

Response to the reviewers of our paper submitted for ACP

On the Weather Impact of Contrails: New Insights from Coupled ICON–CoCiP
Simulations

We thank the reviewers for their thoughtful comments and recommendation of minor revision.

The reviewer's comments are repeated below in blue.

The authors' responses follow in black. Often, we repeat the old text after "Old:" and the revised text follows after "New:".

Review 1 (<https://doi.org/10.5194/egusphere-2025-4512-RC1>)

Comments on "On the Weather Impact of Contrails: New Insights from Coupled ICON–CoCiP Simulations" by Ulrich Schumann and Axel Seifert

This manuscript documents the two way coupling of a contrail plume parameterization to a weather prediction model and simulates a few regional test cases. In general this manuscript is an appropriate and comprehensive treatment. It should be publishable in Atmospheric Chemistry and Physics subject to minor revisions.

Thank you.

It would be nice to highlight some of the major points a bit more clearly. I don't think the 'butterfly effect' analogy really works. To me the two major highlights are that (1) weather forecasts in high traffic regions might be improved by including contrails and (2) the efficacy for contrails on surface warming is low (or undetectable) in a weather context. Note that this does not necessarily carry over to the climate context (e.g. the perturbations to surface temperature are smaller than weather 'noise', but may very well be detectable when averaged over a long period of time.

A series of detailed specific comments and clarifications I would like to see addressed are noted below.

We try to clarify the points addressed as outlined below.

Abstract, Lines 7-9 of the manuscript;

Old: Here, we investigate the contrail-weather interaction using a two-way coupling of the Contrail Cirrus Prediction model (CoCiP) with the global Non-hydrostatic numerical weather model ICON.

New: Here, we couple the Contrail Cirrus Prediction model (CoCiP) with the global Icosahedral Non-hydrostatic (ICON) numerical weather model in a two-way mode accounting for contrail-weather interaction..

Lines 46-47

Old: The coupled ICON-CoCiP model used in this study allow us to investigate and quantify this feedback with respect to weather forecasts.

Are replaced by

New: The coupled ICON-CoCiP model developed for this study allows to forecast contrails interacting with the background atmosphere and allows us to investigate and quantify this feedback with respect to weather forecasts.

Page 1, L18: Contrails only reduce predictability if a model does not account for them. Better to say something like contrails affect the atmosphere and may increase predictability if their effects are simulated. Can you be specific about the effects (beyond ‘warming the upper troposphere’)

We replace the old sentences

Old: Contrails induce a butterfly effect that reduces weather predictability after a few days. Hence, contrails are predictable – but only for a finite period.

By New: Contrails induce a butterfly effect with disturbances growing with time. Contrails induce disturbances similar to random disturbances.

Page 1, L20: can you be quantitative about the effects?

Page 1, L21: Abstract. The ‘butterfly effect’ refers to chaotic systems with propagation of small scales perturbations up to larger scales. “Negligible global mean” values before the butterfly effect dominates is just saying that you cannot predict a daily global mean of contrail Ts or Precipitation signal given the noise in your methods. If you were able to reduce the noise (e.g. with a long simulation) you probably could determine regional mean results. It just means you cannot give global means given your configuration and ability to run the model.

Line 20 said:

Old: Effects on surface temperature and precipitation appear regionally random, with negligible global mean values before the butterfly effect dominates the results.

We now replace this sentence by

New: . Contrails change the surface temperature and precipitation locally by an order 1 K and 0.1 mm/day, with pattern similar to random disturbances and with magnitude depending on ambient weather, with negligible global mean changes.

Moreover we changed the abstract at other places to limit the number of words to 250.

Page 2, L58: The principle of the butterfly effect would imply that any perturbation should change the state of the atmosphere over time. Maybe better to say looking for systematic effects?

Page 2, L58 said: Old: Do contrails change weather forecasts at time scales of a few days significantly, e.g., by the butterfly effect (Lorenz, 1969; Zhang et al., 2003; Rotunno and Snyder, 2008; Selz et al., 2019)?

We replace this by New: Do contrails change weather forecasts at time scales of a few days significantly? Or are initial changes dominated by the butterfly effect (Lorenz, 1969; Zhang et al., 2003; Rotunno and Snyder, 2008; Selz et al., 2019)?

Page 3, L78: BOA —> SRF (surface)

Yes, the figure used SRF while the text used BOA. We now keep the BOA notation (see also reviewer 2) but induce the additional explanation “surface” after BOA .

Page 4, L95: Variance of what? The variance of temperature is just the seasonal cycle...

80 Old: The variance of the four simulations is one measure for the uncertainty of the mean values for these forecasts.

New: The variance of the contrail induced weather changes in the simulations for four different days over the year is taken as one of the measures for assessing the uncertainty of the mean values for these forecasts.

85 Page 5, L123: What about cloud fraction? Is there no cloud fraction in ICON at 26 or 13km? If not, is that realistic for contrail simulation to assume uniform properties in a grid box of that size?

Page 5, L145: So there is a cloud fraction in ICON. How does that interface with CoCiP? That should be explained somewhere....

The sentences in lines 118 to 123 explained what ICON provides as input to CoCiP. CoCiP takes grid cell mean values as input. We do not change this part.

90 Later, in old line 176, we insert that “CoCiP interpolates in the gridded fields ”.

Page 6, L149: but sub-visible Cirrus are real. So why would this be a non-linear bias? Shouldn't these clouds be included?

95 The subvisible cirrus has low concentrations of possibly large ice particles which interact only weakly with the dense concentration of very small ice particles in the contrails. Therefore, they are not taken into account.

Page 7, L183: what is the ICON time-step for the cloud physics?

100 The ICON time step for ice microphysics is 240 s in the coarse grid (120 s in the fine grid). The cloud physics uses the so-called advective time step of ICON. The dynamics uses a smaller time step through sub-stepping. Other physical parameterization like radiation or deep convection can have coarse time steps in ICON, but the cloud microphysics is always tied to the advective time step.

Old: The model can be run with fine and coarse horizontal resolution, with 737280 or 2949120 triangular grid cells, and 26.6 or 13.3 km mean grid scale, and 240 or 120 s time steps.

105 New: The model can be run with fine and coarse horizontal resolution, with 737280 or 2949120 triangular grid cells, and 26.6 or 13.3 km mean grid scale. The cloud physics uses the so-called advective time step of ICON, i.e., 240 or 120 s. The dynamics uses a smaller time step through sub-stepping.

Page 7, L184: I assume subscripts 1 and 2 correspond to contrails and no-contrails?

Yes, and that is explicitly stated in line 185 of the old manuscript. No change.

Page 7, L209: is this a double call to the radiation in the same simulation?

110 No, we have two runs, one with contrails and one without contrails and the ICON RF is computed from the difference between these two results. And that is what was said in these lines. “In the 2-way coupling, the contrail RF is computed with the ICON-internal radiation transfer model by taking the difference between results with and without contrails. “, But we now replace “results” by “the simulation results” -> No change.

115 Page 15, L363: only one line is visible in Figure 5d: suggest they need to be more differentiated from the other data in the plot panel.

We agree and change the plot accordingly. The 1-way result in panel 1 is now blue-colored.

120 Page 18, L420: what is the cause of the non-zero radiative interaction? Does it affect the results for large Tau?

As stated, the cause is related to radiative interaction of the added cirrus with the preexisting “background” cirrus but not understood in full detail. The effect is rather small, so: No change.

125 Page 19, L434: please remind the reader of what the change is in a sentence here. What findings? The difference in particle scattering?

Old: These findings triggered a revision of the CoCiP RF model as explained in Section 2.2.

New: The stronger nonlinearity of the ecRad results triggered a revision of the CoCiP RF model as explained in Section 2.2.

130 Page 24, L495: I see high RF (red) scattered all over the maps in Figure 11.

Old: In linear scales, we see strong net RF values only in areas with high traffic density.

And a few lines later: The variability extends far away from the regions with high traffic density.

New: These sentences are now combined:

135 As to be expected, we see strong net RF values both in areas with high traffic density but surprisingly large values with high spatial variability also in areas far away from the regions with high traffic density.

Page 24, L497: what is the noise level at this time? Might be good to plot the ‘noise’ as a function of time. (E.g. regions without air traffic, or with no contrails in the CoCiP RF areas.

140 We noted that the noise level is far higher than obvious in these plots, because the plots show 24 hour mean ν values, while the noise as high amplitudes a short time scales. This becomes obvious, e.g., in the spectra shown below. ->-No change.

Page 25, L530: If you area average figure 13 differences (or raw values of precip and then take a difference) do. You see any change in averaged precipitation over space (and time).

145 We have not done such area or time averaging but from all the results we do not expect to see a change in the mean values. -> No change

Page 29, L591: How do you define significance and can you show it on Figure 15? It is not obvious if the variability is large and the blue and red are not statistically different. I think you are right, but define it a bit better please.

150 Old: The colored curves reveal the mean temperature changes due to contrail feedback on average over the four runs. Here we show the results only for the first 5 days of the 10-days forecasts. The results for later forecast days are not shown because of increasing variability without significance. For the first 5 days, the significance is obvious when comparing to the twin-experiment results. The temperature changes indicate a mean warming in the ambient atmosphere at heights between about 6 and 13 km.

155 New: The colored curves reveal the mean temperature changes due to contrail feedback on average over the four runs. Here we show the results only for the first 5 days of the 10-days forecasts. The results for later forecast days are not shown because of increasing variability. For the first 5 days, we see that the

contrails induce a mean warming in the upper troposphere at heights between about 6 and 13 km. For the first five days, the contrail induced temperature increases are higher than the changes seen in the twin-experiments, so we see a significant contrail-induced warming.

160

Page 31, L613: Does ICON have a gravity wave drag scheme, or are you talking about resolved scale temperature perturbations. If large scale, how do you define gravity waves? Just a temperature perturbation? Or that it propagates (horizontally and/or vertically) as a ‘difference’ between two simulations? I’m not really sure that is a gravity wave, but it is plausible. Maybe a bit more explanation.

165 ICON does have gravity wave schemes for orographic and non-orographic gravity waves. As described in Zängl et al. (2015), the orographic gravity wave scheme, often called sub-grid scale orography (SSO) scheme, follows Lott and Miller (1997). The non-orographic gravity wave scheme is based on Orr et al. (2010). Nevertheless, being a non-hydrostatic model, ICON resolves part of the gravity wave spectrum and this explicit representation of gravity wave motions is relevant here.

170 In order to explain the results better without referring to the old references we replace

Old: Detailed inspection of the data reveals that the contrails change the local circulation and induce gravity waves spreading sideward and vertically, as expected (Jensen et al., 1998).

175 New: Detailed inspection of the data reveals that the contrails change the local circulation and induce temperature and velocity changes like gravity waves spreading sideward and vertically, as expected (Jensen et al., 1998). Besides using gravity wave schemes for orographic and non-orographic gravity waves, ICON, being a non-hydrostatic model, resolves gravity waves at least partly.

Page 31, L621: what is DKE? ΔKE ?

180 Old: the spectrum of kinetic energy KE of the horizontal windfield versus wavelength $2\pi/k$ with wavenumber k in the 1-way mode and the kinetic energy of the velocity differences DKE between the 2-way and 1-way simulation results. In addition, we show spectra KE_w of vertical velocity (w) and DKE_w of w-velocity differences.

185 New: mean variances and the mean spectrum of kinetic energy $KE=1/2 (u^2+v^2)$ of the horizontal windfield versus wavelength $2\pi/k$ with wavenumber k in the 1-way mode, and the kinetic energy of the spectrum of the horizontal velocity differences $DKE= 1/2 ((\Delta u)^2+(\Delta v)^2)$ between the 2-way and 1-way simulation results. In addition, we show mean values and spectra $KE_w=1/2 w^2$ of vertical velocity and $DKE=1/2 (\Delta w)^2$ of vertical velocity differences.

190 Page 36, L731: Figure 15 shows no significant surface warming, and in Figure 16 it is not significant (only the twin experiment).

Old: Just as thin cirrus clouds (Liou, 1986; Ackerman et al., 1988), contrails warm the ambient atmosphere mainly just below the contrails and cool the stratosphere above the contrails, with a net warming of ambient air (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Within the first 5 days after contrail formation, we see no systematic change in the global mean Earth surface temperature.
195 **Fehler! Verweisquelle konnte nicht gefunden werden.** and **Fehler! Verweisquelle konnte nicht gefunden werden.** indicate that the expected surface warming due to contrails takes more than 5 days to get notable.

200 New: Just as thin cirrus clouds (Liou, 1986; Ackerman et al., 1988), contrails warm the ambient atmosphere
mainly just below the contrails and cool the stratosphere above the contrails, with a net warming of ambient
air (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Within the first 5 days after contrail
formation, we see a net warming of ambient air at contrail levels but no systematic change in the global
mean Earth surface temperature. **Fehler! Verweisquelle konnte nicht gefunden werden.** and **Fehler!**
205 **Verweisquelle konnte nicht gefunden werden.** indicate that any expected surface warming due to contrails
takes more than 5 days to get notable.

Page 36, L751: can you comment on what effects you think dominates in the simulations?

The effects are listed sorted by the time scales.

210 **Old:** Basically, the weak surface warming is a consequence of several effects:

New: Basically, the weak surface warming is a consequence of several effects, here listed according to
their time scales:

*I'm not sure 8 is relevant: any small forcing over time will probably show a small difference: time can
overcome the heat capacity.*

215 You likely question point 7, not 8.

Old: 7) The higher pressure of the atmosphere at lower altitudes implies higher heat capacity of the air so
that the same amount of flux divergence causes less heating in the lower atmosphere.

220 New: 7) The higher pressure of the atmosphere at lower altitudes implies higher heat capacity of the air so
that the same amount of flux divergence causes slower heating in the lower atmosphere, increasing the
fraction of heat radiated back to space before reaching the surface.

Page 36, L754: But it shows the efficacy of contrail RF on the surface is low, and due to the other effects
above, might actually not be significant. ...

225

Old: Still, we do expect surface heating to occur after about 10 days, but we do not see this in the present
simulations because the nonlinear disturbances hide this heating. This does not exclude significant mean
long-term effects, and possibly indirect effects from tropospheric weather changes on the climate system,
including precipitation.

230 New: Still, we do expect surface heating to occur after about 10 days, but we do not see this in the present
simulations because the nonlinear disturbances hide this heating. This does not exclude significant mean
long-term effects, and possibly indirect effects from tropospheric weather changes on the climate system,
including precipitation.

... That's actually important I would say, and deserves more investigation.

235 We agree and extend the first sentence in the last paragraph of the paper:

Old: It would be interesting if the coupled ICON-CoCiP model could also be used to determine the long-
term climate impact of contrails.

New:

240 The slow response of the surface temperature to contrail RF deserves further investigations. It would be interesting if the coupled ICON-CoCiP model could also be used to determine the long-term climate impact of contrails.

Review 2 (Citation: <https://doi.org/10.5194/egusphere-2025-4512-RC2>)

Overview:

The manuscript reports the method used that allows a two-way interaction between a contrail model (CoCiP) and a numerical weather prediction model (ICON). The tests conducted demonstrate that the ICON model can generate realistic ice supersaturation without adjustment while the CoCiP model is able to predict contrail properties consistent with observations and reasonable radiative forcing. The feedback of contrails to weather is further explored. While a warming at flight altitudes is found, the changes of surface temperature, precipitation, and kinetic energy do not appear to be systematic.

The manuscript presents a detailed documentation of the method, with model tests that address the performance of each component. The exploration on the possible weather impact of contrails is also new and insightful. My only concern would be the interpretation of certain figures or results related to the comparison to the twin-experiment being a bit unclear, which may require more explanation or clarification.

Thank you for this assessment.

Main comments:

The interpretation related to the twin ICON runs is a bit unclear. From Section 1 (lines 64-67) and 2 (lines 103-107), the role of the twin ICON runs is to provide a reference for the effect of numerical noise and serve as a basis to determine if the changes due to inclusion of contrail feedback are significant (i.e. the changes are significant if they are systematically different from the changes due to initial noise perturbation).

We agree

However, in the latter discussion in Section 4, the wording in certain sentences or paragraph appears to confuse with this original aim. For instance, in the discussion of Figure 12 (line 518-521), “The lower panel in this figure show that contrails also impact precipitation” is stated and only at the end a comparison to the twin experiment is given to state that “the contrail effects are not much different from the random disturbances...”

In my opinion, the presentation for surface temperature in lines 517-518 (“...contrails indeed change the surface temperature... but hardly in a systematic and statistically significant manner.”) is clearer and the readers should be reminded of this fact.

Basically, we agree with your concerns. Part of your comments overlap with the comments by reviewer 1, and we have changed the related discussion as explained above.

For Figure 17 (similarly for Figure 18 as well), while the authors stated that the deviations in both the two-way coupled and twin experiments are amplified by the nonlinearity of the dynamics (lines 645-647), it is not mentioned that the contrail effect on KE or KE_w, at least with this model set up and resolution, cannot be distinguished from those caused by random disturbances significantly. This is an important value of the twin experiment, and the readers should be better informed.

In view of these remarks, we add at the end of section 4:

Hence, the contrail effects on atmospheric dynamics cannot be easily distinguished from those caused by random disturbances.

Another related question concerns the almost identical signals in Figure 12 for the left and right panels. The geographical distribution and spatial patterns of the signals are very similar for the experiment with contrails and for the twin experiment. In particular, the signals in regions with low traffic density (Figure 9) or low solar optical depth of contrails (Figure 10), e.g. precipitation over the southern part of the Indian Ocean (30-110E, 30-50S) or southeastern Pacific (near 90W, 40S), remain similar. I am therefore curious if the two-way coupling introduces numerical noise in regions without contrails (e.g. due to the interpolation error of the coupler (YAC)?), or if there is certain random component in the ICON model (e.g. stochastic parametrization or random parameters?) that may explain this similarity? Or if the authors would suggest that the similarity is the result of the contrail effect being amplified in regions that are sensitive to any perturbation, such that large changes show up in similar locations. (Similar to the explanation given for Figure 13, but extending to regions where contrails seems distant.) I think this question may be meaningful for the discussion in this manuscript.

We agree, these are relevant questions.

In the simulations presented in this study, we did not make use of any stochastic parameterizations or random parameters during the model integration. The similarity between the two-way coupled simulation and the random control simulation can be explained as follows: Random perturbations grow most effectively in regions with atmospheric instabilities like convective overturning or baroclinic instability. Those are the regions that can be identified in Figure 12. Due to the numerical discretization, disturbances propagate rapidly in the horizontal. In fact, although ICON is based on fully compressible equations it has super-sonic noise propagation due to the discretization of the horizontal diffusion (see e.g. Ancell et al. 2018, BAMS, who describe similar numerical artifacts in WRF). As a result, perturbations originating from contrails spread quickly across the globe, influencing even regions without contrails through (numerical) noise. In areas of instability, this noise can amplify and become visible in difference plots such as Figure 12.

In Section 2.1, we now state:

New: The ICON version used is free of any stochastic parameterizations or random parameters during the model integration.

Moreover, we thought a bit further on why the atmosphere responds to contrails and random disturbances similarly. We read again the papers by Selz et al. (2019 and 2022) and noted that they point out that disturbances grow not only in areas with convection but also in areas with horizontal wind divergence (with vertical motion) and by advection by the rotational wind. Those are the regions that can be identified in Figure 12.

Kästner et al. (1999) and Gierens and Brinkop (2012) noted that upward and divergent flows favor the formation of ice supersaturation, and ice supersaturation occurs often in anticyclonic flows. Hence, there might be atmospheric dynamics reasons for why contrails form mainly in regions where also random disturbances grow preferentially. This deserved further investigations.

Therefore, we now add the following paragraph to “5. Discussion and Conclusions”:

As noted by Selz et al. (2022), random disturbances grow most quickly in regions with atmospheric instabilities like convective overturning or baroclinic instability, depending on horizontal wind divergence, rotation advection and their scales. Kästner et al. (1999) and Gierens and Brinkop (ACP, 2012) noted that upward and divergent flows favor the formation of ice supersaturation, and ice supersaturation occurs often in anticyclonic flows. Hence, there exist dynamical reasons for why contrails form and persist often in regions where also random disturbances grow most strongly. This is supported by Figure 14 showing

obvious correlations in the ICON TOA and BOA RF responses and in the RF results due to contrails and due to random disturbances. Details deserves further investigations.

335 Below are specific comments or technical corrections:

Lines 17-18: Are contrails “inducing” butterfly effect or their effect cannot be distinguished from the typical butterfly effect of initial perturbations?

Old: Contrails induce a butterfly effect that reduces weather predictability after a few days.

340 New: Contrails induce a butterfly effect similar to random disturbances that reduces weather predictability after a few days.

Line 40: The full name of ICON can be introduced already here, or even earlier in the abstract.

Done (but we shortened the abstract otherwise to stay below the limit of 250 words)

345 Figure 1: The variable “SRF-rad” should be “BOA-rad” in the figure.

Changed!

Line 100: “rms” can be introduced here rather than line 260.

Changed!

350 Line 114: Is it correct that the fine grid, 2-day simulations are only used for results in Section 3, and the results in Section 4 is only based on the coarse grid, 10-day simulations?

Yes, correct, and the resolution is now noted in the figure captions 10 to 12.

Line 119: Is “ τ_{cirrus} ” the same as TACI? It is not found in Figure 1.

Yes, TACI= τ_{cirrus} ; now noted in the figure caption of Fig.1

355 Lines 130-154: This part is quite technical, which is great for modellers. The authors may consider summarizing the most important points for general readers and move the details to an appendix. However, this is just a suggestion.

We thought about this but decided not to put this into an appendix. That would (slightly) increase the total space required and the paragraph begins with “To address these issues, ...”, which clearly says to the reader that the next lines cover technical issues.

360 Lines 290-291: Could the authors add a reference to the table or figures that support “the 4-8% higher mean RH_i” in the model? I cannot find this number.

The caption of Figure 2 now ends with New: “The red correlation line in the top panel indicates that the ICON RH_i values are about 5% higher than the radiosonde data in the analysis for SAC satisfied.”

The 5 % value is consistent with the sum of the coefficients a+b in Table 1 as was noted in the text.

365 Lines 268-270: When compared to IFS, are the radiosonde RH_i computed with the ice saturation pressure function used in the IFS (as in line 325)? It is previously mentioned in line 239 that the ICON formulation is used. Would that affect the score of IFS?

370 Yes, we use the ice saturation pressure function of IFS when comparing IFS data to the data derived from the radiosondes and the ice saturation pressure function of ICON when comparing ICON results to the same data.

Old line 238: The relative humidity over ice is then computed with the ice saturation pressure function as used in ICON (Hanst et al., 2025).

375 New: The relative humidity over ice is computed with the ice saturation pressure function as used in ICON (Hanst et al., 2025). When comparing radiosonde data with IFS forecasts we use the IFS ice saturation pressure function.

380 [Lines 274-275: Is this conclusion derived from the fact that ICON scores are higher than IFS scores? Since ICON and IFS have many more differences than just the microphysics scheme, is a comparison between ICON simulations with 1-moment and 2-moment microphysics schemes be more suitable to justify this statement?](#)

No, the conclusions is also the result of comparisons of the 2-moment ICON version (ICON 3) to the 1-moment ICON version (ICON1) as presented by Hanst et al. (2025). This is now clarified at the beginning of this section.

[Line 296: “where” -> “are”/“were”](#)

385 Thanks, Corrected.

[Line 306: Would “near” instead of “at” the tropopause be more suitable? RHi agrees exactly at around 9 km, but show very large differences above and below.](#)

Yes, corrected.

390 [Figure 4: There is an extra “a\)” in x-axis of the first panel. If possible, the three x-axes can use the same limits \(up to 1.6\)](#)

Corrected.

[Line 378: Figure 6 b to d show ageing contrails. Do the authors mean “form” or “persist” in this sentence?](#)

Yes, changed to “form and persist” .

[Line 407: Figure 7c is not exactly “corresponding” to 7 a and b \(only ICON results are shown\)](#)

395 Old: Figure 1 c shows corresponding results at the surface (BOA).

New: Figure 1 c shows corresponding ICON results at the surface (BOA).

400 [Lines 417-421: Are the references to 7a and 7b correct in this paragraph? To me, the stepwise change is visible in 7b, but not 7a. Also, when background clouds are excluded, does it correspond to 7a? The terminology of “added cirrus” and “background cirrus” used in the paragraph is not the same as that used in the figure caption \(“with or without other cirrus”\), which is a bit confusing. The authors may consider using consistent names here.](#)

Old: In the submitted version, the panels a and b were a) without background, b) with background cirrus

405 The RF fluxes are zero for $\tau_{\text{cirrus}}=0$, as expected, but the ecRad-results show a small stepwise change to nonzero values for small τ_{cirrus} , see Figure 1 a and c. This irritating behavior was found to be due to radiative interaction of the added cirrus with the preexisting “background” cirrus. It disappears when the background clouds are excluded from the radiation transfer analysis in ICON-ecRad, see Figure 1 b and the full curves in Figure 1 c. Without background cirrus, the RF values start, as expected, linearly from zero for small values of τ_{cirrus} .

Figure 1. Results of a radiation model test for shortwave (SW), longwave (LW) and net (LW+SW) radiative forcing (RF) from a globally homogenous cirrus layer versus its solar optical depth (τ_{cirrus}) as obtained with ICON-ecRad (coupled in 2-way mode) and with the libRadtran based CoCiP (uncoupled 1-way mode, coarse grid). The lines and error bars represent the mean values and rms deviations for 4 days. a) Top of the Atmosphere (TOA), for case without other cirrus from CoCiP (dashed) and ICON (full lines). b) Same with other cirrus. Note that the curves start from nonzero RF for small $\tau_{\text{cirrus}} > 0$. c) Bottom of the Atmosphere (BOA) as derived from ICON-ecRad with (dashed) and without (full lines) other cirrus.

New: In the revised version, the panels a and b are interchanged, a) with background, b) without background cirrus

The RF fluxes are zero for $\tau_{\text{cirrus}}=0$, as expected, but the ecRad-results show a small stepwise change to nonzero values for small τ_{cirrus} , see Figure 1 a and c. This irritating behavior was found to be due to radiative interaction of the added cirrus with the preexisting “background” cirrus. It disappears when the background cirrus is excluded from the radiation transfer analysis in ICON-ecRad, see Figure 1 b and the full curves in Figure 1 c. Without background cirrus, the RF values start, as expected, linearly from zero for small values of τ_{cirrus} .

Figure 2. Results of a radiation model test for shortwave (SW), longwave (LW) and net (LW+SW) radiative forcing (RF) from a globally homogenous cirrus layer versus its solar optical depth (τ_{cirrus}) as obtained with ICON-ecRad (difference between coupled and non-coupled mode) and with the libRadtran based CoCiP (uncoupled 1-way mode) on coarse grid. The lines and error bars represent the mean values and rms deviations for 4 days. a) Top of the Atmosphere (TOA) from CoCiP (dashed) and ICON (full lines), for case with background cirrus. b) Same without background cirrus. Note that the curves start from nonzero RF for small $\tau_{\text{cirrus}} > 0$ in panel a). c) Bottom of the Atmosphere (BOA) as derived from ICON-ecRad with (dashed) and without (full lines) background cirrus.

Lines 476-477: Apart from these signals, there are also localized maximum of the increase in solar optical depth of contrails in Figure 10 panel bottom right in the Eastern US. Is there any explanation for these signals?

Old: This shows that the optical thickness is mostly just a little smaller with 2-way atmosphere feedback than without (1-way coupling).

New: In the blue colored domains, the optical thickness is slightly smaller, as expected because the 2-way atmosphere feedback reduces the ambient humidity. But, In the red colored domains, the optical thickness is locally much larger (e.g. over Eastern USA) indicating unexpected nonlinear coupling effects discussed further below.

Figure 11: For the twin experiment panels, the top right number is “18” instead of “48”. Are they typos or do they actually correspond to forecast hour 18 instead of 48?

Thank you for identifying this issue. In fact, the figure was wrongly copied and is now corrected

Lines 500-505: Related to the main comments, would this “near-random” displacements of clouds be a possible explanation for the similarity between the experiment with contrails and the twin experiment?

Yes, there is a similarity but this is discussed further later in the paper. -> No change here.

Line 520: Are the numbers 0.5 mK and 0.4mm/day the average over the 4 simulations initialized at the 4 different dates? They appears to be inconsistent with the numbers shown in Figure 12.

Yes, the dates have been checked and are not lightly corrected.

Line 530: The authors may consider adding a short summary of the major take-home messages for Section 4.1 here. Since numerous aspects are discussed, it may be a good place to remind the readers the major conclusion from this part of the analysis.

Here we add the sentence:

New: The results so far have shown several changes in the contrail effects due to the two-way coupling and partly surprising similarity between contrail and twin experiments. In the next section, these effects will be further discussed with respect to the mean values and then summarized in Section 5.

Line 547: missing “.” after “error bars”

Corrected

Line 552: “these two ICON simulations” <- which two are referred to? Combining with the previous paragraph, it seems to be the one-way and two-way simulations. However, the top panel of Figure 14 show the one-way and the twin experiment.

and

Line 555: Similarly, “two ICON runs” may be better clarified to avoid confusion. (This time should be one-way and two-way simulations.)

Old: At TOA, we expect a SW cooling, LW warming, and net warming. This is confirmed with the CoCiP RF model, see the top panel in **Fehler! Verweisquelle konnte nicht gefunden werden..** The contrail RF is computed with CoCiP for these two ICON simulations but without contrail feedback on ICON. Here any random disturbance in the ICON initial values has negligible impact. The mid panel shows the differences between two ICON runs, with and without contrail feedback, and we see the same tendency, but large differences in the details. The ICON-SW effect is not strictly negative and the ICON-LW and Net RF values are nearly double the CoCiP values. With the coupled ICON-CoCiP model we also can compute the RF at the bottom of the atmosphere (BOA or surface), see bottom panel of **Fehler! Verweisquelle konnte nicht gefunden werden..** As to be expected, the RF magnitude is smaller at BOA than at TOA and tends to be slightly negative, though with scatter larger than the mean.

New: At TOA, we expect a SW cooling, LW warming, and net warming. This is confirmed with the CoCiP RF model, see the top panel of **Fehler! Verweisquelle konnte nicht gefunden werden..** The contrail RF is computed with CoCiP for these two ICON simulations but without contrail feedback on ICON. Here any random disturbance in the ICON initial values has negligible impact. The mid panel shows the differences between two ICON runs with and without contrail feedback, and we see the same tendency, but large differences in the details. The ICON-SW effect is not strictly negative and the ICON-LW and Net RF values are nearly double the CoCiP values. Random disturbance in the ICON initial values have strong impact on RF. With the coupled ICON-CoCiP model we also can compute the RF at the bottom of the atmosphere (BOA or surface), see bottom panel of **Fehler! Verweisquelle konnte nicht gefunden werden..** As to be expected, the RF magnitude is smaller at BOA than at TOA and tends to be slightly negative, though with scatter larger than the mean.

Lines 588-589: With reduced humidity, is the age longer or shorter? I am confused by the phrase “only 2% longer”.

You likely refer to lines 578-579.

495 Old: In the 2-way mode, with reduced ambient humidity, the age is only 2 % longer because of reduced ice particle sedimentation, but the EF is 28 % smaller because of optically and geometrically thinner contrails.

New: In the 2-way mode, with reduced ambient humidity, the age is 2 % longer likely because of reduced ice particle sedimentation, but the EF is 28 % smaller because of optically and geometrically thinner contrails.

500 To the background. Normally we expect a decrease of mean age for reduced ambient humidity (Gierens and Unterstraßer, 2010) but this is not the case here, and therefore the sedimentation effect is mentioned.

Lines 616-617: Could the authors provide further explanation of what exactly are “numerical disturbances near the resolution limit”?

505 Old: In addition, the contrail disturbances may overlap with numerical disturbances near the resolution limit.

New: In addition, the contrail disturbances may overlap with numerical disturbances near the resolution limit, e.g., as identified by Korn (2017).

Figure 17: For the DKE twin (long dashed grey lines), are there only 5 days shown instead of 10?

510 Yes, now corrected. No also included the 1/3 power line of mesoscale vertical velocity spectra (Schumann, 2019)

Lines 659-660: As the contrail results is similar to that for the initial disturbances, does it mean that contrails do not significantly foster or slow down the “loss of memory” (or predictability) compared to initial value error?

515 **Old:** We also prepared such plots from the twin experiments with initial disturbances varying from 10^{-14} to 10^{-10} . We found that the results look very similar to the contrail results, and are virtually independent of the initial amplitude of the random disturbances applied.

New: We also prepared such plots from the twin experiments with larger initial disturbances of 10^{-10} instead of 10^{-12} . We found that the results are virtually independent of the initial amplitude of the random disturbances applied and look very similar to the contrail results in both cases. So, contrails influence forecasts similar as initial value errors.

520 Lines 731-732: Figure 15 does not show surface warming nor the evolution beyond 5 days. Figure 16 also show no significant change in T2m, but warming at 11km. The conclusion has to be better justified.

Old: **Fehler! Verweisquelle konnte nicht gefunden werden.** and **Fehler! Verweisquelle konnte nicht gefunden werden.** indicate that the expected surface warming due to contrails takes more than 5 days to get notable.

525 New: **Fehler! Verweisquelle konnte nicht gefunden werden.** and **Fehler! Verweisquelle konnte nicht gefunden werden.** indicate that any surface warming due to contrails would take more than 5 days to get notable.

530 Lines 738-750: I assume that this part is suggesting different possible causes of the weak surface warming by referring to other studies. I would therefore suggest changing the first sentence “...the weak surface warming is a consequence of...” to “...the weak surface warming may be explained by...”.

Done.

Lines 755-759: This paragraph seemingly lacks evidence in the manuscript. Apart from one sentence in lines 612-613, there is no clear support for the mechanism described here. In particular, the disturbance may be related to numerical methods (lines 771-776). Therefore, I suggest rephrasing this part, with this study providing insights on the possible impact of contrails on dynamics in weather timescales, but requires further investigation to confirm.

We have repeated the spectral analysis shown in Fig 17 now also with the fine grid (though only for 3 instead of 10 days integration time). Now, it becomes obvious that the spectra are also affected by the grid resolution and the numerical approximations used. This better justifies the conclusions.

New: See the changes in the paragraph describing Figure 17.

and

Old: Line 755 etc.: Contrails cause disturbances to weather dynamics, see, **Fehler! Verweisquelle konnte nicht gefunden werden.** etc. The warming of air inside and below contrails induces weak updrafts and local circulations. Often, the local buoyancy induces weak gravity waves spreading horizontally. Depending on ambient stability, contrails change the local atmospheric circulation in the whole troposphere in the neighborhood of contrails forming, and later also the lower stratosphere. With the speed of gravity waves and sound, the disturbances from contrails spread horizontally and soon change the atmospheric dynamics in a larger horizontal domain.

Old, Line 771 etc.: Part of the quick spread of disturbances might be caused by the grid discretization and the numerical integration method used in ICON. In fact, as in other models (Ance11 et al., 2018), small numerical disturbances spread in ICON even faster than with the speed of sound because of the iterative scheme used for advection. ICON uses numerical damping methods which spread small disturbances with decreasing amplitudes vertically and horizontally (Zä11gl et al., 2015). The grid approximations used so far may underrepresent the coupling of the three momentum components by mass conservation, causing checkerboard-noise in the vertical velocity divergence pattern (Korn, 2017) and possibly other disturbances (Langguth et al., 2020; Gassmann, 2021).

We reduce these part as follows:

New: As shown above, contrails cause disturbances to weather dynamics, see **Fehler! Verweisquelle konnte nicht gefunden werden.** etc. Closer inspection of the data details (not presented) shows that the warming of air inside and below contrails induces weak updrafts and local circulations resolved in the numerical model. The disturbances spread quickly horizontally and soon change the atmospheric dynamics in a larger horizontal domain How realistic these disturbances are simulated and how they spread and interact with the weather at ICON scales in detail has not yet been investigated.

And a bit later:

New: As evidenced by Figure 17, part of the growth of disturbances is caused by the grid discretization and the numerical integration method used in ICON. In addition, although ICON is based on fully compressible equations, we noted super-sonic noise propagation due to the discretization horizontal diffusion (Zä11gl et al., 2015), as also seen in other models (Ance11 et al., 2018). Moreover, the grid approximations used so far may underrepresent the coupling of the three momentum components by mass conservation, causing checkerboard-noise in the vertical velocity divergence pattern (Korn, 2017) and possibly other disturbances (Langguth et al., 2020; Gassmann, 2021). Hence, it might be worthwhile to couple CoCiP also to other NWP schemes to see how far the noise depends on the numerical methods used.

Finally, we went over the abstract and the manuscript with some further minor changes.

Abstract New: and complete (exactly 250 words)

Contrail forecasts typically neglect feedbacks with the atmosphere. Here, we couple the Contrail Cirrus Prediction model (CoCiP) with the global Icosahedral Non-hydrostatic (ICON) numerical weather model in a two-way mode accounting for contrail-weather interaction. The models exchange atmospheric and contrail state variables after each time step using the coupler YAC. ICON includes a new two-moment cloud ice microphysics scheme that enables skillful predictions of ice supersaturation. CoCiP now limits the uptake of ambient ice supersaturation when many contrails form. Radiation is calculated in ICON using the ECMWF radiation scheme ecRad. Contrail radiative forcing is computed from the difference of ICON results with and without contrail feedback. The coupled system results are broadly consistent with offline CoCiP simulations. The ICON results are validated against radiosonde observations and compared with ECMWF forecasts with improved score values. The significance of the computed contrail effects is tested by numerical noise perturbation or twin experiments comparing the results of forecast pairs with initial values differing randomly. Contrails induce a butterfly effect with disturbances growing with time. Contrails induce disturbances similar to random disturbances. Within the first 5 days, contrails warm the ambient air at contrail levels. Contrails change the surface temperature and precipitation locally by an order 1 K and 0.1 mm/day, with pattern similar to random disturbances and with magnitude depending on ambient weather, with negligible global mean changes. After 5 days, the weather changes are dominated by the butterfly effect. The slow response of the surface temperature to contrail RF deserves further investigations.

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