introduced as water vapor. Initialization is applied within a single model time step, after which contrails interact with the environment and evolve further, both responding to and modifying the surrounding atmosphere.

Contrails are initialized under the assumption that they have already entered the post-vortex phase, approximately 450 s after formation, when atmospheric conditions begin to play a dominant role in their evolution (Bier and Burkhardt, 2022). They

are assigned to dominate their development (Bier and Burkhardt, 2022). Each contrail is prescribed 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.

260 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 (about $154 \times 150\text{ m}^2$). This choice follows Bier and Burkhardt (2022), who incorporated parameterizations for contrail nucleation (Kärcher et al., 2015) and vortex-phase crystal loss (Unterstrasser, 2016) in the contrail-cirrus scheme CCMod of the climate model ECHAM5. For the U.S. west coast—our focal region—they report annual-mean contrail number
265 concentrations consistent with our adopted value, equivalent to a soot number emission of $1.5 \times 10^{15}\text{ kg}^{-1}$, representative of present-day conditions.

This initialization is further supported by earlier work. Bock and Burkhardt (2016b) applied the same fixed number concentration for contrail-cirrus simulations based on European observations, while in situ aircraft measurements (Schröder et al., 2000; Febvre et al., 2009) report similar magnitudes for young post-vortex phase, as reported by Schröder et al. (2000), Febvre et al. (2009), and Voigt et al. (2011).
270 , further supports this choice. Similarly, Unterstrasser et al. (2017) examined contrail-cirrus evolution using a Large Eddy Simulation model with a Lagrangian ice microphysics module contrails. Unterstrasser et al. (2017) simulated contrail-cirrus in an idealized environment. Their simulations initialized all large-eddy model, initializing contrails at five minutes of age ; with an average ice crystal concentration of about with average concentrations of 20 cm^{-3} and local concentrations reaching 200 cm^{-3} and local maxima up to 200 cm^{-3} . The contrails were 500 m deep and 200 m wide, ensuring a consistent starting perturbation 500 m wide.
275

Additionally, Bier and Burkhardt (2022) incorporated parameterizations for contrail ice nucleation (Kärcher et al., 2015) 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
280 category is used within the two-moment bulk microphysics scheme (Seifert and Beheng, 2006). At $\sim 150\text{ cm}^{-3}$ 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. In the present study, a single ice category is used within the two-moment bulk microphysics scheme (Seifert and Beheng, 2006). At $\sim 150\text{ cm}^{-3}$ 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. In the present study, a single ice
285 post-vortex stage—our focal region when contrail and natural ice evolve through similar growth, evaporation, sedimentation, and mixing processes—and reflects the atmospheric conditions of the area, as outlined in their global distribution of annual mean contrail ice crystal number concentrations and contrail cross-sectional areas. this simplification is considered acceptable for our purposes.

In our model, water vapor emissions equivalent to the aircraft's fuel burn are introduced along the flight path as either water
290 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 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
295 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. This initialization occurs within a single time step, after which the contrail interacts with the surrounding environment and undergoes further evolution. Table 1 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. Using a single ice
300 category may introduce biases, particularly once contrail and natural ice begin to mix within the same grid cell. This effect is resolution-dependent: coarser grids enhance numerical blending, whereas finer grids reduce it. Future sensitivity studies using both finer and coarser resolutions would help quantify the influence of grid spacing on these mixing-related effects.

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
305 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
310 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).

Having designed all eight perturbation cases to initialize contrails within cloudy, ice-supersaturated regions colder than the critical temperature for contrail formation, we now compare their subsequent evolution under differing background conditions to identify the key factors governing persistent-contrail growth.

Figure 4 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-ice~~ supersaturated 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
320 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 According to the Schmidt–Appleman Criterion, contrail formation requires plume saturation with respect to liquid water, which can occur even when the ambient

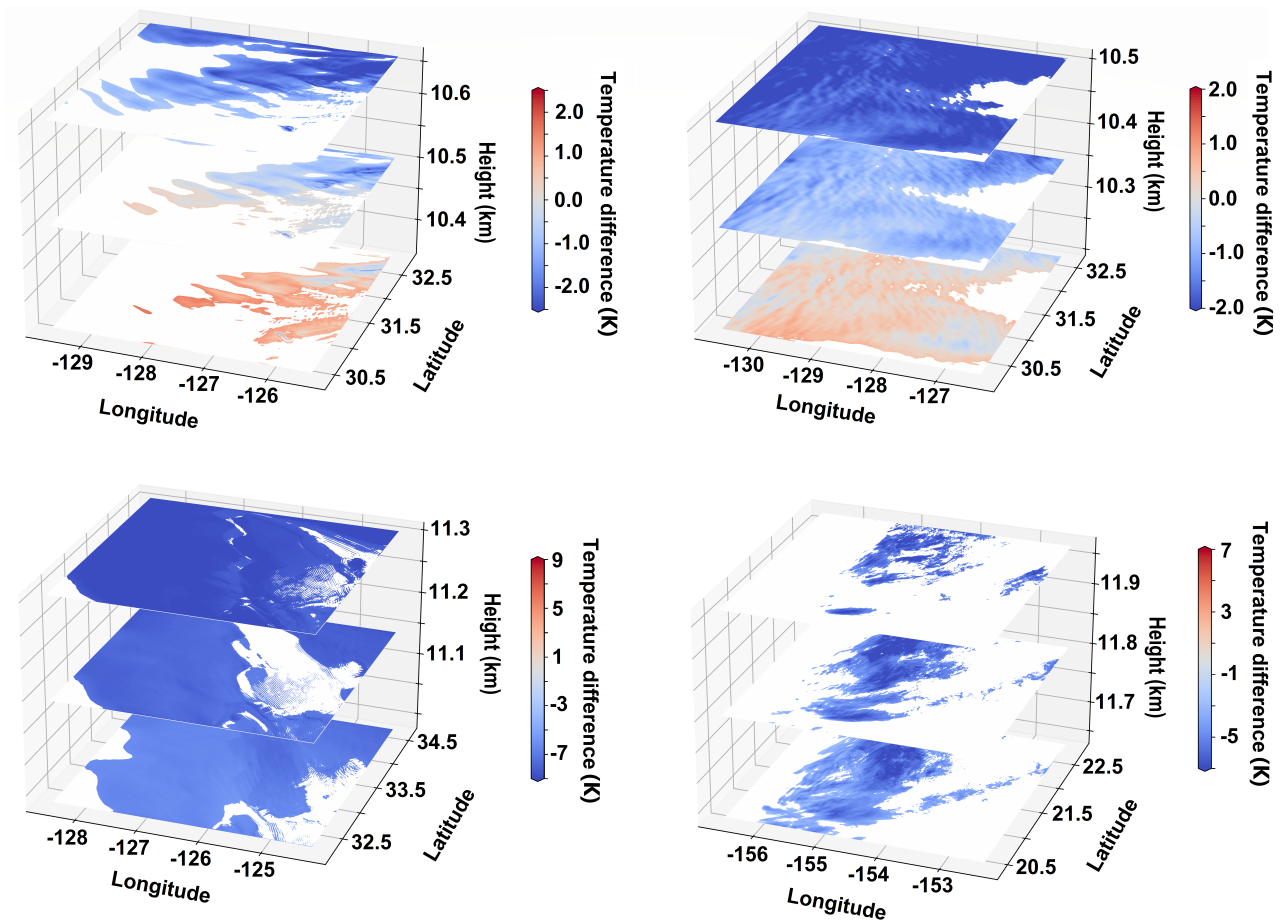


Figure 4. Temperature difference from the contrail formation threshold within ~~saturated-ice-supersaturated~~ regions for four representative simulations. These examples illustrate the variability of conditions favorable for persistent contrail formation at three consecutive height levels and were used to guide contrail initialization in the perturbation runs. Please note the differing values in the color bar.

325 ~~atmosphere is subsaturated with respect to ice. However, for contrails to become persistent—our primary focus due to its~~
~~significant climate impact—relies on ice supersaturation . Persistent contrails commonly develop in regions their climate~~
~~relevance—ambient ice supersaturation is additionally required to sustain contrail’s growth. This requirement aligns persistent~~
~~contrails with environments~~ favorable for natural cirrus ~~cloud formation development~~, where they can either contribute to ~~cloud~~
~~development (Teschke et al., 2016; Marjani et al., 2022) or disrupt existing cloud processes additional cloudiness (Teschke et al., 2016; Marja~~
330 ~~or modify existing clouds~~ (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 such as~~ temperature, humidity, and background cloud properties. Their persistence and spreading depend on environmental interactions ~~, shaping their and their temporal evolution,~~
335 ~~which together shape both~~ microphysics and radiative effects. To explore this, we first examine key characteristics of the simulated contrails in ~~Ice-Supersaturation-Regions-ice~~ ice supersaturation regions (ISSRs). Figure 5 ~~presents~~ shows ice crystal number concentration (N_i) snapshots for four different cases at various stages of contrail development at flight altitude. ~~Initially, in younger~~ At early 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~~ vary. In all
340 cases, the highest N_i remains concentrated in the core ~~at each time step, while N_i gradually decreases,~~ while values gradually decrease 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-hour-of age~~ after two hours.

The ~~differences in how these~~ spreading of initially linear contrails ~~spread over time are~~ is primarily driven by variations in horizontal wind shear—changes in wind speed and direction across the contrail—as well as atmospheric turbulence. ~~When~~
345 ~~wind shear is strong, the contrail stretches, becomes~~ Strong shear stretches contrails into wavy, or ~~develops~~ filament-like structures, ~~as different segments experience varying wind forces. In contrast, when shear is weak, the contrail retains~~ while
weak shear preserves a more uniform ~~, linear~~ shape. Additionally, ~~atmospheric turbulence plays a role in disrupting turbulence~~ disrupts 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~~
350 ~~spreading pattern. In highly turbulent conditions, the contrail may appear more~~ specially at the edges where contrail ice crystals interact with surrounding clouds, producing irregular dispersion. Under strong turbulence contrails appear fragmented, whereas in ~~calmer conditions, it maintains a more coherent structure over time~~ calm conditions they remain more coherent. The evolution of simulated contrail ice crystal concentration for all eight cases is available as animations at the original model grid resolution ~~. The link to these animations are provided in~~ (Appendix Video A1).

355 3.2 Contrail-Induced Changes in Relative Humidity within Ice Supersaturation Regions

~~Although relative~~ Relative humidity over ice (RH_{ice}) is a thermodynamic ~~atmospheric parameter~~ state variable rather than a direct contrail ~~variable-like property such as N_i , it is still influenced by contrail processes over short timescales~~ yet it can be
substantially perturbed within contrail-affected regions. Figure 6 shows the RH_{ice} across multiple simulations, where the linear structure of contrails is clearly distinguishable, leaving a visible fingerprint within the atmospheric background.
360 A common feature across all cases is that contrail regions stand out distinctly, exhibiting RH_{ice} values near 100% (Naiman et al., 2011; Un). This near-saturation condition is ~~especially prominent~~ particularly evident 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 the exceptionally high number concentration of small ice crystals effectively reduce humidity to

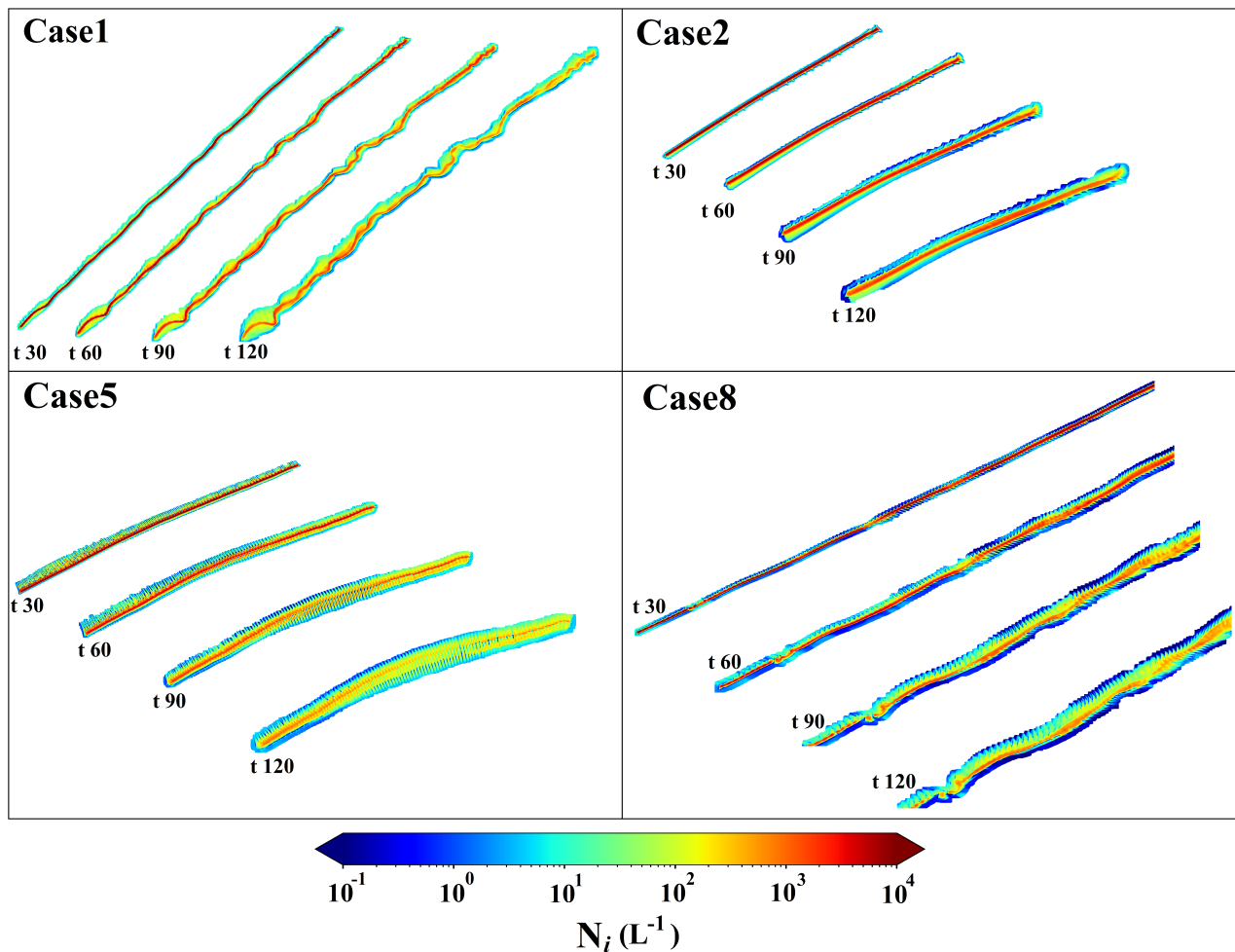


Figure 5. Horizontal spatial distribution of contrail ice crystal number concentration (N_i) at flight altitude for four selected cases, shown at 30, 60, 90, and 120 minutes after contrail initialization.

saturation. Their high ~~—with their large~~ 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.

~~—rapidly depletes atmospheric supersaturation in the core.~~ 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~~ ~~tends~~ ~~to fall~~ below saturation. This drop in humidity leads to the in situ loss of smaller ice crystals due to sublimation.

Another feature ~~, albeit apparent in our simulations, though spatially~~ 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 turbulence and mixing across the sharp gradient in~~ ice crystal concentration ~~of between~~ the contrail and the ~~comparatively~~
375 ~~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~~
380 ~~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.~~

surrounding natural cloud. Figure 7 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~~
385 ~~ISSRs. In contrast, within the contrail core, ice crystals remain very small, even.~~ The exact contrail width is case-specific, but the consistently much smaller crystal sizes in the contrail core compared to the surrounding cloud reflect a typical pattern in our simulations. Inside core, crystals remain mainly very small ($< 5 \mu m$) even after 90 ~~minutes after contrail initialization.~~

~~This extremely small effective radius in the contrail core is a defining characteristic, driven by the initially very~~ minutes of evolution, reflecting the initially high number concentration ~~of small ice crystals. This high concentration rapidly depletes~~
390 ~~initial that rapidly consumes~~ available water vapor ~~, ultimately limiting the potential for further crystal growth as the contrail ages and limits subsequent growth. This persistence of small crystals is another defining feature of contrails, shown in different observational studies (Voigt et al., 2010; Wang et al., 2022b). At the contrail edges, transient peaks of much larger crystals occasionally appear in our simulations, likely related to the elevated RH_{ice} in these regions (see Figure 6). Although sedimentation rates were not explicitly analyzed in this study, the occurrence of such large edge crystals suggests enhanced local sedimentation~~
395 ~~with possible implications for contrail evolution.~~

~~While our model captures the common~~ these simulations reproduce the key characteristics of linear contrails in ISSRs, ~~including contrail morphology, turbulence—namely smaller ice crystals relative to the surrounding natural cloud and a reduction in relative humidity toward saturation within the contrail core—detailed aspects such as contrail morphology, turbulence-induced effects, and small-scale variations during expansion, these aspects~~ mixing during expansion are not the
400 ~~primary~~ focus of this study. Instead, the following sections take a broader perspective, ~~analyzing how contrail evolution in ISSRs influences ice crystal number concentration (investigating how identical ice-crystal perturbations evolve under different atmospheric conditions, and how the evolution of N_i) and ice water content (IWC) under varying atmospheric weather conditions. The goal and IWC proceeds within the contrail. The objective~~ is to identify ~~key factors governing persistent contrail~~ the key environmental factors governing persistent contrail development in cloudy, ice-supersaturated regions.

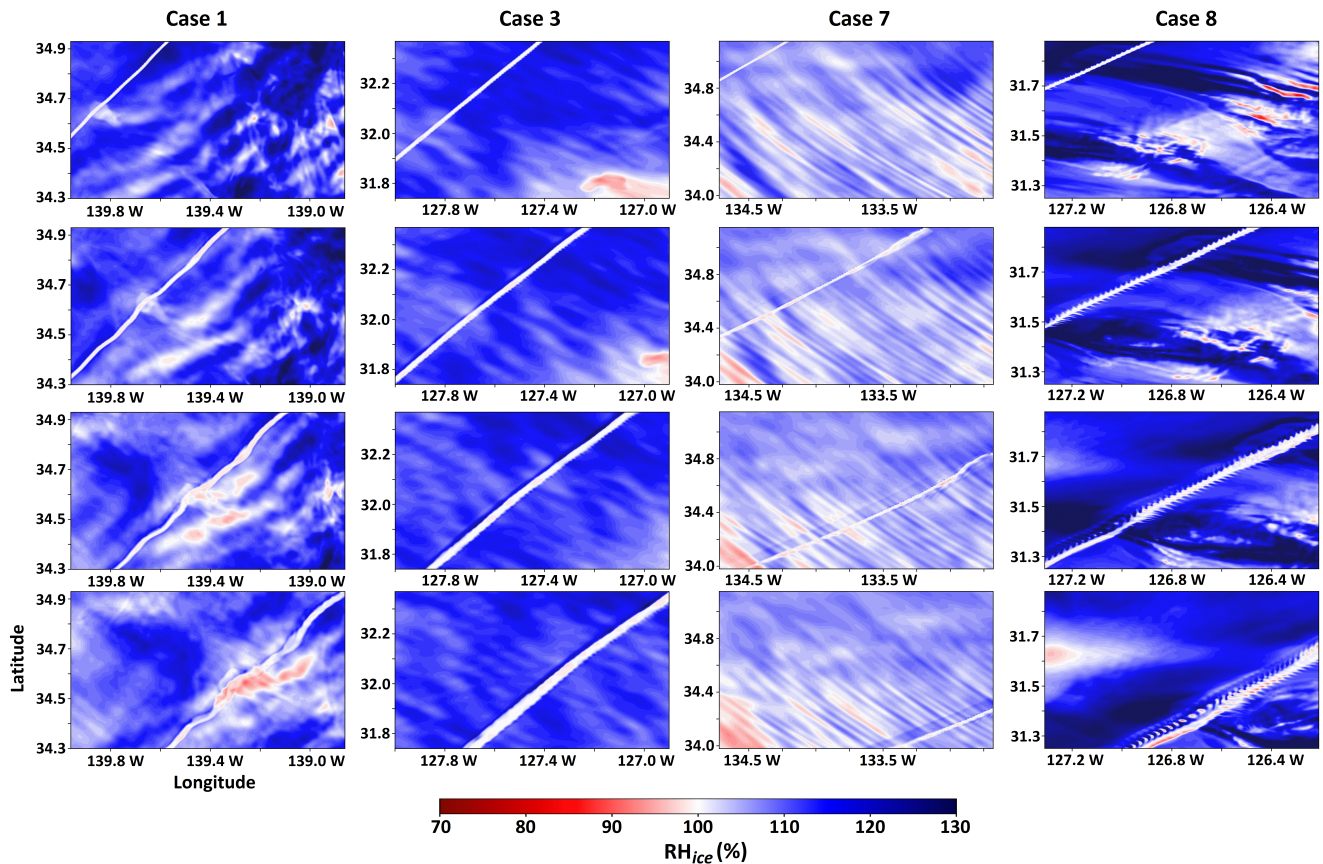


Figure 6. Horizontal spatial distribution of relative humidity with respect to ice (RH_{ice}) at flight altitude in cloudy ice-supersaturated background regions across multiple simulations (Cases 1, 3, 7, and 8 from left to right). The snapshots represent different contrail ages (10, 30, 50, and 70 minutes 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.

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

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

This section examines the temporal evolution of contrails across eight ~~different simulations~~, ~~comparing the simulations~~
by comparing perturbation runs (with contrails) to ~~the~~-control runs (~~natural cloudy background~~-cloudy background without

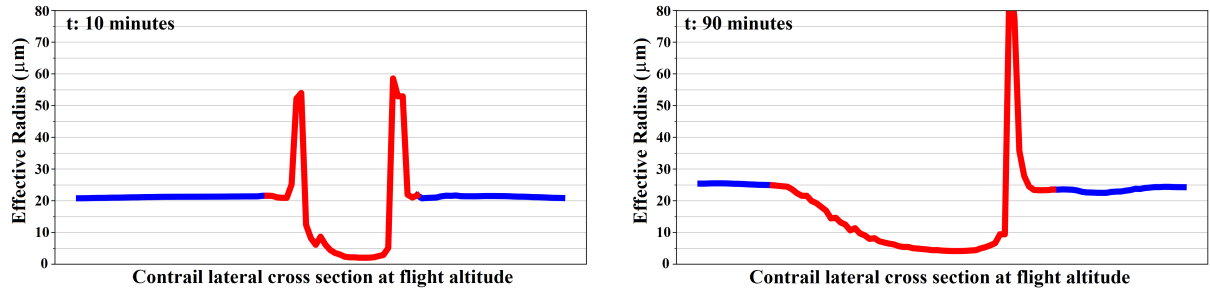


Figure 7. Lateral cross-section of the ice crystal effective radius at flight altitude. These samples illustrate a general pattern observed in our simulations; however, this structure is not uniformly present along the entire contrail flight track. The red curve represents the contrail region, while the blue curve corresponds to the surrounding cloudy background.

contrails). The duration of each simulation varies, as contrails exit the domain at different times depends on when the contrail exits the domain.

415 As will be shown in Figures 8 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 5). In these figures, the 10 show Time-Height plots of perturbation-control differences in the contrail region. The x-axis represents the indicates elapsed time since contrail initialization, while initialization, and the y-axis indicates vertical model level differences relative to the original contrail height. The zero height level corresponds to flight altitude shows model levels relative to flight altitude (labeled as zero), with positive

420 values indicating levels below it. Each grid cell displays the anomaly of the average represents the horizontally averaged anomaly (perturbation minus control) at a given time step and height level. However, horizontal variability is not captured, as and height. Because 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.

This approach enables the analysis of contrail extent, horizontal variability is not equal between the cases. This framework

425 highlights contrail-induced atmospheric modifications, providing insights into their vertical growth and allows us to assess their vertical development and temporal evolution. By doing so, we aim to identify key factors influencing contrail development under varying atmospheric conditions within, thereby identifying the key factors controlling contrail growth in ISSRs.

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

Ice crystal number concentration (N_i) anomaly (perturbation minus control) is shown in Figure 8. At flight altitude in Case 1,

430 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} .

435 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
440 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
445 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
450 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~~.
455 ~~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, constrained crystal growth as the contrails spread downward. In contrast, in all other cases the N_i anomaly extends well below the saturated layer, reinforcing indicating that contrail ice crystals had more opportunity to grow while sedimenting in saturated air. As a result, by~~ By the time they reached the subsaturated layer, ~~they were large enough these larger crystals were able~~ to persist, enabling the contrail to develop beyond the saturated region, as evident in Cases 1,
460 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 5, 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~~ The vertical development of Case 7 is ~~relatively larger than that of somewhat larger than in~~ Case 6, with N_i contours decreasing more gradually and without ~~a sharp reduction upon entering the sharp reduction~~

470 ~~observed when Case 6 enters~~ the subsaturated region. This ~~difference is likely due to the rate at which relative humidity drops contrast~~ reflects differences in how relative humidity falls below the saturation ~~threshold—gradual threshold—gradual~~ in Case 7 but ~~sharp and~~ abrupt in Case 6. Observational studies, such as Li et al. (2022), ~~show have shown~~ that contrail cirrus can persist in slightly ice-subsaturated air, rather than being ~~limited to exclusively ice-saturated~~ ~~restricted to strictly saturated~~ or supersaturated conditions. ~~Regarding contrail persistence in slightly subsaturated air~~ Consistent with this, the 80% relative
 475 humidity contours in Case 1 ~~exhibit a more gradual decline decline only slowly~~ after 100 minutes. ~~This indicates that the,~~ indicating a much more gradual 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 is mirrored~~ in the N_i anomaly patterns, particularly in the 30 and 10 L^{-1} contours. ~~This further reinforces the idea,~~ reinforcing that the rate ~~at which relative humidity decreases of humidity decline~~ in subsaturated air ~~plays a crucial role in contrail development and contrail~~ strongly influences
 480 contrail growth and 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~~ ways:

(1) A thicker supersaturated layer ~~allows provides~~ sedimenting ice crystals ~~to grow further in fresh supersaturated air with additional supersaturated air for continued growth~~, and (2) A deeper supersaturated layer ~~enables allows~~ ice crystals to ~~grow~~
 485 become large enough to ~~persist survive~~ in slightly subsaturated air, ~~allowing contrail extension well enabling contrail extension~~ beyond the saturation layer.

Contrail Evolution and Ice Crystal Survival in a Deep Supersaturated Layer

The ~~relative humidity contours in the control run for Case 4 indicate that the atmosphere remains near saturation across a considerable vertical depth reveals a deep layer of near-saturated conditions, as indicated by the relative humidity contours~~
 490 (Figure 8). ~~Looking at the The~~ vertical cross-section of IWC in the background weather condition ~~of this case, relatively high values are evident shows high values extending from lower altitudes upward~~ (Appendix Figure A1). ~~This elevated IWC spans a deep atmospheric layer, extending from lower altitudes upward, suggesting that cloud formation was influenced, consistent with cloud formation driven~~ by strong vertical transport. ~~Later As shown later~~ in this study ~~, we will show that~~ the natural cloud in Case 4 has a strong greenhouse effect ~~, related to a high cloud related to its high~~ optical thickness. These characteristics
 495 ~~suggest the presence of point to~~ 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 Such conditions should, in principle, permit~~ unrestricted vertical extension through fall streak development, ~~as there is no ISS layer thickness restriction. However, since the ISS layer imposes no thickness constraint. Yet~~ the 30 and 10 L^{-1} ~~contours of N_i contours~~ in
 500 Figure 8 show a vertical extent comparable to cases with a ~~more limited thinner~~ supersaturated layer (e.g., Cases 3, 5, and 8), ~~suggesting that other indicating that additional~~ factors may be ~~constraining limiting~~ the contrail's vertical growth.

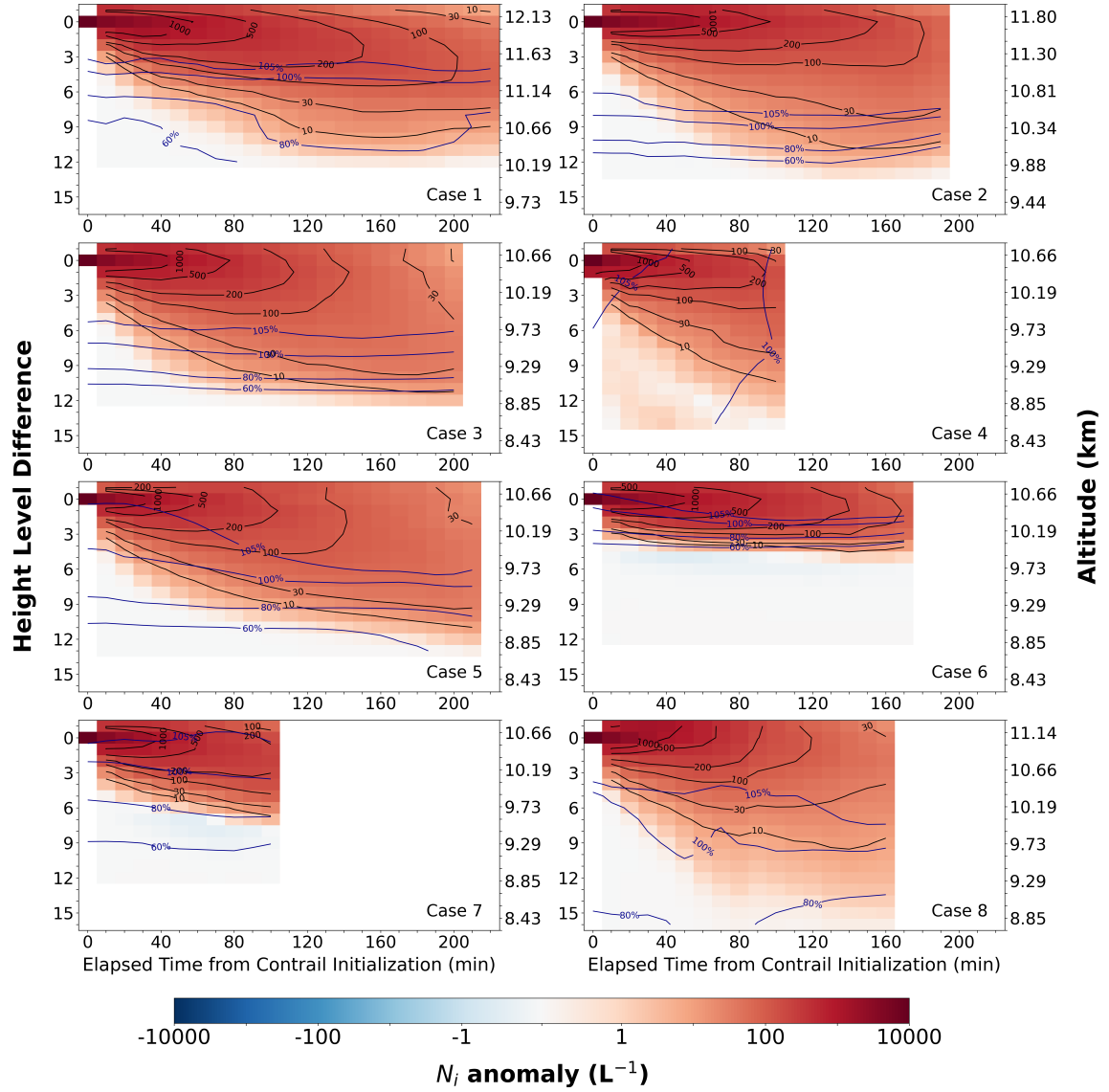


Figure 8. Time–height evolution of contrail ice crystal number concentration (N_i) anomalies for different cases, defined as the difference between the perturbation (contrail) and control (natural cloud) runs over the same region. The x-axis shows time since initialization; the y-axis shows height level 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.

It seems that while ~~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 ~~persistent contrail formation~~, but the mere presence of an ISSR does not determine how far contrails may ultimately grow. The following sections examine additional atmospheric variables that ~~influence contrail development and their subsequent~~ shape contrail growth and their 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~~ The distinguishing feature in this case is a continuous decrease in relative humidity from the beginning of the simulation (blue contours in Figure 8 and panel c in Figure 2). Unlike in cases with higher or sustained humidity, where crystals undergo 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~~ here remain growth-limited from the outset and, without a continuous water vapor supply, a larger fraction sublimate before they can develop further.

Moreover, ~~in this case,~~ part of the contrail was initialized within a fine-scale ~~gravity-wave-induced~~ gravity-wave-induced ice cloud and remained ~~within in~~ the simulation domain for ~~up to about~~ 60 minutes before advecting out (Figure 9). ~~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 Gravity wave dynamics generate small-scale fluctuations and lead to that create localized subsaturated regions. Additionally, these dynamics may limit the contrail's ability to mix and spread freely and restrict mixing~~ 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~~ ISSRs, this inhibited spreading likely enhanced ice crystal sublimation here.

530 Atmospheric Stability and Contrail Ice Crystal vertical Growth

~~In~~ Contrail ice crystals in Case 8, ~~contrail ice crystals exhibit a distinct upward vertical~~ exhibit a pronounced upward development above flight altitude (Figure 8). While some ~~upward vertical~~ extension occurs in all cases, ~~primarily due to turbulent diffusion, vertical due to turbulence,~~ mixing, and wind shear, ~~in this case,~~ the N_i 1000, 500, and 200 L^{-1} contours ~~extend upward more prominently~~ rise more prominently here. As previously ~~discussed~~ noted, young contrails ~~are highly water~~

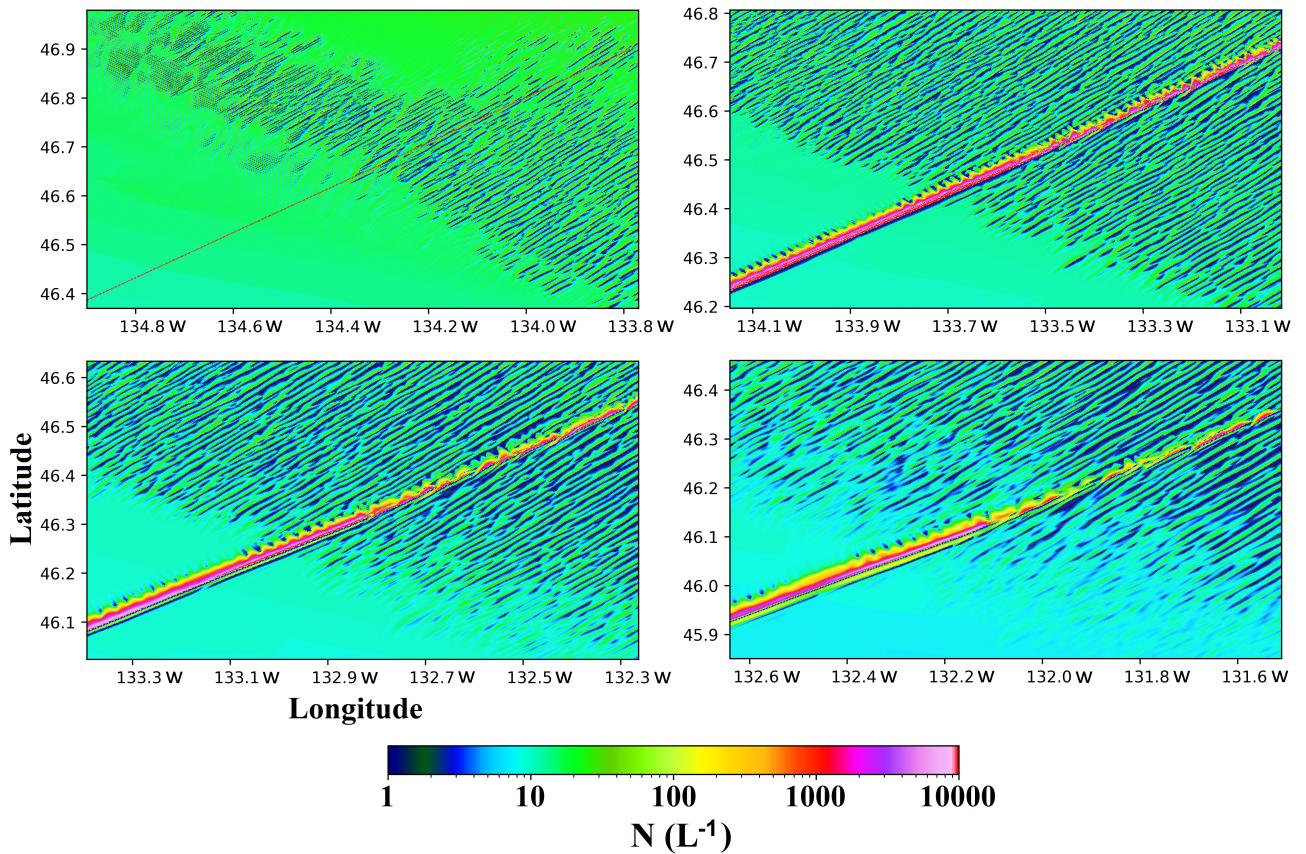


Figure 9. Horizontal spatial distribution of contrail ice crystal number concentration at flight altitude within a thick supersaturated layer in Case 4, alongside the evolution of fine-scale gravity wave-induced ice clouds. The panels correspond to contrail ages of 0, 20, 40, and 60 minutes (from top 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.

535 vapor-thirsty, meaning that their development in ISSRs results in a high rate of deposition. This effect is clearly seen in the map
of act as strong moisture sinks, leading to high deposition rates that are evident in the RH_{ice} shown in fields (Figure 6. However,
high deposition not only reduces relative humidity to near saturation but also). This deposition reduces humidity toward
saturation and releases latent heat, creating a localized producing a small positive temperature anomaly (Appendix A2). As a
540 however, this temperature difference is typically very small—only The resulting temperature increase is minor—typically
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—and its buoyancy effect is likely negligible compared to background wind shear, mixing, turbulence of the surrounding
environment turbulence, and the overall large-scale stability of the upper troposphere.

Time-series of the atmospheric Case 8 shows a distinctly lower Brunt–Väisälä frequency at flight altitude during-in the control run is illustrated in Figure ?? . Case 8 exhibits a distinctly lower frequency compared to the other cases (Table 1), indicating weaker atmospheric stability. In a less stable atmosphere, even a minor temperature perturbation or buoyancy difference can induce a such conditions, even small temperature perturbations from latent heat release can produce relatively large vertical displacement. Since the restoring force is weak, the contrail may ascend due to latent heat release, displacements. 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 therefore suggests that atmospheric stability may influence not only the cross-sectional area of young contrails 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 (Unterstrasser et al., 2017), but also may influence their subsequent vertical expansion as they develop into contrail cirrus.

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.

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.

3.3.2 Contrail induced Ice Water Content anomalies Under Various Weather Conditions

Figure 10 is similar to Figure 8 but displays the anomaly in shows the ice water content (IWC) anomaly—representing the changes that is, the change in IWC within the contrail region compared to the same area in in the perturbation run relative to the corresponding area of the background cloud in the control run. In contrast to N_i , the IWC anomaly increases as the contrail ages. With the exception of The maxima of IWC and N_i anomalies generally do not coincide in space or time, with Case 4 ; the maximum IWC anomaly does not spatially or temporally coincide with as the only exception. In the other simulations, 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 well below flight altitude. This pattern indicates The IWC contours suggest that the thickness of the ice-supersaturated layer beneath the contrail strongly influences both the position controls both the location and magnitude of the peak IWC anomaly this peak, with the maximum anomaly contour located positioned just above the subsaturated layer. These simulations suggest that contrails formed in ISSRs typically reach their In Cases 2, 3, 5, and 8, which have thicker ISS

layers below flight altitude, contrails reach peak IWC anomaly around about 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 altitudes, closer to Even in Cases 6 and 7, where the ISS layer is much thinner, the maximum occurs after roughly 90 minutes. Overall, in contrail cirrus (long-lived contrails), the IWC maximum tends to occur near the base of the supersaturated layer ~~(however, the maximum, while the 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. maximum at that time remains close to 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~~ maximum similar to Case 3 ~~but exhibits a different evolution. The anomaly grows relatively quickly, but with a different development over time.~~ The IWC increases rapidly 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, decelerates.~~ Another distinct feature of this case is its much stronger vertical growth (fall streak) compared to all other cases, despite the ISS layer beneath not being the deepest. Here, the gradual transition between the 100% and 80% RH_{ice} contours plays a key role in sustaining the downward growth of the contrail. This indicates that, beyond ISS thickness beneath flight altitude, the structure of the slightly subsaturated region—especially its depth and the rate of humidity decrease—strongly influences contrail ice growth and the resulting IWC anomaly and facilitates continued descent of the fall streak. Hence, when planning flight management strategies, it is essential to account not only for the vertical structure and thickness of ISSRs beneath flight level, but also for the characteristics of the slightly subsaturated layer below, which influence contrail growth potential. This aligns with the study of Marjani et al. (2022), which investigated contrail impacts within cloudy regions using satellite-based assessments and detected contrail signals a few hundred meters below flight altitude.

~~In contrast, aviation-induced IWC~~ By contrast, several cases exhibited only weak IWC anomalies. Aviation-induced IWC is weakest in Cases 1, 2, and 4. ~~4 (Case 7 was excluded as it quickly moved is omitted from this discussion because the contrail advected out of the simulation domain, limiting its development domain before its development could be analyzed).~~ The control simulations for Cases 1 and 2 (Appendix A3) ~~reveal that both cases also exhibit A1) show~~ very low background IWC, particularly ~~around near~~ flight altitude. These ~~are the two cases where contrails were initialized~~ two cases involved contrail initialization 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~~ Such cold conditions likely 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, but under markedly different background conditions.~~ Here, the contrail formed at ~~an altitude of~~ 10,664 meters, m with an average

temperature of ~~approximately about~~ 221 K—~~about roughly~~ 10 K warmer than Cases 1 and 2—~~and~~ within a deep ISSR. ~~Furthermore Unlike those cases,~~ 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).~~ ~~shows relatively~~
615 ~~high background IWC, indicating a background environment capable of sustaining higher ice water content due to the warmer temperatures. Despite this contrast, the contrail-induced IWC anomaly remained among the lowest.~~

3.3.3 Excess Water Vapor, Contrail Lifetime and Growth Potential

~~Even though Although~~ both contrails and natural ice clouds are ~~composed consist~~ of ice crystals, their microphysical properties differ ~~significantly markedly~~. Young persistent contrails are characterized by exceptionally high ice crystal number concentrations
620 ~~, consisting composed~~ of extremely small ice crystals—a feature ~~not typically rarely~~ observed in natural clouds. ~~Due to their high~~ ~~Owing to their large~~ surface-area-to-volume ratio, these ~~abundant small ice numerous small~~ crystals have very short deposition and sublimation timescales. ~~Consequently As a result,~~ young persistent contrails ~~are highly efficient at consuming efficiently consume~~ available moisture in ISSRs, rapidly depleting excess water vapor ~~. This rapid moisture depletion creates and creating~~ a near-saturated environment at ~~contrail~~-flight altitude (as ~~was~~ shown in Figure 6).

625 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 formation.~~ ~~Observations show that~~ highly supersaturated conditions ~~often persist~~ 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 ~~here~~ as the mass of water vapor exceeding the saturation threshold ~~over~~
630 ~~ice~~ at a given temperature and pressure (~~Eq. ??~~)—plays a critical role in contrail evolution within ISSRs. ~~Specifically, this variable significantly affects This parameter strongly influences~~ contrail-induced ~~ice water content (IWC) anomalies, a point thoroughly examined IWC anomalies, as discussed in detail~~ by Unterstrasser (2016).

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

In this study, the saturation vapor pressure over ice, e_{si} , was computed using the Magnus–Tetens approximation following the
635 ~~Murray (1966), as implemented in our simulation. The corresponding saturation vapor density, ρ_{si} , was then obtained from the ideal gas law (Eq. 2), where $R_v = 461.5 \text{ J kg}^{-1} \text{ K}^{-1}$ is the specific gas constant for water vapor and T is the temperature in Kelvin. The actual water vapor density was calculated from the specific humidity, q_v , and air density, ρ , as in Eq. 3. Excess water vapor mass was then determined as Eq. 4~~

$$\rho_{si} = \frac{e_{si}}{R_v T} \quad [\text{kg m}^{-3}] \quad (2)$$

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

$$\rho_v = q_v \rho \quad [\text{kg m}^{-3}] \quad (3)$$

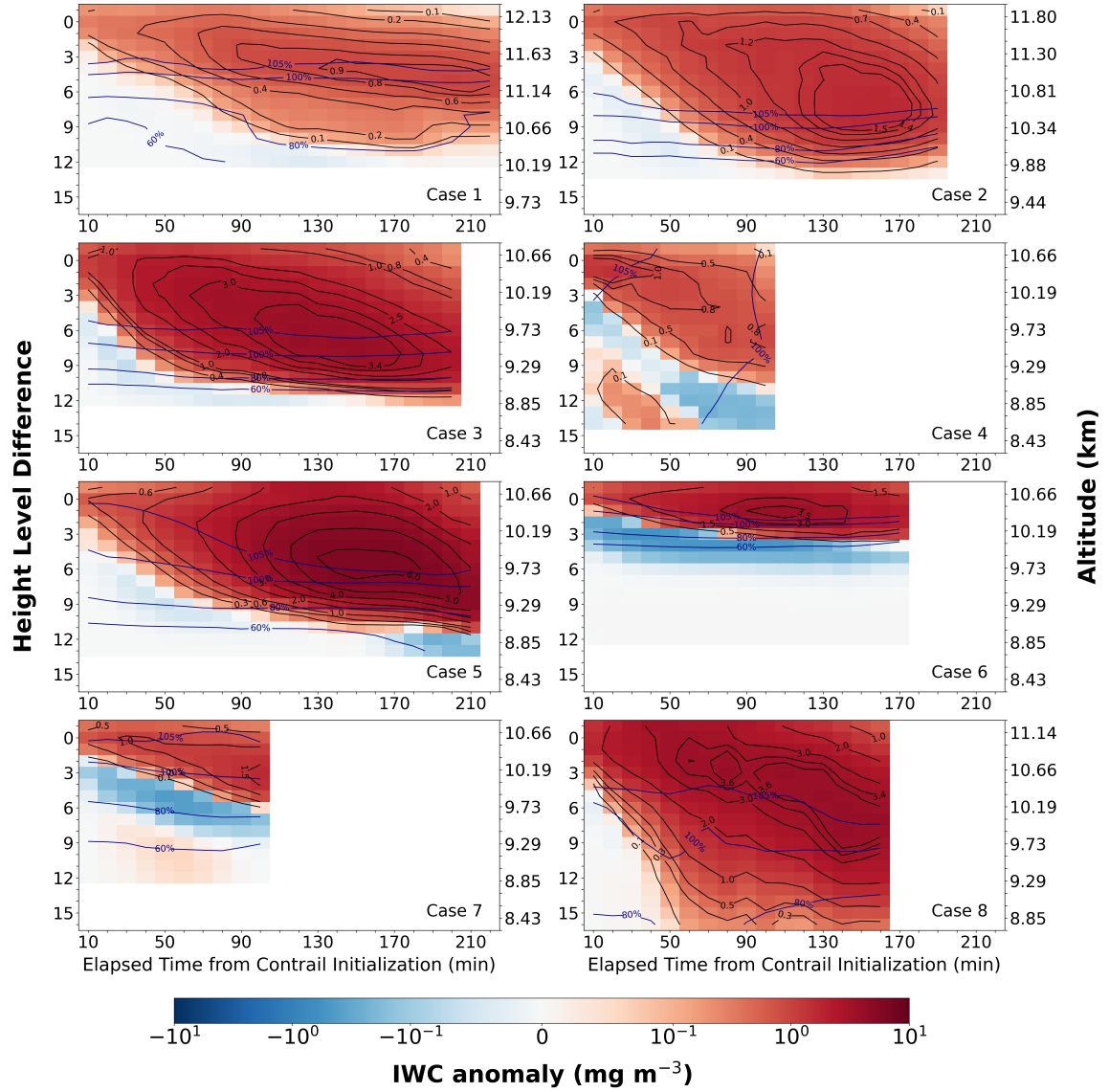


Figure 10. Time–height evolution of contrail ice water content (IWC) anomalies for different cases, defined as the difference between the perturbation (contrail) and control (natural cloud) runs over the same region. The x-axis shows time since contrail initialization; the y-axis shows height level differences 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.

$$\rho_{\text{excess}} = \rho_v - \rho_{si} \quad \text{when} \quad \rho_v > \rho_{si} \quad (\text{kg} \cdot \text{m}^{-3}) \quad (4)$$

Role of Excess Water Vapor in Contrail Evolution and Microphysical Properties

Figure 11 illustrates the ~~temporal-vertical-distribution~~ time-height evolution of excess water vapor density ($\text{mg} \cdot \text{m}^{-3}$), averaged ~~within the contrail area only~~ over the contrail region in the control simulations (~~natural cloud only~~ natural cloud). This representation reflects the moisture availability in the contrail region ~~prior to its formation~~ without contrail influence.

The largest IWC anomalies were simulated for Cases 5, 3, and 8, respectively, while ~~the weakest anomalies occurred in~~ Cases 1 and 2. ~~Meanwhile, 2 were among the weakest.~~ Case 4 ~~exhibited~~ showed a distinct pattern, with ~~a more pronounced an~~ initial increase in IWC followed by a ~~slower rate of change over time~~.

~~Case~~ gradual reduction over time (Case 7 is omitted from this discussion because the contrail advected out of the domain before its development could be fully analyzed). Notably, Cases 1, 2, and 6 were among those with the highest N_i , which remained elevated at flight altitude for an extended period. Cases 1 and ~~Case~~ 2 formed at higher altitudes (~~approximately~~ ≈ 12 km) ~~with significantly lower temperatures~~ ($T < 215$ under very low temperatures ($T < 210$ K)). ~~Despite their initially high relative humidity~~ Although relative humidity was high (above 110%), the absolute amount of excess water vapor ~~available is~~ noticeably limited due to the low temperatures is small (less than 2.5 mg m^{-3} throughout), owing to the cold conditions. This limited ~~excess water vapor directly affects contrail moisture supply~~ restricted ice crystal growth, resulting in their ~~prolonged presense at~~ persistence near flight altitude. ~~This aligns with our earlier findings that~~ Consistently, these two cases ~~exhibited~~ showed prolonged N_i anomalies at flight altitude ~~while also showing minimal growth but only minimal increases 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. In agreement, Gryspeerdt et al. (2024) reported that contrails forming at higher altitudes tend to persist longer and exhibit increased lifetimes. We note that our simulations assume a constant initial ice crystal number concentration, while in reality colder conditions at higher altitudes would likely activate more during the contrail formation.

Although both Cases 1 and 2 had limited excess water vapor, Case 2 ~~exhibited~~ showed slightly higher values and ~~, additionally,~~ its temporal pattern ~~differed, with a gradual and constant increase in excess water vapor, indicating a~~ a distinct temporal pattern: a gradual, steady increase that sustained moisture supply to the contrail region ~~throughout its development.~~ This pattern aligns with findings by. This behavior is consistent with Unterstrasser et al. (2017), who ~~emphasized the importance~~ highlighted the role of sustained moisture availability—~~associated with prolonged but weaker~~ often linked to prolonged but weak updrafts—in supporting contrail persistence. Consequently, Case 2 maintained a high ice crystal number concentration ~~and exhibited a~~ longer lifetime and slightly higher IWC anomaly compared to ~~throughout the 3-hour simulation and exhibited greater IWC growth than~~ Case 1. ~~However, the thickness of the underlying supersaturated layer also likely 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, with other cases of similar altitude and temperature.~~

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

680 ~~In contrast,~~

~~In~~ Case 8, ~~despite initially having high values of the~~ excess water vapor ~~(values up to 4–5 reached 4–5 mg m^{-3}), did not reach comparable maximum IWC anomalies. Its excess moisture was rapidly consumed initially, accelerating, yet the IWC anomalies did not attain comparable values. The high moisture supply was present mainly at the beginning of the simulation and then gradually diminished. This initial abundance accelerated ice crystal growth and sedimentation. As a result,~~ causing the IWC anomaly ~~quickly reached to rise more rapidly than in other cases to 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.~~ However, it did not continue to develop further, illustrating that not only the total amount of available water vapor but also its temporal distribution strongly influences contrail growth potential.

685

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~~ Here, the maxima occur only at a very early stage, after which the contrail gradually decays. This case, ~~characterized by~~ marked by a deep supersaturated layers with ~~weak only moderate~~ ice supersaturation, resembles ~~conditions typically associated with the conditions usually linked to~~ liquid-origin ice clouds.

690

~~The comparison of the median time~~ Both Figure 11 and Figure 2 show that the contrail initially formed and evolved in a ~~region with positive excess water vapor, which gradually decreased over time and even reached negative values. Time series of excess water vapor density in the natural ice for the natural cloud (control run) and the contrail-affected region (perturbation run) is shown provided in Figure A4. 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, These results reveal that while excess water vapor declines gradually in the control run—likely due to weakening mesoscale updrafts—its depletion is significantly markedly accelerated in the presence of the a contrail. In the perturbation run, excess water vapor initially decreases sharply decreases sharply at first and then stabilizes as values approach zero. This behavior explains near zero, consistent with the rapid initial increase in the IWC anomaly, followed by stalled growth —and even a decline—as additional and, eventually, a decline as~~ sublimation is required to maintain near-saturated conditions.

695

700

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

705

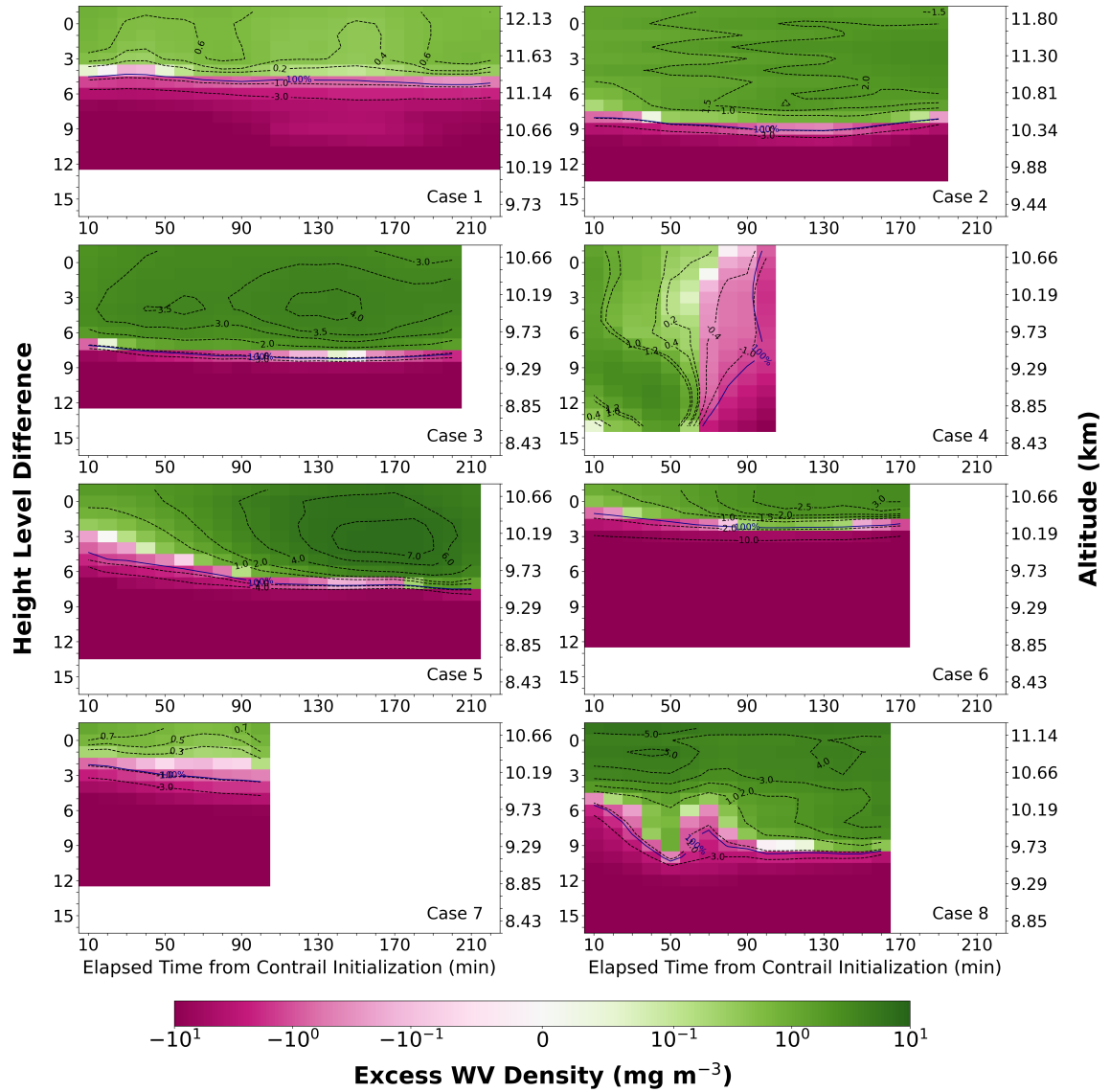


Figure 11. Time–height evolution of excess water vapor density ($\text{mg} \cdot \text{m}^{-3}$) in the contrail area for different cases in the control runs, representing background conditions without contrail influence. The x-axis shows elapsed time after contrail initialization, while the y-axis represents shows height differences relative to flight altitude (with 0 at flight level).

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).

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~~influenced by the contrail. This approach ensures that the ~~comparison analysis~~ isolates contrail-induced effects from the broader atmospheric variability ~~present in~~within the full simulation domain.

3.4.1 Contrail-induced Thermal Radiative Effects

Figure 12 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~~, which typically exert stronger radiative effect than in situ-origin cirrus clouds due to their higher optical thickness (Krämer et al., 2016).

~~The strongest contrail-induced radiative~~ In contrast, the strongest impacts occur in Cases ~~5, 8, and 3, respectively, with 5 and 8~~. Case 5 ~~showing the highest anomaly of~~ shows the largest anomaly, 24 W m^{-2} at 140 minutes. Case 5 ~~exemplifies after 120 minutes, exemplifying~~ 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~~benefiting from a steady, gradual moisture supply. ~~Additionally, it has sufficiently~~, and supported by deep ISSRs below flight altitude ~~—(unlike Case 6, which had almost the same conditions except that contrail growth was restricted by a very thin supersaturated layer beneath the contrail flight level where growth was constrained by a thin subsaturated layer).~~

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

~~Interestingly, the radiative impact of~~ onset mirrors its early IWC anomaly growth. Interestingly, Case 2, ~~which represents contrails forming at high altitude, is not among the lowest. As expected, it increases gradually, reaching~~ despite forming at higher altitude with limited water vapor—still reaches 18 W m^{-2} after 150 minutes ~~—, a value comparable to other cases with greater available water vapor~~moisture availability.

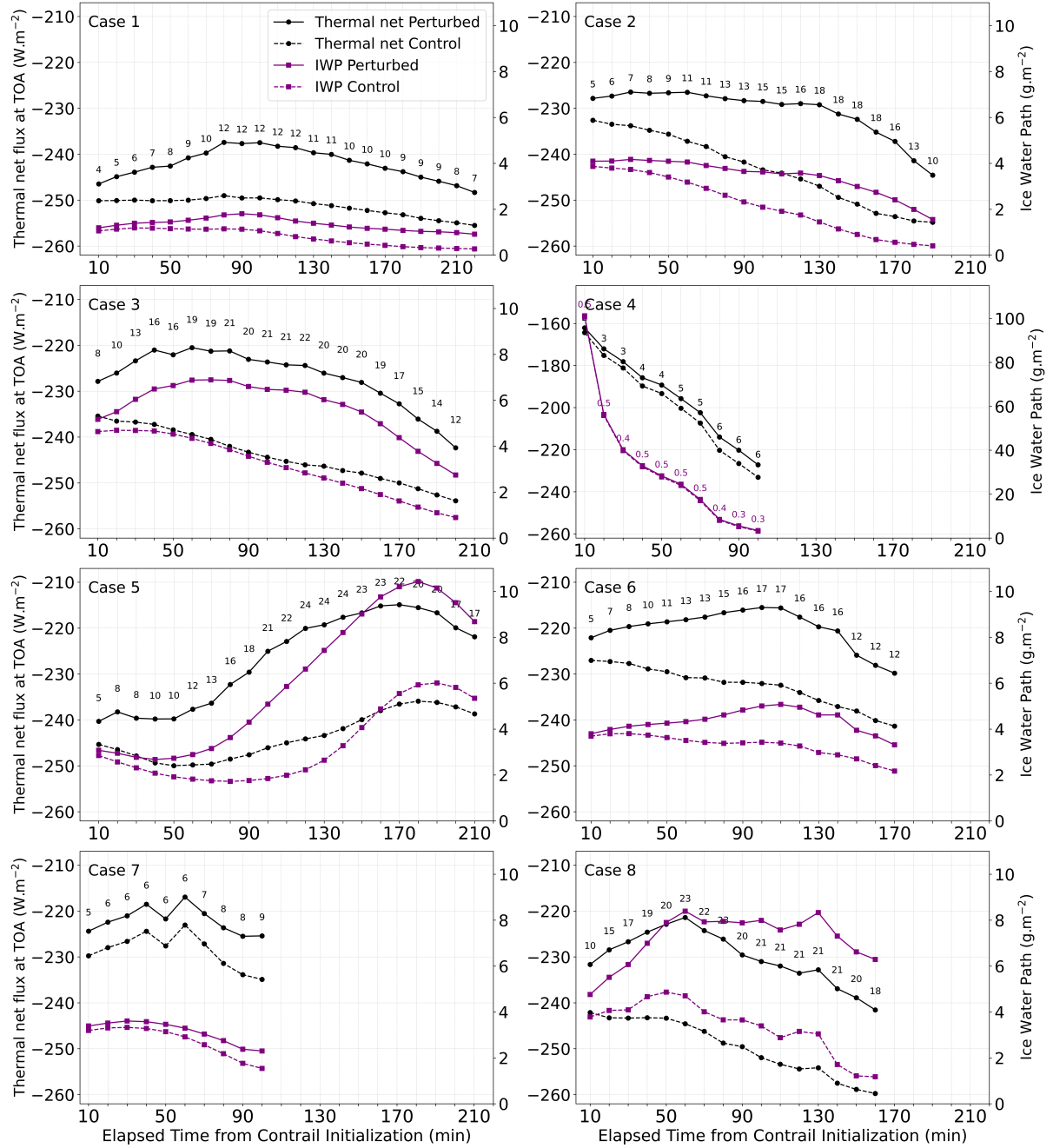


Figure 12. Time series of thermal net flux at the top of the atmosphere (left y-axis) and ice water path (IWP, right y-axis) for control and perturbation simulations across eight cases. Differences between control and perturbed runs quantify localized thermal radiative impact of contrails Circles denote thermal net flux and squares denote IWP, with solid lines for perturbation and dashed lines for control. Numbers above the thermal net flux markers report the differences between perturbation and control simulations to facilitate comparison.

Relationship between Thermal Radiative Effects and Ice Water Path

740 Figure 12 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. 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 A5, indicates a positive association between these variables—suggesting that larger
745 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.~~ This relationship holds across the simulations, except in Case 4.

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
750 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 13 presents the time series of solar net flux at the top of the atmosphere for all cases, together with the corresponding albedo time series.

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
755 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 the trapping of outgoing longwave radiation (greenhouse effect) remains dominant. A version of Figure 13, normalized using a standardized reference irradiance corresponding to June 21st—when solar irradiance typically reaches its annual maximum—is
760 provided in Appendix A6. Even under these peak solar conditions, the cooling effect from reduced solar flux cannot fully compensate the warming caused by longwave radiation trapping.

4 Conclusion

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
765 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~~154 m horizontal resolution. In these simulations, we introduced an identical perturbation—a fixed ice crystal
770 number concentration of 150 cm^{-3} —along targeted flight tracks that satisfied the Schmidt–Appleman criterion throughout the

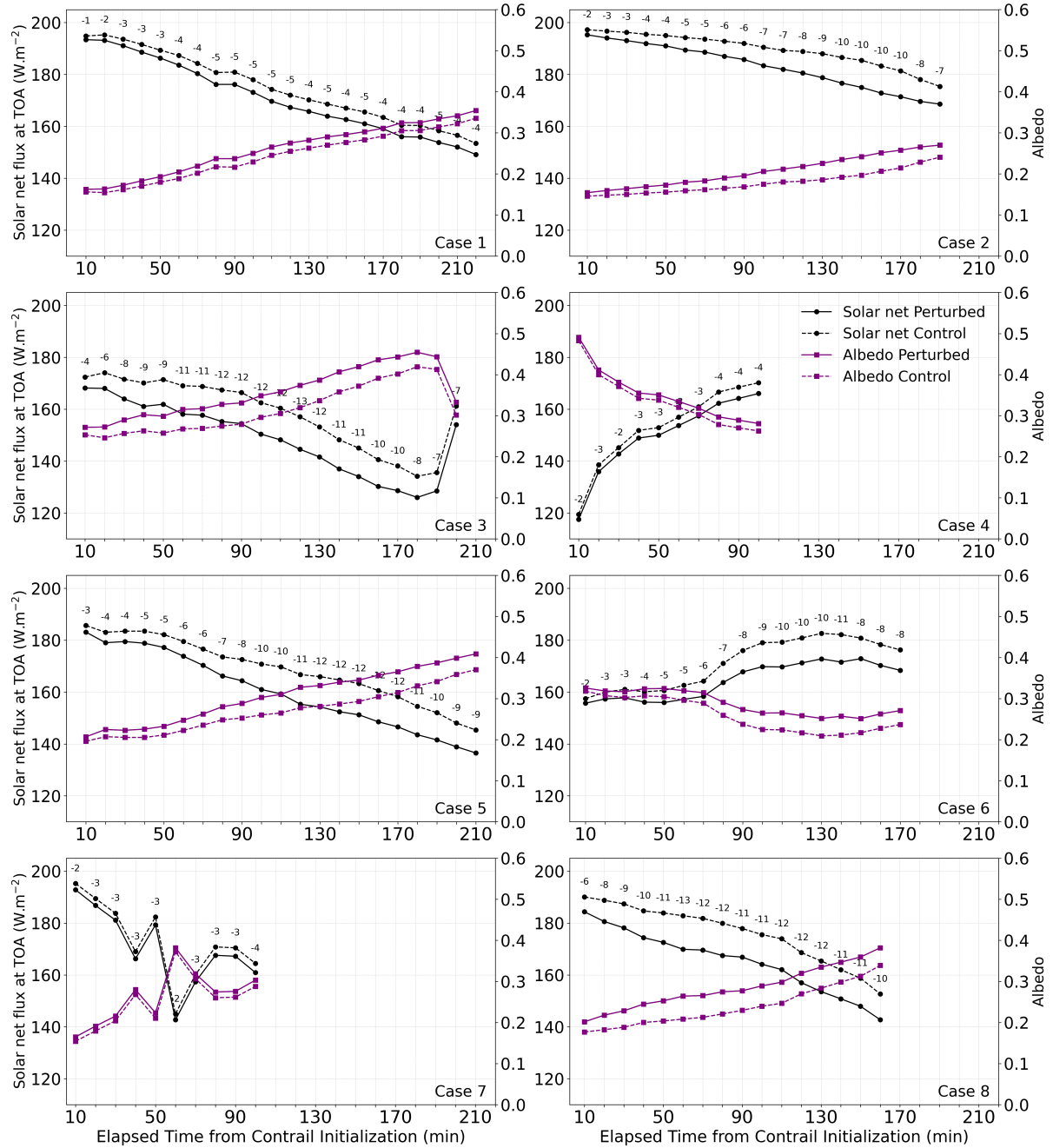


Figure 13. Time series of solar net flux at the top of the atmosphere (left y-axis) for control and perturbation simulations across eight cases (left axis). Flux values S_{net} are standardized using a reference irradiance ($S_{\text{ref}} = 231 \text{ W.m}^{-2}$), corresponding to March 1st at latitude 34° , allowing direct comparison across cases. The right axis shows albedo (perturbed for perturbation and control runs). Circles denote standardized solar net flux and squares denote albedo, plotted with purple square solid lines representing perturbation runs and dashed lines representing control runs. Numbers above the solar net flux markers indicate perturbation-control differences to facilitate comparison.

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.

775 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
780 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
785 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.

In our ICON-LEM configuration (~150 m horizontal resolution), we used the standard two-moment microphysics scheme with a single ice category. At this resolution, we assume that a cloudy grid cell is predominantly occupied by either natural
790 cirrus ice or contrail ice. We acknowledge that this simplification may introduce some biases in the results; however, the fine LES resolution substantially reduces artificial mixing of distinct ice modes and is adequate for studying the dispersion phase of contrails. Given that LES studies of dispersion-phase contrail evolution remain limited, our approach provides a useful step toward improving our understanding of these processes. In future work, applying the same framework at both finer and coarser resolutions would help assess the sensitivity of the results to grid spacing and further clarify the role of resolution in simulating
795 dispersion-phase contrails.

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 ~~+56~~
154 meters was chosen to fully resolve the initial vertical cross-sectional area of the contrail within a single grid box. As a
800 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

805 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.

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

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~~ 154 meters, based on the
815 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>

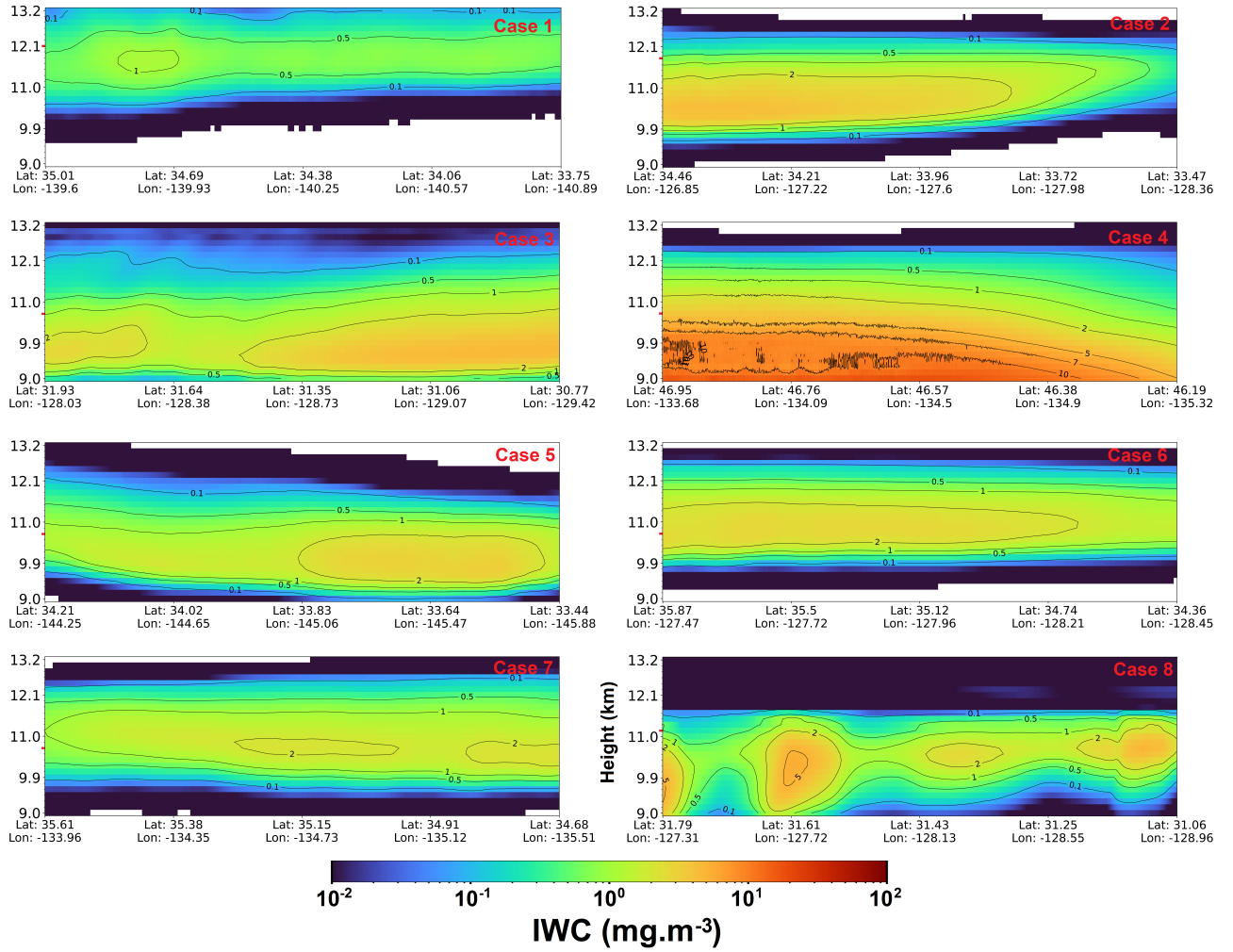


Figure A1. Vertical cross-sections of background ice water content (IWC) along the flight track for all eight cases at the moment of contrail initialization, based on the control simulations. The data are averaged over a broad region perpendicular to the flight path, representing the overall mean atmospheric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

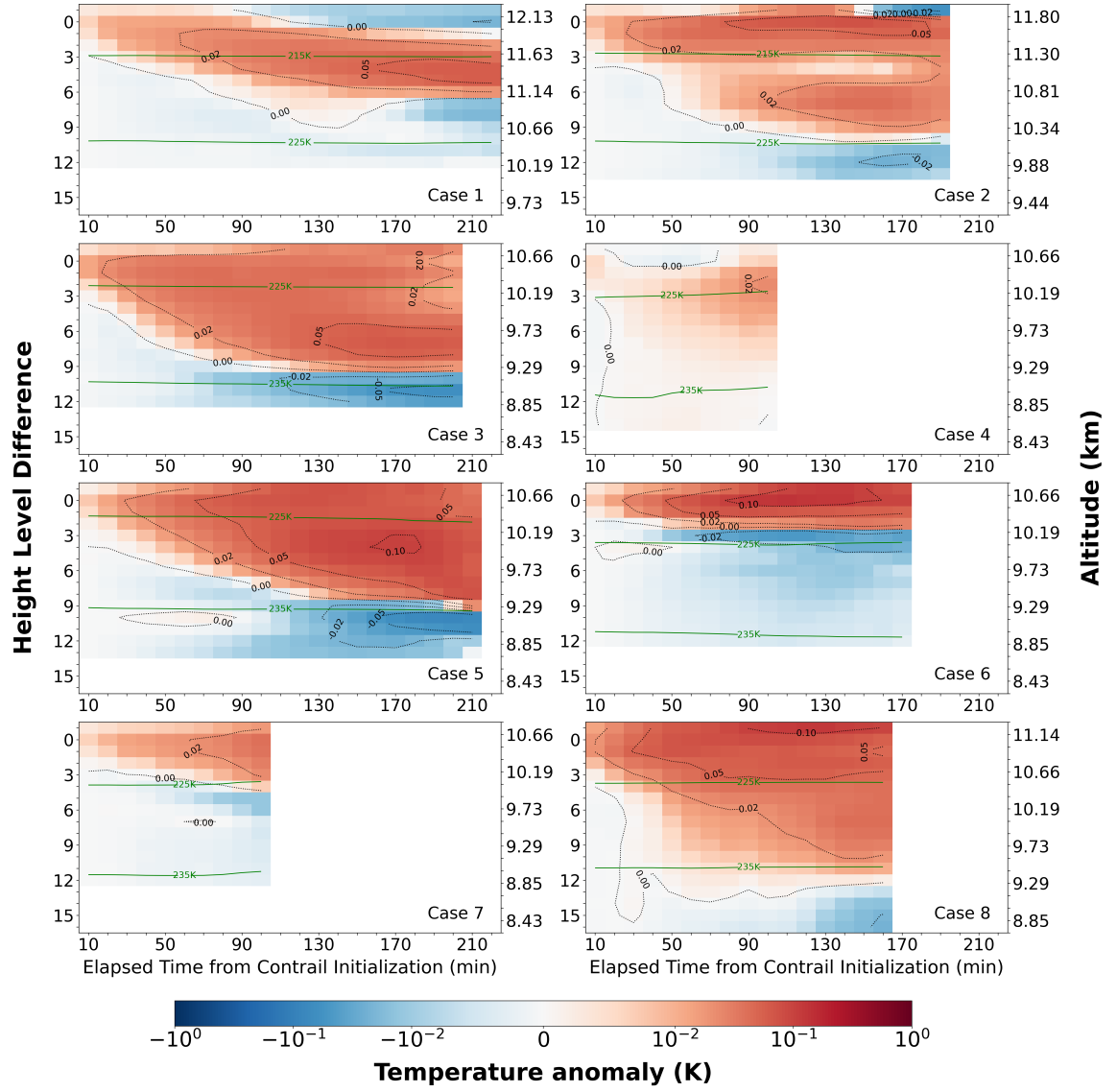


Figure A2. Time–height evolution of temperature anomalies for different cases, defined as the difference between the perturbation (contrail) and control (natural cloud) runs. The x-axis shows time since contrail initialization; the y-axis shows altitude. Green contours mark 215, 225, and 235 K from the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

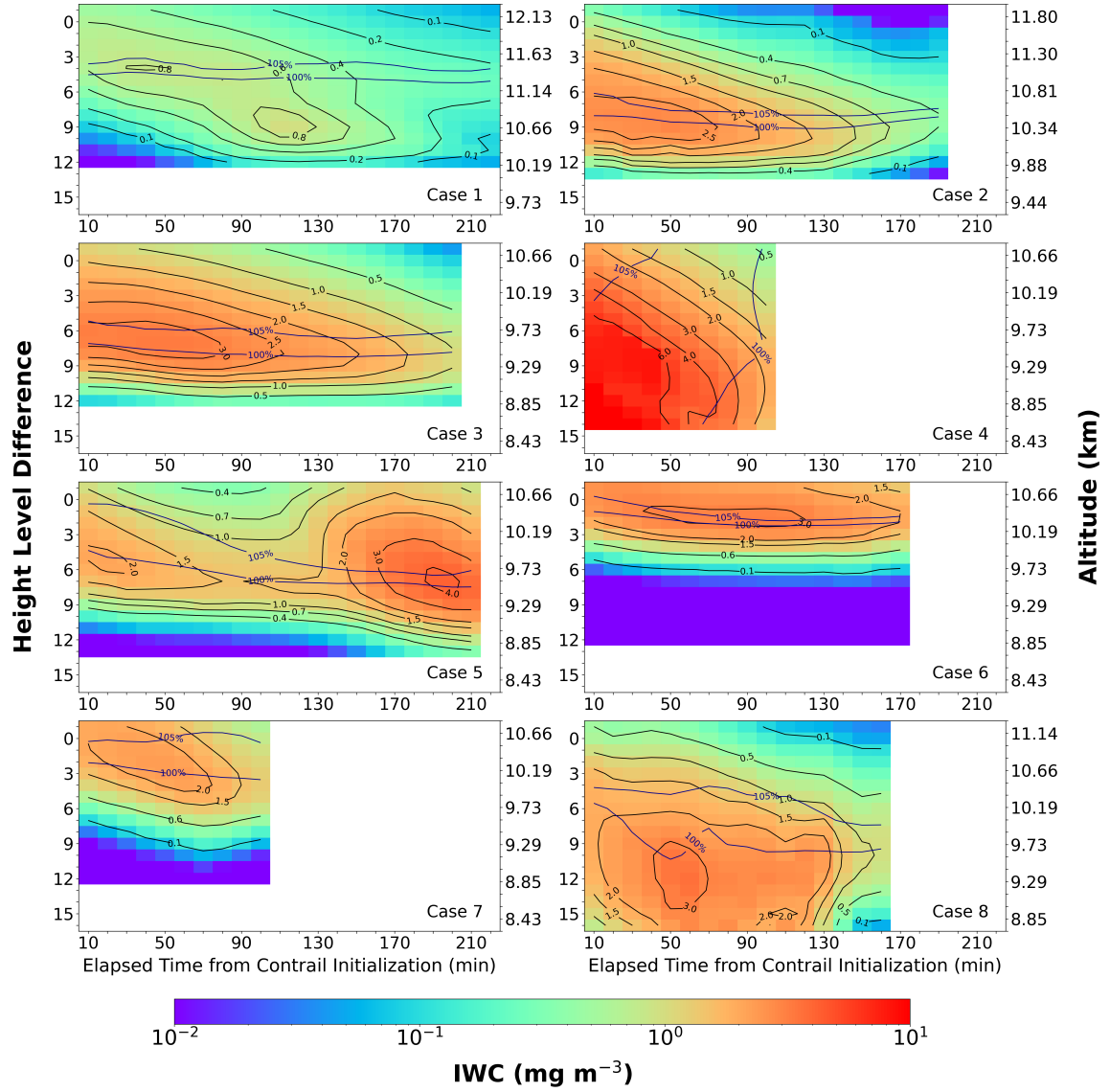


Figure A3. Time–height evolution of IWC in for control (natural cloud) runs. The x-axis shows time since contrail initialization; the y-axis shows altitude. Black contours denote IWC anomalies ($\text{mg}\cdot\text{m}^{-3}$), while blue contours indicate relative humidity over ice (RH_{ice} , %) from the control run.

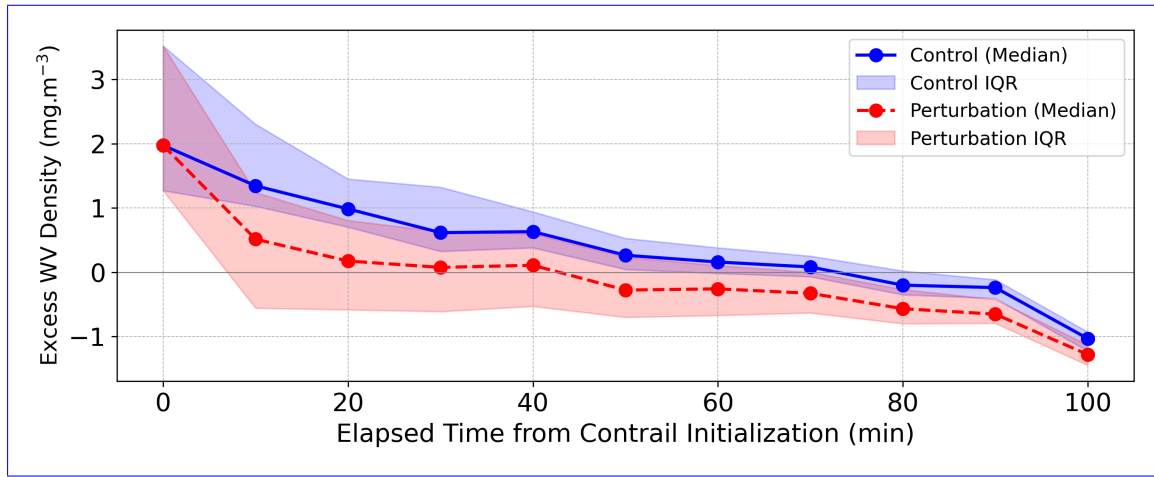


Figure A4. Time series of excess water vapor for the control (blue) and perturbation (red) runs in Case 4, at flight altitude. The blue line represents the evolution in the natural cloudy region, where excess water vapor remains positive until approximately 70 minutes, followed by a gradual decline, 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).

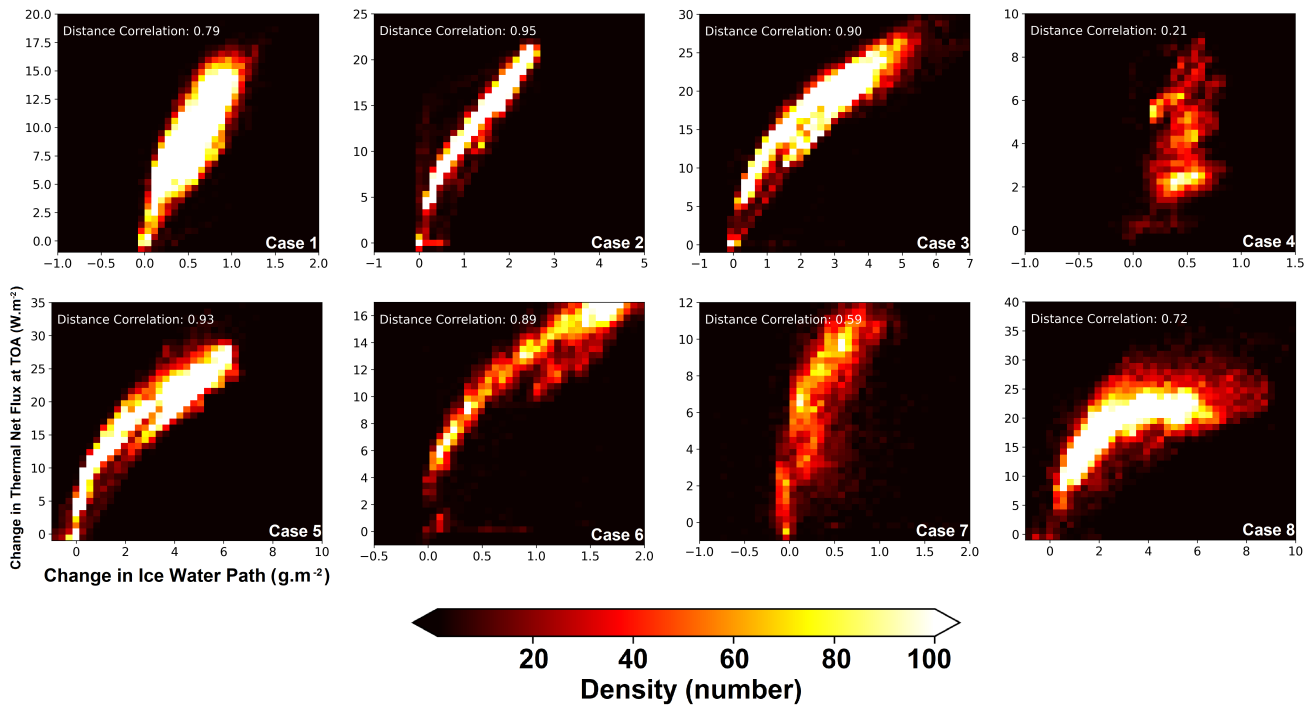


Figure A5. Overall 2D histogram of pointwise contrail-induced changes in ice water path (IWP) and changes in thermal net flux at the top of the atmosphere for all eight cases. The computed distance correlation coefficient indicates a positive association between these variables, suggesting that larger pointwise increases in IWP are related to greater reductions in outgoing longwave flux.

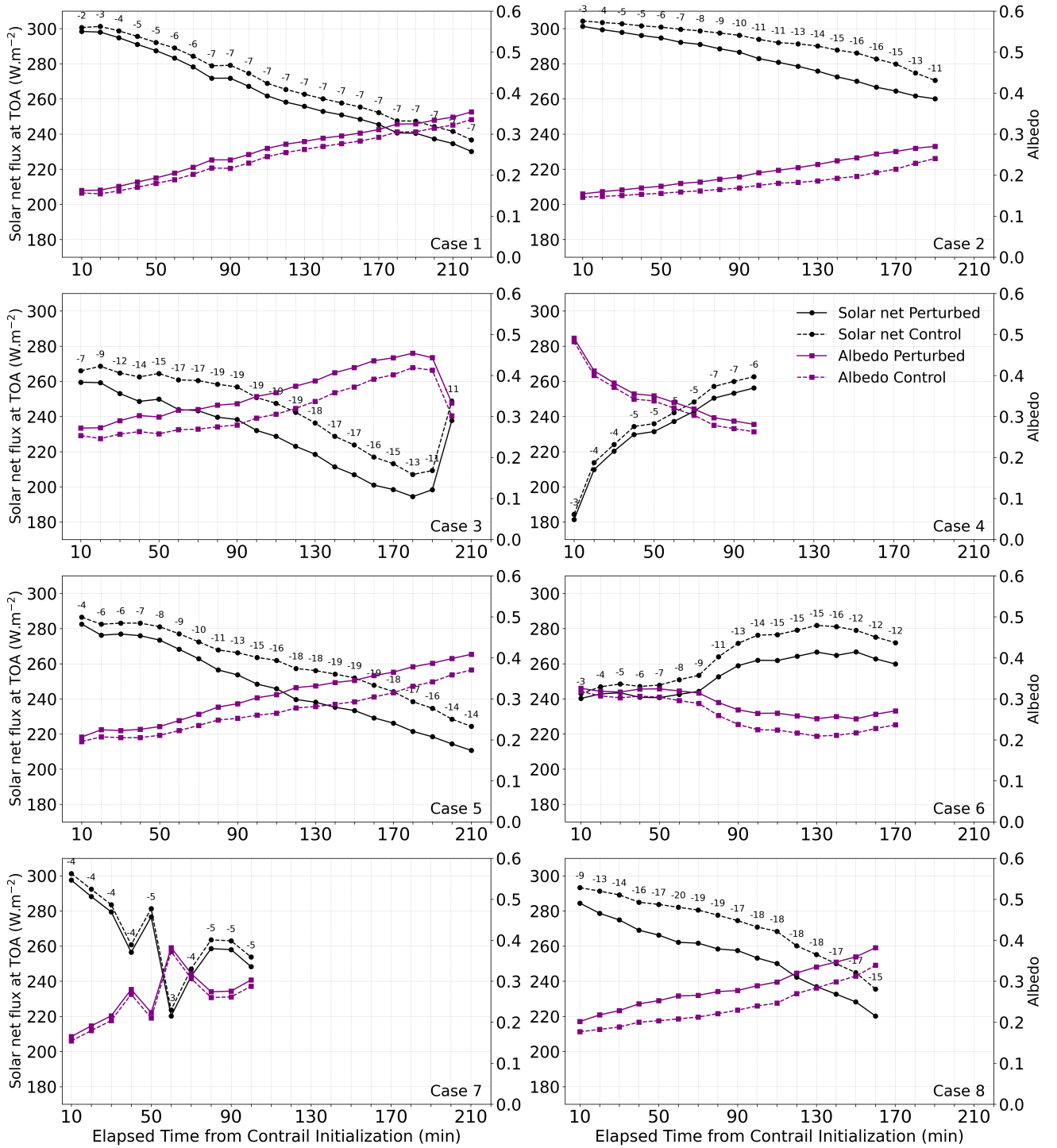


Figure A6. Same as Figure 13, but standardized using a reference irradiance of $S_{\text{ref}} = 365 \text{ W}\cdot\text{m}^{-2}$, corresponding to June 21st at latitude 34° , when solar irradiance is at its annual maximum in the Northern Hemisphere.

Appendix B: Contrail Formation Conditions - A Closer Look

The Physics of Contrail Formation: The Schmidt–Appleman Criterion

820 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 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).

825 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 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}

830 The slope of the mixing line, denoted by G , depends on atmospheric pressure and several aircraft-specific parameters and is calculated using Equation (1). ~~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, we adopt values of $M_w = 1.25 \text{ kg}_{\text{wv}} \text{ kg}_{\text{fuel}}^{-1}$, $c_p = 1005 \text{ J kg}^{-1} \text{ K}^{-1}$, $Q = 43.2 \text{ MJ kg}_{\text{fuel}}^{-1}$, and $\eta = 0.3$, following Bock and Burkhardt (2019).~~

835
$$G = \frac{c_p M_w P_a}{0.622 Q (1 - \eta)}$$

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 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
840 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.

Atmospheric Temperature and Humidity in Contrail Formation

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

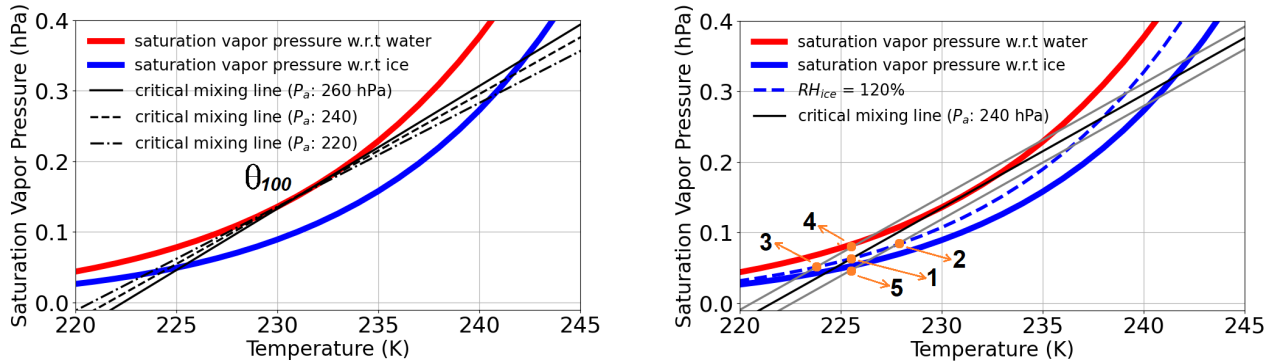


Figure B1. (Left) Threshold mixing lines are shown for three different atmospheric pressures. The tangent point between each mixing line and the water saturation curve indicates the threshold temperature at water saturation. It is evident that at higher ambient pressures, the tangent occurs at warmer 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).

850 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.

855 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).

860 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
865 saturation, and no contrail will form.

Summary of Appendix B and Context for Figure 3 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 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.

870 . 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.

. SM conceived the study, developed the methodology, performed the model simulations, carried out the data analysis, 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
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