# Improving Forecasts of Persistent Contrails through Ice Deposition Adjustments

Zane Dedekind[1], Alexei Korolev[1], and Jason A. Milbrandt[1]

[1]Meteorological Research Division, Environment and Climate Change Canada, Toronto, Ontario, Canada

**Correspondence:** Zane Dedekind (zane.dedekind@ec.gc.ca)

We thank the reviewer for their detailed evaluation and the constructive comments provided in this second report. We have addressed the major concerns.

### Overview remarks

1. Is it really necessary to simulate contrails in order to obtain a better impression of the NWP prediction skill of RHi?

   No, it is not necessary to simulate contrails to obtain a better impression of the NWP prediction skill for relative humidity over ice (RHi). However, a major takeaway from the research is that to predict contrails effectively, NWP models must first represent RHi much more accurately. Because persistent contrails can only form and evolve within ice-supersaturated regions (where RHi $> 100\%$), any error in the RHi field directly leads to incorrect contrail forecasts.

2. Schmidt-Appleman criterion with an existing ice-crystal-loss parametrisation of the vortex phase. Including the parametrisation of Kärcher et al. (2015) could have provided an estimate of the initial number of ice crystals before vortex-phase losses. The comment from the other reviewer “This includes, e.g., the number of ice particles (ice nucleation) and assumptions on sub-grid-scale variability” may refer to this point, i.e. that ice crystal formation in contrails also depends on the meteorological environment. For me, it seems CoAT is the algorithm for contrail initialization in GEM-P3, isn’t it?

   While initial ice crystal activation is influenced by the local meteorological environment at the engine exit and something we plan to implement later, this study focuses on the sensitivity to soot emissions. We estimate the initial ice crystal number ($N_0$) using the emission index (Eqs. 3 and 4), assuming full activation to isolate how variations in soot impact the population prior to vortex-phase losses. The subsequent survival of these particles is explicitly dependent on ambient atmospheric conditions through the survival fraction ($f_s$) in the Unterstrasser (2016) parameterization (Eq. 5). By varying soot regimes, we demonstrate how the initial ice crystal population, prior to vortex-phase processing, ultimately dictates contrail properties and persistence.

3. Recently, other approaches to improve supersaturation forecasting in NWP models have been described (e.g., Hanst et al., 2025).

   Inclusion of the Köhler and Seifert (2015) and Hanst et al. (2025) articles into our discussion:

   *To address this, two-moment schemes have been developed that treat ice particle number density as a prognostic variable, allowing the phase relaxation time to emerge naturally from microphysical relationships rather than being artificially constrained by diagnostic adjustments (Köhler and Seifert, 2015). Recently, Hanst et al. (2025) demonstrated that implementing a simplified version of Köhler and Seifert (2015), which includes a 2 hour relaxation timescale to simulate the recovery of ice nucleating particles due to atmospheric mixing within an ensemble forecasting framework, improves the reliability of predicting the onset and persistence of ice-supersaturated regions.*

## Major Comments

1. Treatment of contrails within GEM-P3 – Although the description of the CoAT model has improved, the manuscript still does not explain how contrails are handled in GEM-P3. I could not find any information, even though Figures 5-8 display GEM contrail results.

   We have explicitly mentioned and explained in the text in Line 255-260 and also in Section 2.5.5, but we will address the reviewers specific questions below and include some more information for clarity.

   Line 255: "When assessing contrail persistence for individual flights (Table 2), not contrail-forming regions and their associated properties, the CINC and CQI contributions after the vortex phase are added to the cloud ice number and mass concentrations from the P3 microphysics scheme. These combined quantities are referred to as the total ice number concentration and total ice mass concentration, which are subsequently advected by GEM's advection scheme.".

   "Section 2.2.5 Simulation configurations

   Two control simulations were performed: CNTL and CNTL-DA. The setups are identical except that CNTL assumes a constant deposition coefficient ($\alpha_D$ = 1), whereas CNTL-DA applies a variable $\alpha_D$. Both use a part of the CoAT configuration, diagnosing persistent contrail, forming regions and properties, such as contrail depth, ice particle survival (IPS), CINC, CQI at each timestep as if an A321 or B747 aircraft were uniformly distributed across the model domain. FlightRadar24 tracks are excluded, so no explicit contrail ice is added to the P3 microphysics or advected by GEM (CoAT excluding flights). Both simulations use an emission index of 1 × 1015 kg-1, representing the HS regime. Sections 3.1.1–3.1.2 compare the ice-supersaturated regions between CNTL-DA and CNTL, while Section 3.1.3 examines the sensitivity of contrail formation and related properties to $\alpha_D$.

   Subsequent sensitivity experiments employ the full CoAT configuration, which includes FlightRadar24 tracks (Table 2; Fig. 1a), to analyze contrail occurrence and persistence under varying soot-emission regimes for flights overpassing Toronto near 14:00 UTC (Sections 3.2.1–3.2.3). When contrails form, the resulting contrail ice is added to the P3 ice category and advected. All sensitivity simulations use the DA configuration. The complete set of simulations and their configurations is summarized in Table 3."

(a) Do you use separate cloud categories for natural cirrus and contrail-cirrus? If not, how can the two cloud types be distinguished? Are natural and contrail cirrus governed by the same physical processes? How is the competition between the two cloud classes implemented?

No, here we do not treat natural cirrus and contrail cirrus as separate cloud categories. When CINC and CQI variables are shown in any of the figures, they show persistent contrail-forming regions. However, if total ice number concentration or total ice column depth (TICD) is shown, CINC was added to the first ice category in the P3 scheme, and contrail-cirrus is no longer separated from natural cirrus.

For example, in Figure 5 the panels show persistent contrail-forming regions across the entire domain, assuming aircraft are present in every grid box. The colored regions represent diagnostic CINC and CQI values indicating initial ice generation after the vortex phase. At this stage, these values are not added to the P3 scheme and are not advected in GEM. The figure, therefore, highlights regions that are favorable for persistent contrail formation, overlaid on cirrus clouds produced by P3.

When a flight track intersects a region favorable for persistent contrails, the resulting contrail ice is added to the first ice category of P3 and subsequently advected. Figures 7 and 8 display these simulated contrails for the specific flights listed in Table 2, rather than the persistent contrail-forming regions. In this case, the only way to distinguish between natural cirrus and contrail-cirrus is to analyze the ice particle properties.

When persistent contrails from individual flights are assessed, then P3 handles the physical processes of ice growth/sedimentation and sedimentation as it would with all other clouds. We have added the following modifications to the manuscript:

*"the CINC and CQI remaining after the vortex phase are integrated into the cloud ice number and mass concentrations within the P3 microphysics scheme. Consequently, these contrails evolve through the same microphysical growth and loss processes as naturally occurring clouds. These combined quantities, representing the total ice number and mass concentrations, are subsequently advected by GEM's dynamical core."*

Modifications made to Section 2.2.5:

*When persistent contrails form, the resulting contrail ice is integrated into the P3 microphysics scheme for evolution and advected by GEM's dynamical core.*

(b) The caption of Fig. 7 states that CINC is advected, which would imply that contrail ice crystals are treated as a passive tracer. The heading of Sect. 2.2.4 ("tracking...") also suggests that contrails are only advected. This remains unclear. Because I do not understand the contrail-modelling approach of GEM-P3, I still do not grasp how you define persistence. We have removed the word "Tracking and replaced it with Evolution and advection

The reviewer is correct in picking up this inconsistency, which leads to confusion. The caption for Fig. 7 should be: "*Contrail evolution and advection of individual flights. The total ice column density (TICD) is obtained by verti-*

*cally integrating the total ice number concentrations between the 310 hPa and 290 hPa layers, ... "*

Persistent contrails are defined on Line 218 - 221: "If ice supersaturation persists (i.e., RHi $\geq$ 100%), contrails can remain and evolve into long-lived cirrus. Although Li et al. (2023) demonstrated that contrails may persist under ice-subsaturated conditions, for consistency with the parameterization of Unterstrasser (2016), which assumes formation and growth under ice-supersaturated conditions, we restrict persistence to regions where ice supersaturation is maintained."

On line 231 we explicitly define what persistent is: When the conditions for SAC and for contrail persistence (RHi $\geq$ 100 %) are satisfied, GEM uses the wake vortex model from Unterstrasser (2016), which focuses on the interaction between ice microphysics and wake vortex dynamics.

While many studies apply or mention a temporal threshold (e.g. Kärcher et al., 2021; Hofer and Gierens, 2025; Kärcher and Corcos, 2025) to define persistence, largely to account for contrails that survive briefly in ice-subsaturated air, our study adopts a thermodynamic definition (Gierens et al., 2020; Bier et al., 2023). We define persistent contrails strictly as those forming and evolving within ice-supersaturated regions ($RH_i \geq 100\%$). Under these conditions, the time constraint becomes less important, as the environment inherently supports the long-term growth and survival of the simulated contrails.

2. Figures5-8

   (a) Figures 5-8: Fig. 6 – Does the CINC field represent the contrail from the red flight track, or from previous/other flights? If it is the former, why does CINC remain larger than zero well above the 300 hPa flight altitude? The relationship between the plotted flight track and the CINC field is therefore ambiguous.

   CINC indicates regions where regions of persistent contrail formation, not contrails from individual or previous aircraft tracks. Therefore, these panels show areas that were favorable for persistent contrail formation, where the properties of these regions are dependent on aircraft type and emissions.

   The differences in CINC within these regions reflect variations in soot emissions, which influence the number of ice particles that can form. As a result, the panels illustrate how contrail ice properties may vary under different emission conditions.

   (b) Fig. 8 – This figure shows changes in contrail IWP, which suggests that contrail ice particles are not treated as passive tracers. Please clarify the governing processes.

   As noted in the previous comments, once contrail ice particles from an individual flight are added to the GEM-P3 ice concentration to form the total ice concentration, they are no longer passive tracers and instead undergo physical processes and advection. The ice water path (IWP) and the total ice column depth changes because the contrail ice actively interact with the moisture field through depositional growth, which is further refined in our study by the calculated deposition coefficient $\alpha_D$. This confirms they are active tracers in the model microphysics.

3. Generality of the optimal deposition coefficient – In my previous review I asked: “You determined an optimal deposition coefficient for one synoptic scenario: How universally valid is this value? ... Is your optimal value also relevant for other microphysical models, or do you consider it to be only a tuning parameter of your P3 model?” The authors replied that it is now a direct calculation... Yet, my original question has not been answered: Whether a similar adjustment of $\alpha_D$ would be required in other synoptic situations, and whether the resulting value can be transferred to other models?

   Here, unlike in our first manuscript, we do not choose an optimal deposition coefficient. Therefore, this approach is universal because it is physically based and can be applied to other microphysics schemes and to any synoptic condition. We emphasize that the adjustment of the deposition coefficient ($\alpha_D$) is a correction of a fundamental physical simplification, the assumption that $\alpha_D = 1$, which leads to systematic underprediction of the humidity fields in NWP models. Because $\alpha_D$ is diagnosed from local temperature, pressure, and particle size in our updated manuscipt, it represents an intrinsic kinetic limitation of ice growth at low temperatures.

### Minor Comments

4. Line 7-“high-resolution simulations of what?” - please specify.

   We modified the sentence to:

   *High-resolution, limited-area simulations were performed using the Global Environmental Multiscale (GEM) model coupled with the Predicted Particle Properties (P3) microphysics scheme to investigate the evolution of ice supersaturation and the formation of persistent contrails over eastern Canada and the northeastern USA.*

5. Lines 50-55-Volatile particles (UFP) are always formed; the ambient temperature controls only how much they contribute to ice crystal formation.

   Yes, that is a mistake on our part. We have clarified the text to reflect that while UFPs are always present.

   *In contrast, in soot-poor exhaust, ubiquitous ultrafine aqueous plume particles contribute to ice formation at very low ambient temperatures where they can overcome the Kelvin barrier. Low-soot alternative fuels ($10^{13}$ (kg-fuel)$^{-1}$–$10^{14}$ (kg-fuel)$^{-1}$) generally yield fewer ice crystals and shorter-lived contrails, with the final ice number being ultimately determined by the activation of ultrafine aqueous plume particles when soot levels are insufficient to quench plume supersaturation.*

6. Line 58-You write “contrail formation”. Contrail formation is completed within the first few seconds; the wake vortices therefore affect the evolution... over minutes, not the initial formation stage.

   The statement can be correct in its scientific intent because wake dynamics are the primary determinant of the effective initial state of the contrail, but to make it absolutely clear we have modified the confusing statement: *"...investigate wake vortex dynamics, showing how turbulence..."*.

7. Sentence on condensation and freezing - The wording could be misinterpreted. It should read: “Water vapour first condenses onto soot and ambient aerosol particles; the resulting liquid droplets subsequently freeze.”

   We have adopted the reviewer’s suggested phrasing to more accurately describe the two-step microphysical process.

8. Citation of Li et al. (2023) - The statement “Although Li et al. (2023) demonstrated that contrails may persist under ice-subsaturated conditions” is misleading.

   We have rephrased this to

   *"Although contrails form in ice-supersaturated conditions, Li et al. (2023) demonstrated that contrails may persist in ice-subsaturated conditions. However, to remain consistent with the Unterstrasser (2016) parameterization, which assumes both formation and growth occur within ice-supersaturated environments, we restrict simulated persistence to regions where ice supersaturation is maintained.".*

9. Line 287- “initially detected?” - the meaning is unclear.

   We have clarified the sentence:

   *"This mask isolates the spatial extent of the simulated contrail and is applied uniformly to all sensitivity simulations to ensure spatial consistency".*

10. Line 289- It would be clearer to write “no contrails are initialized”. .

    We adapted the sentence. *..., in which no contrails are initialized, ..."*

11. Caption of Fig. 7-I do not think concentrations are advected. Ice crystals are advected.

    When describing model physics, variables like ice number and mass concentrations are being advected. Here, we keep to the structure to be more precise in which variable is being advected.

12. Eq. 8 - The notation should indicate that P denotes a percentile of TICD

    Yes, we have included it. *...where P denotes a percentile of TICD ...*

13. Use of “formation” and “persistence” – These terms are not used consistently throughout the manuscript; please adopt a single definition for each and apply it uniformly.

    Done.

**Technical Corrections**

14. “Albany” and “Albony” appear in the text.

    Corrected.

15. Equation 1 - Write the function as $dgr(RHi, T, ...)$ to make clear that it is not a constant.

    Equation 1 has been updated to $dgr(T,\ p,\ \mathrm{RH_i},\ r)$ to show its dependence on ambient conditions and particle size explicitly.

16. Table 1-Round the drift distances to integer values.

    Done.

17. Text vs. figure - In the text you refer to 240 hPa, but the red line in the figure appears to be at 250 hPa.

    It should be 250 hPa.

18. Definition of TICD - TICD is never defined explicitly.

    It is defined in section 2.2.4 as the total ice column depth and in Fig. 7, but now we explicitly mention after Eq. 8: *where TICD is calculated as the vertically integrated total ice number concentration between 310 and 290 hPa within ice-supersaturated regions,,...*

## References

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