Review of “Understanding the Role of Contrails and Contrail Cirrus in Climate Change: A Global Perspective” by Singh et al. (2024)

Overview

The manuscript summarises the microphysical processes concerning contrail formation, ageing and transition into cirrus clouds. The current understanding of the role of aviation soot in affecting contrail formation and cirrus activation is reviewed, from all three perspectives of in situ measurements, remote observations, and modelling. Recently gained knowledge of contrail cirrus occurrence from filed observations is highlighted in the paper. The article emphasised two key impactors that causes the high uncertainties in estimating the climate impact of contrail cirrus, namely contrail coverage and soot indirect effect. Available contrail observation datasets models for contrail property and evolution studies, and for understanding the climate impact of contrail now and future are listed in the manuscript. The uncertainties and research gaps in contrail cirrus and its radiative forcing are identified by the authors. Research needs for a better understanding of the impact of contrail cirrus are pointed out in the manuscript to bridge the knowledge gaps. Finally, the manuscript looks into the current status of contrail avoidance and climate trade-offs from the aspects of slightly deviating the aircraft from contrail forming regions and using climate-friendly aviation fuels.

The manuscript is well written with a clear structure and is easy to follow. However, to have a comprehensive understanding of the role of contrails and contrail cirrus in climate change and the status of the knowledge, there are some more aspects that the authors should elaborate.

Major comments:

1. The authors detailed the different processes evolved in contrail formation, evolution and transition into cirrus clouds. It is of high importance to understand these processes, which also lay the foundation for the modelling of contrails and contrail cirrus’s radiative impact. However, the radiative impact of contrail cirrus (including linear contrails) is closely associated with optical properties and the coverage of contrail cirrus, in which the age of contrail cirrus plays an important role. As this is a review article, it would be good to provide an overview (a summary table or view graph) of contrail characteristics (size, number density, extinction properties, width, length, optical depth…) at various stages of contrail formation and evolution, namely jet, vortex, dissipation, and diffusion regimes, respectively, especially in the diffusion stage, during which the radiative impact is the most critical, from the perspectives of both measurement and modelling.
2. In Sect. 3, the authors introduced difference models for contrail properties and evolution in individual and overlapped contrails cases. Microphysical processes implemented in the models are described briefly. The treatment of contrails in global models is also reviewed. The Hadley Centre climate model HadGEM2 from the UK Met Office has also been implemented with contrail parameterization for evaluate contrail’s radiative forcing.

   Rap, A., P. M. Forster, A. Jones, O. Boucher, J. M. Haywood, N. Bellouin, and R. R. De Leon (2010), Parameterization of contrails in the UK Met Office Climate Model, *J. Geophys. Res.*, 115, D10205, doi:10.1029/2009JD012443

I suggest the authors add a cross-model intercomparison and assessment table, especially for the multiple models for simulating contrail properties and lifespan and evaluate the models against observations. From this, the readers will get a comprehensive overview of the performance of current available contrail models. It will also outline what is need in the future for model development from the perspective of properly characterise contrails and contrail cirrus.

3. The same for Sect. 4. The authors reported independently the results from various climate impact models and future RF projections. The agreement and disagreement between models on the climate impact of contrail cirrus now and in the future are not discussed. And if there are any disagreements, what are potential causes for the models to behave differently.
4. (1) In Sect. 5, several observational datasets that are directly linked to contrail and detection, such as air traffic data, engine emission indices, in-situ contrail observations and satellite image libraries, are included. However, it is also highly important to include datasets with critical parameters for contrail formation, such as temperature and relative humidity with respect to ice in the upper troposphere and the tropopause region. One of such datasets is provided by the In-service Aircraft for a Global Observing System (IAGOS) research infrastructure with high spatial and temporal resolution, which has already been used for contrail occurrence studies and assessment of forecast models, e.g., Gierens et al., 2020 (doi:10.3390/aerospace7120169).

   (2) Regarding the satellite-based contrail dataset, the human-label contrail datasets, the AI detection and machine learning algorithms are helpful in monitoring contrails, perhaps even for contrail lifetime and coverage studies. The case studies mentioned by the authors are mostly based on contrails with clear line shapes. However, these datasets are rather small and are limited to certain regions, camera angels and quantities and spatial resolution. I am not convinced it is of great help to improve the estimation of contrail's radiative forcing which are closely associated with contrail ice particle microphysical and optical properties. To achieve this, contrail optical thickness should be retrieved, which are not well resolved by satellite images and rely on robust retrieval algorithms. Furthermore, satellites cannot detect contrails until tens of minutes later, and overlapped contrails and embedded natural cirrus add extra challenges to contrail detection and parameterization for satellite observations. Finally, ice supersaturated regions in the UTLS, where contrails prefer to occur, exhibit strong variability in locations, time and scales. From all above, I think the authors should be prudent in judging the capability of satellite contrail datasets and AI detection algorithms to support contrail mitigation and robust estimation of contrails' climate impact.

5. Sect. 7 Microphysical processes of contrail formation in relation to the role of soot/background aerosols and heterogeneous/homogeneous freezing mechanism also poses big uncertainties in understanding the effects of contrails. Though it is known that fresh contrail contains thousands of ice particles, it is still debated on the ice nucleating properties of soot particles for contrail formation, see e.g.,

   Righi et al., Exploring the uncertainties in the aviation soot–cirrus effect, Atmos. Chem. Phys., 21, 17267–17289, https://doi.org/10.5194/acp-21-17267-2021, 2021

Testa et al., Soot aerosol from commercial aviation engines are poor ice nucleating particles at cirrus cloud temperatures, EGUsphere [preprint], ttps://doi.org/10.5194/egusphere-2023-2441, 2023

Testa et al., Contrail processed aviation soot aerosol are poor ice nucleating particles at cirrus temperatures, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-151, 2024

Contrail-cirrus observation, either with remote-sensing or in-situ measuring technique, has high requirements for instrumentation, facilities, and platforms, technically and financially. In-situ instruments provide high temporal and resolution data but must meet the harsh conditions of cold temperatures, vibrations and limited dimensions for airborne measurements. The measurement of soot cores at extremely cold temperatures ~60°C is challenged so far with ice nucleating particle counter. To integrate a complete set of high precision instruments for contrail cirrus properties is also demanding. Remote-sensing techniques are vulnerable to the blender of natural and contrail cirrus and should be provide high enough temporal and spatial resolution to track the width, length, depth of the contrails, etc.

Further research is also needed to address these uncertainties and gaps.

6. Water vapour observation and humidity sensors. Dense, wide-coverage and high-resolution temperature, water vapour and relative humidity with respective to ice (RHi) are essential for studying and predicting contrail occurrences and properties. In particular, these data should be provided with high accuracy and precision. They are also valuable for evaluating weather and contrail forecast models. The IAGOS infrastructure provides quality checked temperature and RHi data obtained from routine passenger aircraft measurement since 1994, which have been used in various studies. The IAGOS capacitive hygrometer is the same prototype of Humicap sensor from Vaisala that are widely used in weather balloon sondes. It is one of the three operational global water vapour observation programmes as documented in the WMO report on supporting water vapour measurements within an aircraft meteorological data relay programme. The other two technology types for aircraft-base water vapour measurement are the Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor system and the Water Vapor Sensing System II (WVSS-II) developed by FLYHT, which provide data to meteorological centres. Rolf et al. (2023) has conducted an evaluation of compact hygrometers for continuous airborne measurements in the range of 20 to 20,000 ppmv.

   Rolf et al., Evaluation of compact hygrometers for continuous airborne measurements, Meteorol. Z. 2023 Vol. 20 Issue 20, DOI: 10.1127/metz/2023/1187

   Basically, the technology for airborne water vapour and humidity sensor are well established. What matters more is the quality of the data, maintenance of the programmes and the joint between datasets and programmes. How to incorporate the programmes and networks to facilitate contrail observation, reconcile observations with contrail forecasting, and conduct safe contrail mitigation are still missing and should address in future research.

7. In the conclusion, the author should elaborate what is the well-established knowledge and where are the research difficulties and gaps that careful investigation and dedicated research is required.

Minor comments:

Some of the figures and tables are not well clarified in short captions with abbreviations, e.g., Figure 7 and Table 2, Table 4, etc. The colour bar scales and ticks are not readable, e.g., Figure 13.

Line 55: Why not just use "Aviation-induced cirrus" instead of "Contrails and resulting contrail clouds formation"?

Line 78: "Many global climate chemistry models used to study … do not incorporate the impacts Models that do account for contrails…": What impacts does the author mean, e.g., contrail cirrus characteristics, contrail parameterization or so?

Line 136: "optical characteristics and lifespan of contrails are significant dynamics of contrail formation and…": "dynamic" is usually referred to the movement of air parcels. Does the author mean "optical characteristics and lifespan are key aspects of contrail formation"?

Line 232: Previous studies have studied the occurrence frequency distributions of ice-supersaturated regions (ISSRs) with high temporal-resolution aircraft measurements. The variabilities of ISSRs in the upper troposphere and in different regions with high air traffic density have also been explored using aircraft and weather forecast reanalysis data, such as:

> Petzold et al., Ice-supersaturated air masses in the northern mid-latitudes from regular in situ observations by passenger aircraft: vertical distribution, seasonality and tropospheric fingerprint Atmos, Chem. Phys. 2020 Vol. 20 Issue 13 Pages 8157-8179
>
> Reutter et al., Ice supersaturated regions: properties and validation of ERA-Interim reanalysis with IAGOS in situ water vapour measurements, Atmos. Chem. Phys. 2020 Vol. 20 Issue 2 Pages 787-804

Line 242-246: The two sentences repeat each other.

Line 271: The impact of soot on contrails and soot was discussed based on mostly old literature. There were new studies appearing in the past years, e.g., Testa et al. (2023 and 2024). The authors should sample more recent studies to provide the current understanding in this topic.

Line 280: The authors described the cirrus observation near Munich in 2012 and traced soot emissions related to the cirrus formation with back trajectories. Can the authors provide the source of the case study? Or give more details on the observation and back-trajectory calculations?

Line 334: The authors cited Wolf et al. (2023) for their exploration of the dependence of contrail cirrus RE on different parameters. Can the authors refine the main messages of Wolf et al and provide readers an overview on the impact of these parameters or conclude which parameter have the greatest impact on cirrus RF?

Line 357: In this paragraph, the authors discussed dynamics and ice crystal evolution in the wake within the regimes of vortex dissipation and diffusion. Figure 6 is used here to illustrate the contrail formation processes in aircraft vortex. However, the processes in Figure 6 are happening within ~100 sec upon the emission of aircraft exhaust, namely the het and vortex regimes in Figure 5. It fits more in the previous paragraph.

Line 446: “In exhaust rich in soot, the number of soot particles… increases with decreasing ambient temperature. This, in turn, raises plume cooling rates and levels of plume supersaturation over liquid water.” The causal relationship is reversed. The increased cooling rates and supersaturation is caused by decreasing temperature in the plume, not by the increasing of soot particles. The freezing of water vapour on particles would actually release heat and consume the supersaturation in plume air masses.

Line 462: in the context of contrails formation → in the context of contrail formation

Line 526: Sect. 2.7. The authors sampled recent studies reporting the observations of contrails and contrail cirrus in slightly ice-subsaturated environments, which is new knowledge of contrail formation and evolution. However, as this subsection is about lessons learned from observations of contrails and their properties, the authors may also consider from measurement perspective the limiting factors of contrail property observations.

Line 569: Mahnke et al. (2022) was cited, but it didn’t appear in the reference list.

Line 638: In this study → In this model

Line 671 and Line 679: The order of the two paragraphs can be reversed for readability.

Line 719: This sentence repeats the previous one.

Sect. 3.2.2: Paragraph 2-4. Regarding the development of the contrail cirrus parameterization in the mode ECHAM5-HAM, the content jumps back and forth. Following a chronological order of the citations may show the improvement of the parameterizations in the model better. Paragraph 3 and 4 can be combined by saying “Bock and Burkhardt (2016) extended the contrail cirrus parameterization (CCMod) initially proposed by Burkhardt and Kärcher (2009) by introducing contrail cirrus ice crystal number concentration and volume as additional prognostic variables.”.

Line 990: I guess the authors mean that the maximum flight density will occur at a higher, rather than a lower, altitude around 200 hPa in2050 compared to 240 hPa in 2006, if flight altitudes are expected to rise by 0.3 to 1.5 km. From Table3, readers cannot recognise which row represents the projection resulted from altitude increase. The authors should explain shortly the different simulated scenarios. “They found that the maximum flight density would occur at a lower attitude in 2050” is redundant (Line 991).

Line 1016: mWm-2 -> mW m^{-2}, the same elsewhere in the context.

Line 1037: With the values listed in the table, a 3-4-fold increase is expected in central Europe, and over 400% increase in North America. For readability, the authors should note shortly what stands for RCP4.5, RCP 8.5, SC1, 2 and 3.

Line 1133: The Schmidt-Appleman criterion is commonly cited as Schmidt, 1941, Appleman,1953 and Schumann, 1996.

Line1413: “rarer but more ice crystals” -> rarer but larger crystals

Line 1470: The paper by Moor et al. (2017) reported soot reduction at cruises with adequate measurements and should be added here.

Line 1472: “Our study involved the measurement …” -> Their study…

Formatting issues:

1. Line 110: The formatting of subsection title is not in coherence with the other subsections. There is a mixture of British and American English, e.g., “Ageing” and “Aging” (Line 106).
2. Punctuation. Period is missing, e.g., Line 78, Line 1041, or Line 1120 repeated period, Line 570 mistake, and Line 491 with uppercase after a comma).
3. Citations. Author names are missing in Line 827 – 828. Citation formatting error, e.g., Line 1140: Minnis et al. (1998 and Minnis et al. 2013).
4. References. The references are not in the same format. Some have a DOI, while many other don’t. A DOI should be provided to each reference. The font style and size are not the same through the list.