Improving Forecasts of Persistent Contrails through Ice Deposition Adjustments

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We sincerely thank Reviewer 1 for the constructive feedback. The suggestions and comments improved the quality of the manuscript.

We have substantially revised the preprint in response to the reviewers' comments, incorporating two main updates:

1. A full solution for calculating the deposition coefficient-based (α_D-based) reduction factor has been implemented. α_D depends on temperature, pressure, humidity, and ice particle radius. These are now referred to as the deposition-adjusted (DA) simulations, replacing the previous sensitivity experiments Dep_0.6, Dep_0.8, and Dep_0.9, which are no longer required (Suggested by reviewer 2).

2. The analysis has been extended beyond a single emission index (EI = 1×10^{15}) to a range of EI values representing soot-rich to soot-poor regimes, allowing assessment of their impact on contrail evolution (Suggested by reviewer 1).

Below we present a detailed response with the reviewer comments in black, our responses in blue and additions to the manuscript in blue italics.

1. The topic of the deposition or accommodation coefficient has been discussed often in the literature. The accommodation factor is certainly a relevant parameter. However, there are also other effects which could be important: This includes, e.g., the number of ice particles (ice nucleation) and assumptions on sub-grid scale variability.
   This is correct; however, our methodology is applied within the context of numerical weather prediction models, where the deposition coefficient is typically set to unity. To address the important issue of accurately simulating upper-tropospheric humidity and, consequently, persistent contrails, we have included an explicit calculation of the deposition coefficient in this study.

2. In respect to the SAC criterium I have a specific remark: The paper concludes among others that the "CoAT simulations revealed that SAC alone is insufficient". It is not clear for what part of the SAC criterium this applies. Please note: It is well known that the SAC criterium does not guarantee the persistence of the contrail. It only decides on contrail formation. So, any warming of the ambient air, e.g. by sinking in the wake vortex, affects the survival of the contrail. This is not an issue of the SAC criterium. This part needs to reformulated.

That is correct and we take the criticism and we removed the statement which was not well phrased. What we intended to convey is that our simulations show cases where, even when the SAC criterion and ice supersaturation were satisfied, contrails did not form—particularly under slight ice-supersaturated conditions and for heavy aircraft such as the B747. We attribute this to differences in wake vortex characteristics between aircraft types. When the relative humidity over ice exceeded 102 %, persistent contrails and contrail-forming regions developed for both the A321 (medium-weight category) and the B747 (heavy-weight category).

3. Is the GEM (as the name suggests) a global model? Or is it a limited area model (as indicated by the information on page 7, lines 148 ff)?

   This can be confusing. GEM is a global modeling framework developed by Environment and Climate Change Canada that can be configured for different spatial scales. In the HRDPS system, GEM is used in a high-resolution configuration (2.5 km grid spacing) for regional weather prediction over Canada. We use these generated 2.5 km output fields, as referenced in our manuscript, to drive our regional 1 km $\times$ 1 km resolution simulations.

4. The description of P3 uses the term "property-based approach" (line 157). I do not know what an property based approach is. So, it seems, I have to read all the references given? Line 164 says "with prognostic liquid fraction off" – does this mean the model works without treating liquid water? Why is this a critical assumption for this application and why did you need to menton it?

   In the P3 (Predicted Particle Properties) microphysics scheme, the particle property approach means that instead of using fixed categories for different hydrometeors (e.g., cloud ice, snow, graupel), the model predicts key physical properties of ice particles — such as mass, number concentration, bulk density, and rime fraction — directly through prognostic equations. This allows the model to evolve particle characteristics continuously based on environmental conditions, rather than switching between discrete species. In other words, particle behavior emerges from their predicted properties, not from pre-defined categories. We made some slight modifications to the description:

   The P3 microphysics scheme is unique in that the ice phase uses the property-based approach, in contrast with the traditional approach of predefined ice-phase categories (e.g. ice, snow, graupel and hail), whereby all ice-phase or mixed-phase particles are represented by one or more generic or "free" categories whose bulk physical properties—such as mass, number, density, and rime fraction—evolve freely and continuously.

5. The P3 model within GEM is applied using 3 ice categories (line 164). Which are these categories? How are the outputs of CoAT (lines 218/219) related to these ice categories?

   In the GEM-P3 setup with three ice categories, the model predicts three distinct but physically consistent ice populations whose bulk properties evolve freely, allowing representation of various ice types (e.g., cloud ice, snow, graupel) without prescribing fixed categories. In this study, contrail ice crystals from CoAT are initialized in the first P3 ice category, representing small, pristine ice particles.

6. Why is figure B1 in an appendix, which contains nothing else than just this figure? In this figure, the various radiosonde contributions are hard to distinguish. I see red and blue colors but the rest is just in a color mix which I cannot discriminate. Moreover, the figure is hard to read because I am unfamiliar with the various Radiosonde names and their positions (GRB etc.). Which radiosonde shows the results for the airport of Toronto? Where in your map (Fig 1 a) is Toronto? By the way, Fig 1a is not referenced in the text. Line 253 says the "largest contribution to the underestimation is GEM's is its inability to capture the DTC sounding (Fig- B1)". I cannot understand this by only looking to the figure B1. Please provide further explanations (without abbreviations).

   We have simplified the figure to improve readability and added the locations of all sounding stations in Figs. 1a, 1b, and 3c. Where relevant, station names are now spelled out in the captions. Table 1 provides the full list of stations, including their names, locations, and identifiers. Toronto has been explicitly marked in all applicable figures and captions. Figure 1a is now properly referenced in the Aircraft Flight Data section. Additionally, Fig. B1 has been clarified by combining multiple station profiles while omitting White Lake (DTX), making the differences more apparent. We have added the following text in Appendix B:

   Excluding the White Lake (DTX) station from the analysis yields a closer agreement between the control (CNTL) and the deposition-adjusted control (CNTL DA) simulations and the observational distribution. This discrepancy arises not from deficiencies in the sounding data, but from GEM's limited ability to represent the extreme ice-supersaturated conditions frequently observed over DTX.

7. Why do you need to average over a 5 km x 5 km domain around the soundings. I thought the sounding positions are recorded (by GPS) during the radiosonde measurements versus time and, hence, known?

   We use the exact location of each radiosonde to determine its position within the model domain. To account for model uncertainty in predicting ice supersaturation, we also include a 5 km $\times$ 5 km area surrounding the balloon's location. We added the following to the manuscript for clarity:

   Knowing the balloon's trajectory enables matching its observations to the nearest model grid point in both space and time. For example, a balloon launched at 12 UTC requires several minutes to reach cruising altitude, so temporal alignment is also necessary. The drift distance was therefore calculated between the launch site and the 300 hPa pressure level (approximately jet cruising altitude) for multiple stations at 12 UTC on 25 Nov 2023

8. A caption like "3.1.2 The outlier: DTX sounding" implies that the reader already knows what a DTX sounding is. Where can I see the DTX sounding position?

   The reference to the Station Identifier is in Table 1. See more in comment 6 above. We have made several new additions to help the reader.

9. Line 280:do you mean Fig 4? Line 283: do you mean Fig 5?

   Yes, thank you.

10. Fig 5 is insufficiently explained. There are 8 panels which are grouped into 4 subpanels. The various panels are not explained. What do they show? The upper parts of these panels show color pots. What do the colors mean?

    We have modified Fig. 5 and added the following text to the manuscript:

    On this day, these low clouds significantly attenuated the ceilometer signal at CYYZ, Toronto, making it nearly impossible to retrieve data from cirrus clouds between 1300 UTC and 1700 UTC (Fig. 4). However, a descending high cloud base was still noticeable, aligning with the descending moist layer observed in the CNTL and CNTL DA simulations (Fig. 5a and 5b, top panels). The CNTL and CNTL DA simulations show three panels each of time-height vertical profiles of RH_i and the corresponding CINC for A321 (middle panels) and B747 aircraft (bottom panels).

    The CNTL DA simulation captures the ice-supersaturated layer, favoring persistent contrail formation, between 8 km and 10 km, while the CNTL simulation shows no ice-supersaturation in this altitude range. Here, aircraft-specific differences become evident: the A321 forms contrails at $RH_i \geq 100\,\%$, whereas the heavier B747 requires $RH_i \geq 102\,\%$. In these marginally ice-supersaturated conditions, the B747's initial number of emitted ice crystals sublimates within the descending vortex. To produce contrails under the same ambient conditions (T, P, RH_i, atmospheric stability) observed between 1200 UTC and 1230 UTC, the B747 would require ambient temperatures $\sim 2\,°C$ lower.

    After 1445 UTC, the CNTL simulation remains mostly ice-subsaturated to only weakly ice-supersaturated (maximum $RH_i \approx 104\,\%$), supporting only a shallow layer with a CINC of ~ 0.4 cm^{-3} for an A321 aircraft. In contrast, the CNTL DA simulation develops a pronounced ice-supersaturated region (RH_i up to 112 %) conducive to persistent contrail formation near 10 km. Under these conditions, contrails from the A321 appear first at $RH_i \geq 100\,\%$, followed by those from the B747 around 1515 UTC as RH_i rises to $\approx 102\,\%$. The CNTL DA simulation produced deeper contrail forming region with enhanced CINC up to 1.4 cm^{-3} for both aircraft types compared to the CNTL simulation.

11. Fig 6 is also hard to digest. The axes are not explained. What is CINC (cm-3)? How can a reader digest headings like "Soundings for APX A321 aircraft"?

    Fig. 6 was removed. CINC is now clearly defined as contrail ice number concentration in other figure captions as well as in the text.

12. I simply do not understand what you want to show. Fig 7: What is ice particle survival (in percent)? How is it computed, and why is it important?

    Fig. 7 (now Fig. 6) has been modified to make it clearer. Ice particle survival has been removed because it is not important.

References