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Review of Past Decade of Aviation Contrail Research: Insights and Future Directions for Operational Mitigation

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Abstract

Airline operators require reliable and accurate contrail prediction for effective operational mitigation. While scientific understanding of aviation-induced contrails has improved over the past decade, significant challenges remain, particularly uncertainties regarding relative humidity and physics modeling. The Ames Contrail Simulation Model (ACSM) was developed over a decade ago, in the early 2010s. The goal of this report is to update scientific findings since that initial development and propose improvements to ACSM.

The lifecycle of contrails involves a series of complex cloud microphysics processes. This report is intended for both atmospheric scientists studying aviation contrails and for readers from other fields, such as air traffic operation researchers and software engineers, who seek to understand the physics behind aviation contrails.

Table of Contents

1. Introduction

Airline operators require reliable and accurate contrail prediction for effective operational mitigation. While scientific understanding of aviation-induced condensation trails (contrails) has improved over the past decade, significant challenges remain, particularly uncertainties regarding relative humidity and physics modeling. The Ames Contrail Simulation Model (ACSM) was developed over a decade ago, in the early 2010s. The goal of this report is to update scientific findings since that initial development and propose improvements to ACSM.

This report is organized as follows: Section 2 reviews key research work on aviation contrails. This work is further categorized into several subtopics: updates on the general scientific understanding of contrails and their impacts, key challenges, and gaps in contrail prediction for operational mitigation, alternative contrail models besides the Contrail Cirrus Prediction tool (CoCiP) and ACSM, operational mitigation strategies, and contrail identification using satellite and in situ observations. In particular, the research work using satellite data to detect and track contrails, including recent machine learning approaches, is discussed in detail. Section 3 reviews the most widely used CoCiP tool, which has become the benchmark physics-based contrail prediction tool. A new python library based on CoCiP model, called pycontrails, provides open-source access. Section 4 begins with an overview of the ACSM models, followed by several proposed improvements. Section 5 contains the conclusion and plans for future work. Future work includes developing a new contrail prediction tool based on an enhanced ACSM model, comparing the results with pycontrails, and integrating the contrail prediction tool with National Aeronautics and Space Administration (NASA)’s satellite platform to predict and validate contrails in an end-to-end system.

2. New Scientific Findings

While predicting contrail formation is generally accomplished, accurately predicting consistent contrails remains a major challenge due to the inability of current numerical weather prediction models to reliably predict ice supersaturation at specific times and locations. Satellite images can directly capture contrails, particularly young, linear contrails. Recent advances in machine learning have shown promising progress in identifying contrail locations, extracting geometric and optical properties, and estimating radiative forcing (RF), when linear contrails and contrail cirrus are observable. Singh et al.'s review article provides a comprehensive overview of contrail microphysics processes [1]. A new report from the National Academies of Sciences, Engineering, and Medicine, sponsored by NASA, provides recommendations to develop a national research agenda to better understand, quantify, and support the development of technical and operational solutions to significantly reduce the global climate impact of aviation-induced contrails from commercial aviation [2].

2.1 General understanding of aviation contrail climate impact

In a 2018 Nature Communications article [3], Karcher from the German Aerospace Center (DLR), presented a comprehensive review of aviation induced contrails (AICs). Overall, the AICs are estimated to have a greater climate impact, measured by their RF, than carbon dioxide (CO_2), as shown in Figure 1. However, the estimates carry significant uncertainty due to the complexity of the problem, e.g., modification of natural cloud by particle emissions. As of yet, no scientific consensus about the overall climate impact has been reached.

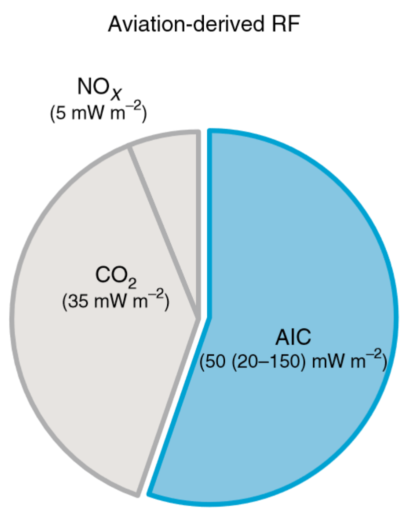

Figure 1 Estimated climate impact of aviation (carbon dioxide (CO2), nitrogen oxides (NOx), and aviation-induced contrail (AIC)) (original source [1]), with AIC impact range from 20-150mW /m^2 due to contrail life cycle uncertainties.

In Table 1 below, the contrail research studies have been further organized into five subtopics based on the contrail life cycle:

Table 1: The various stages of the contrail life cycle and key research areas

Stage	Physical Process Description	Physics model, observation, or measurement
Formation	Engine-exhaust water vapor and aerosol mix during cold and supersaturated conditions	Schmidt-Appleman criterion
Ice nucleation & sublimation	Nucleation occurs from aircraft wingtip vortices downwash, forming new ice crystals. Some particles are lost due to sublimation and the rest form linear contrails.	Large eddy simulation, In-situ measurement of aerosol and ice water content
Spreading	Linear contrails spread into contrail cirrus, interact with natural cirrus formations, and may be transported by the wind as far as several hundred miles.	Cloud microphysics, Satellite observation
Radiative and climate impact	Contrail cirrus reflect solar longwave radiation (cooling) and trap surface shortwave radiation (warming).	Global climate model
Mitigation	Suggested short-term solutions include using synthetic and biofuels, long-term solutions include using hydrogen and Liquid Nitrogen Gas (LNG) fuels and air traffic management.	

The primary particles emitted by engines that drive ice nucleation are soot particles under well-established Schmidt-Appleman criterion (SAC). However, in low soot and extremely cold conditions, nanosized, ultrafine aqueous particles can also trigger ice formation.

In general, the nucleated ice crystal count is linearly related to the emitted soot particle count. However, at a microscopic level, the actual ratio of ice crystal count to soot particle count varies with local soot concentration and temperature. Figure 2 shows that the assumption of an equal number of ice crystals and soot particles holds only in soot-rich, extremely cold conditions. In contrast, under soot-rich, near formation temperature conditions, up to ten times fewer ice crystals are emitted than soot particles due to formation loss [4]**.** This finding underscores the need to model the initial ice crystal count as a fraction of the emitted soot particles, ranging from 10% to 100% depending on local temperature conditions.

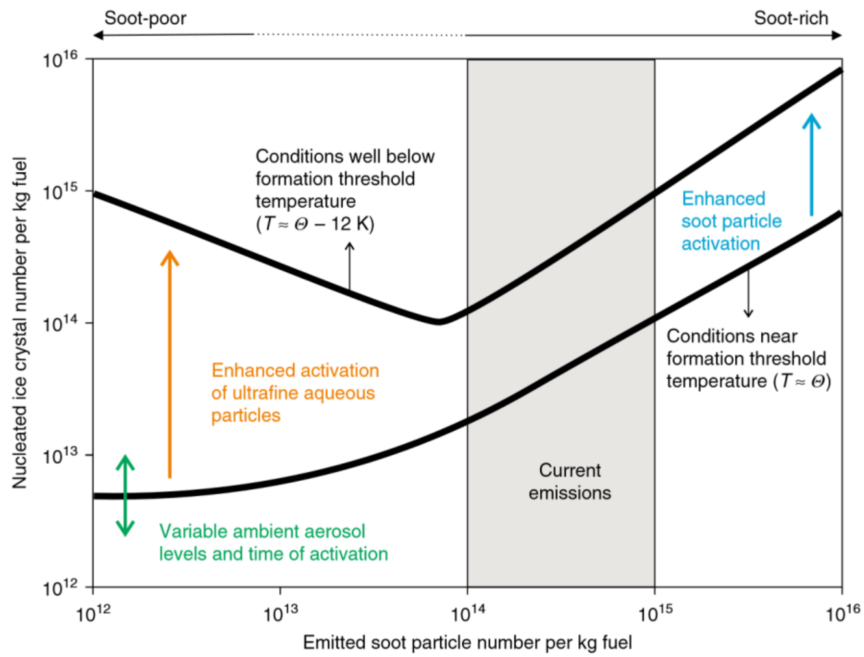

Figure 2 Relationship between emitted soot particle number and nucleated ice crystal number (original source [1])

Those newly formed ice crystals are then partially lost through sublimation, with the extent of this loss dependent on the number of nucleated ice crystals and the ice supersaturation ratio. To paraphrase, higher supersaturation and fewer ice crystals result in less sublimation loss. While large eddy simulations can capture this detailed process, they are computationally expensive. In a simplified estimation, the sublimation loss ratio is approximated between 25% to 75%, with an average value of 60%**.**

Satellite imagery has proven effective at identifying contrails, capable of tracking contrail development, and able to measure their geometric and optical properties to some extent. However, detecting contrails from satellite images depends on several factors, such as optical depth (OD>0.1) and natural cirrus cloud coverage. While satellite imaging and in situ aircraft aerosol and ice water content measurement provide valuable information on linear contrails, they cannot replace physics-based modeling for capturing the full life cycle of contrails.

Optical depth is a key factor in determining RF. While in situ measurements reveal variability, a constant value of approximately 0.3 is often used for simplified estimations.

Aircraft flying at higher altitudes, such as supersonic aircraft flying in the lower stratosphere (above 12 km or 39000ft), can help reduce the contrail climate impact because of dry air conditions at those levels.

The special Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6), published in 2022 [5], updated the science-community understanding of aviation contrails and their climate impact. In this report, aviation-direct greenhouse gas (GHG) emissions accounted for a little less than 3% of global CO_2 emissions in 2019. Between 2010 and 2019, international aviation had among the fastest growing GHG emissions among all transportation segments at 3.4% per year.

A 59% reduction (42-68% interquartile range) in transport-related CO_2 emission reduction is required to achieve the goal of limiting global warming by 1.5°C by 2050, compared to 2020 levels of emissions. Thus, the panel strongly suggested that sustainable alternative fuels (SAF) like biofuels, hydrogen, and their derivatives be the most prominently used fuels in the aviation sector. Aviation contrails are not considered to be direct GHG emissions. However, they still have an impact on the climate and contribute indirectly to the warming effect.

Effective radiative forcing (ERF) is commonly used to measure the short-term climate impact of aviation contrails, while global warming potential (GWP) and global temperature potential (GTP) are commonly used to assess their long-term impact. D.S. Lee et al. (2021) [6] estimated that aviation-induced cirrus cloud coverage contributes about 57% of the current net ERF of global aviation. However, a later study [7] that compared cirrus cloud observations before and after COVID-19 suggested that these findings may be smaller but nevertheless remain significant.

Sustainable aviation fuels created by blending hydrocarbon kerosene with non-hydrocarbon fuel can provide additional benefits of reduced soot formation and reduced contrail cirrus formation. Similarly, liquid hydrogen (LH_2) powered aircraft can reduce contrail formation because of the absence of soot particles from LH_2 exhaust. The increased water vapor content from LH_2 exhaust may increase contrail occurrence, but it has a lower ERF because of lower optical depth. As of the publication of this paper, the net ERF is still unknown.

Ice-supersaturated areas, which are preconditions for persistent contrail formation, tend to be tens to hundreds of kilometers long horizontally, but only a few hundred meters thin vertically. Because of this unique feature of ice-supersaturated areas, it is feasible to alter flight trajectories, particularly by changing flight altitudes, to avoid such ice-supersaturated areas and thereby reduce persistent contrail formation, provided that the location and time can be accurately predicted. However, the current numerical weather models cannot predict the formation of persistent contrails with sufficient accuracy both in time and space [8], mainly because of inaccurate relative humidity over ice (RH_i) value. RH_i is typically not directly measured by physical sensor but derived numerically from the value of relative humidity over water (RH_w)

A European Commission (EU) report analyzed the aviation non-CO_2 climate impact (mainly NO_x and contrails) and proposed potential policy measures under the EU Emission Trading System [9]. In this report, the ERF is recommended as a better metric for assessing climate impact of short-lived climate forcers like contrails, compared to traditional RF. It represents the difference in the radiative flux at the top of atmosphere between scenarios with and without contrails. Simply stated, it is net RF with calibration or adjustment based on local cloud conditions. Studies suggest that using ERF as a metric will reduce contrail-contributed radiative forcing by 30-60%. However, regardless of the metric used, contrails remain the largest aviation non-CO_2 impact on global warming. The commission also recommend using GWP, specifically for a time span of 100 years, as a CO_2-equivalent metric (CO_2-e) when comparing non-CO2 emissions with CO_2 emissions for the purpose of emission trading policies.

2.2 Prediction of persistent contrail formation regions

In a series of papers about how well persistent contrails can be predicted for practical contrail-avoidance aircraft operations [8] [10], researchers at DLR suggested that in order to develop a viable mitigation strategy, weather prediction models must reliably and accurately answer three questions:
1. When and where are contrails are formed?
2. Which of these contrails are persistent?
3. How large would the radiative forcing of these contrail be?

The authors concluded that predicting ice super-saturation at a specific location and time is particularly challenging for the following three reasons:
1. Strong variability in the water vapor field in the atmosphere

2. Low number of humidity measurements at the cruise altitude for data assimilation
3. Oversimplified parameterizations of cloud physics in weather models

To overcome the first two challenges, the authors suggested that more measured sensor data on relative humidity by aircraft equipped with hygrometers flying at cruise level are urgently needed. The authors also claimed that satellite data cannot fill this gap since their vertical resolution is insufficient. The third challenge can be addressed by improving physics-based contrail models and develop new data-driven hybrid models using machine learning.

Lastly, the authors proposed an empirical method to enhance the prediction of relative humidity using a statistical regression method that incorporates local dynamic variables. Based on in situ aircraft measurement, approximately 98.5% of the time, ice supersaturation primarily occurs below the tropopause. Therefore, aircraft cruising above the tropopause (approximately 10 km/36,000 ft) do not need to be concerned about persistent contrail formation. According to another study by Teoh et al. [11], around 2% of all flight distances contribute to about 80% of the total energy forcing of all flights as so called "big hitters". So selective avoidance of contrail formation with large warming effect is recommended.

The necessary conditions for identifying contrail-avoidance regions are discussed in more detail below:
1. **Contrail formation condition**: Contrails form when engine-exhaust aerosols mix with water vapor in cold, supersaturated air, as defined by the Schmidt-Appleman Criterion [12].
2. **Contrail persistence condition**: Newly formed contrails can persist if the surrounding air is also supersaturated over ice.
3. **Warming or cooling effect**: Assess whether the contrail has a warming or cooling effect and quantify the effect.

Regarding the first condition, by comparing numeric reanalysis data with the actual measured sensor data from aircraft, the authors have found that accurate prediction of contrail formation regions using SAC is generally satisfied. The accuracy of temperature predictions plays a key role in achieving reliable results regarding contrail formation. So even when the deviation in relative humidity between measured and numeric data is relatively large, the SAC condition can still be predicted quite reliably.

However, on the second condition, accurately predicting ice supersaturation presents a major challenge. The authors conclude that the current weather models cannot reliably predict persistent contrail regions at a specific time and location due to lack of direct ice supersaturation prediction**.** While there is a statistical linear correlation between relative humidity over ice obtained from sensor measured data and numeric data, it does not accurate enough to be applied to practical operation, which requires reliable prediction of the ice-supersaturation region at a specific time and location. The suggested solutions would be: (1) enhance NWP relative humidity prediction accuracy; (2) predict short-term relative humidity using satellite observational or in-situ measurement data.

Regarding the third condition, a contrail climate impact model is needed to calculate the net RF to determine whether a contrail has a warming or cooling effect and exactly how much of an effect. The authors used a widely adopted parameterized contrail climate model developed by Schumann et al. [13].

Ebert and Curry in their paper [14] presented a numeric method to calculate the ice cloud shortwave optical depth, which is a key factor for calculating RF, as a function of ice particle effective radius and ice water content (IWC). The relation is shown in Figure 3. The mass extinction coefficient, $\tau/IWP,$ is linearly proportional to shortwave optical depth τ, where the ice water path (IWP) can be calculated by multiplying IWC with cloud depth (D_c). Therefore, the value of y-axis in the figure, mass extinction coefficient, can be expressed by $\tau/(IWC * D_c)$.

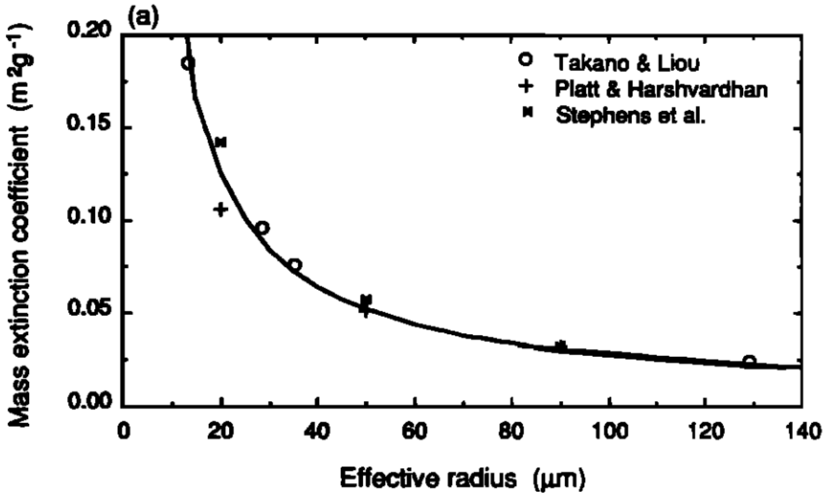

Figure 3 Relationship between mass extinction coefficient, which is linearly related to shortwave optical depth, and effective radius (original source [13])

2.3 Contrail modeling

Rosenow and Fricke [15] presented a physics-based model for calculating individual contrail RF, where the system diagram is shown in Figure 4. While the data flow diagram generally aligns with other physics-based contrail models such as CoCiP model [16] and ACSM [17], it differs in specific modules and underlying assumptions.

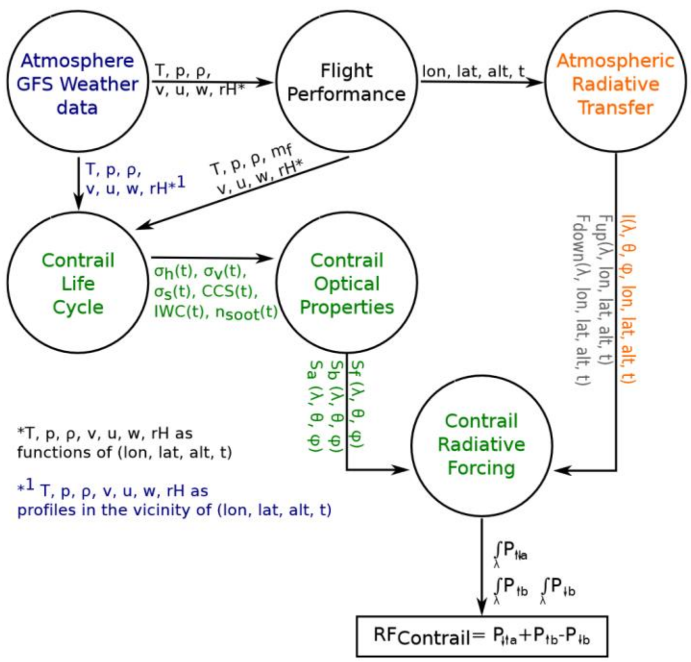

Figure 4 Data flow diagram for calculating contrail radiative forcing calculation (original source [14])

Penner et al. [18] developed a micro-scale aerosol particle-based model focused on meso-scale contrail life cycle modeling, which is outside the scope of this report. However, such aerosol models are valuable for improving our understanding of complex aerosol-cloud interaction during contrail formation stage.

In summary, here are several general recommendations to enhance the reliability and accuracy of physics-based models:

1. **Data fusion for atmospheric variables**: Numeric weather models differ in scope, resolution, update frequency, and available variables. For example, the Global Forecast System (GFS) data provides global forecast with 6-hour updates and a 16-day horizon, whereas Rapid Refresh (RAP) data provides hourly updates with an 18-hour horizon for North America. Applying data fusion techniques to preprocess atmospheric variables from multiple weather models could improve input reliability.
2. **Satellite imagery for validation and calibration:** Satellite observations enable direct detection and characterization of linear contrail clouds, supporting both model validation and parameter calibration.
3. **Expanding multi-objective outputs**: Besides instantaneous net RF and effective RF, additional metrics should be included to assess both short- and long-term climate impact and evaluate the economic trade value based on the CO_2 -equivalent emissions.

2.4 Contrail mitigation strategies

From an operational standpoint, the most effective approach to mitigating contrail climate impact is to fly over persistent contrail formation regions or ice supersaturation regions (ISSR).Secondary mitigation tactics, in order of preference, are to fly below or around these regions [19] [20].

It is widely recognized that there is significant variability in longwave, shortwave, and net RF caused by contrails. Studies using satellite data have shown that the probability distributions exhibit a long-tail effect, meaning that a small fraction of contrails, called "big hitters", contribute disproportionally large RF. Therefore, some researchers suggest implementing contrail-avoidance strategies specifically targeting those high-impact contrail regions.

A common strategy for mitigating contrails is to avoid all regions where persistent contrail can form as determined by SAC, regardless of whether they have a net warming or cooling effect. This is typically achieved by adjusting the aircraft's cruising altitude. For example, Sun et al. utilized crowdsourced Automatic Dependent Surveillance-Broadcast (ADS-B) data and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data to estimate total flight distance saved over global persistent contrail formation regions by adjusting flight altitude [21]. Such analysis offers a broad evaluation of potential contrail formation frequency and the effectiveness of altitude adjustment to prevent contrail formation on a macro scale. However, the method is not suitable for operational implementation for the reasons discussed in Section 2.2.

Recent studies supported by Europe's CICONIA (Climate Effects Reduced by Innovative Concept of Operations - Needs and Impacts Assessment) project claimed that "very encouraging outcomes from preliminary studies show that probabilistic rerouting can compensate most of the mitigation potential loss due to weather" [22].

2.5 Detecting and tracking contrails using satellite imagery

Satellite imagery provides direct observations of contrails, especially linear contrails. The Contrail Detection Algorithm (CDA) and Automatic Tracking Contrail Algorithm (ATCA), developed by DLR researchers, use two types of satellite data for detecting and tracking [23] [24]: high spatial resolution (1km) imagery from the Moderate-resolution Imaging Spectroradiometer (MODIS) sensor on polar orbiting satellites for contrail detection, and high temporal resolution (up to 5 minutes) imagery from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) sensor in rapid scan mode on geostationary satellites for tracking their evolution. Distinguishing contrail cirrus from natural cirrus clouds using isolated satellite images is difficult. The main strategy is to continuously track contrails from their early, easily identifiable linear phase until they dissipate, as demonstrated in Figure 5. As a result, this approach can identify the initial contrail location and estimate the length of the contrail life cycle. Subsequently, DLR researchers developed neural network algorithms to estimate the contrail cloud optical properties, such as optical depth and RF, using these satellite images [25].

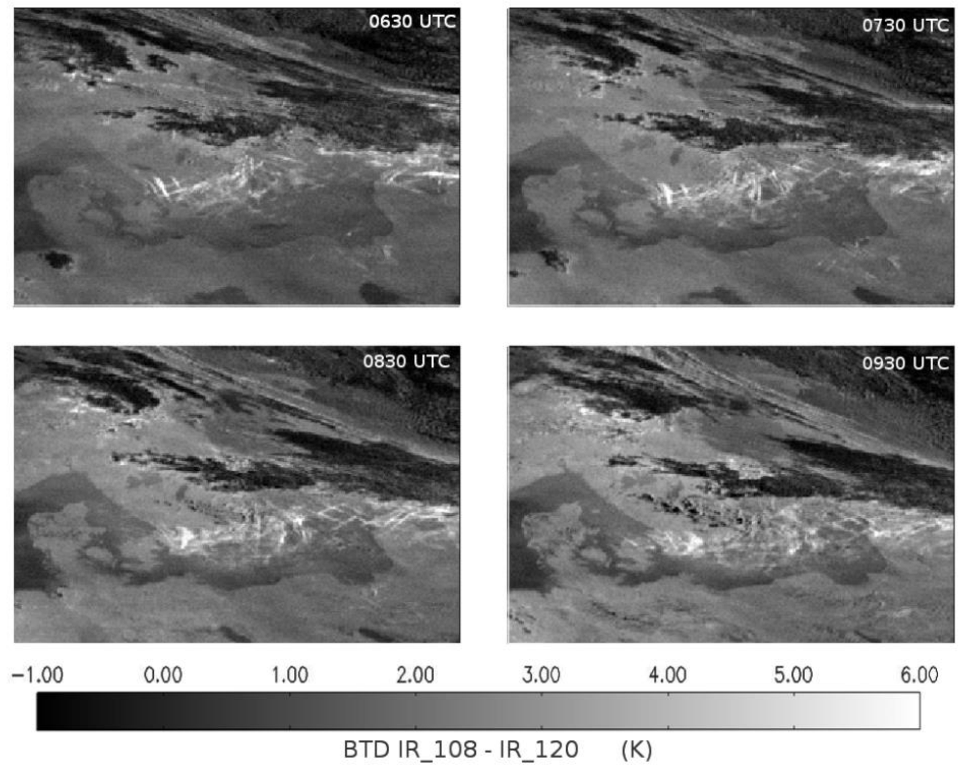

Figure 5 Tracking contrail development from satellite images (original source [23])

The local wind field was used to predict future contrail locations in satellite image processing, aligning with the advection model in physics-based simulations. Accurately extracting altitude information from satellite data remains a key challenge. Satellite observations indicate that the average contrail lifespan, including short-lived contrails, is around 60 minutes, which is shorter than previous estimates from physics-based models. This difference is at least partially due to difficulties in detecting thin contrails in their early or late stages.

Different types of satellite data have been shown to be effective for contrail detection and tracking. For example,
1. Low earth orbiting satellites, including polar-orbiting satellites: Provide high-spatial resolution images, ideal for detecting contrails.
2. Geostationary satellites: Provide high-temporal resolution images, useful for both detecting and tracking contrail evolution over time.

Table 2 summarizes the satellite type and their applications for contrail detection and tracking.

Table 2: Compare satellite types and their usage for contrail detection and tracking.

Category	Geostationary Satellite	Low Earth Orbit Satellite	Polar-Orbiting Satellite
Orbit Type	Fixed position	Low altitude orbit	Sun synchronous
Coverage Area	Fixed region	Regional	Global
Temporal Resolution	High (images collected every few minutes)	Moderate to low (several times per day to several times per month)	Low (images collected every few days)
Spatial Resolution	Moderate (kilometer)	High (submeter to meter)	High (meter scale)
Primary Use	Detect & track	Detect	Detect
Example	GOES, Himawari	Sentinel	Landsat, Aqua, Terra

Duda et al. at NASA Langley Research Center have published a series of papers regarding detecting linear contrails and deriving their optical properties and RF using polar orbiting satellite MODIS imagery [26] [27] [28]. They developed a consistent analysis system by using a single set of satellite data and contrail detection algorithm to compare interannual changes of linear contrail coverage and their climate impact. They enhanced the contrail detection algorithm developed at DLR [23] using masks or filters to better distinguish linear contrails from natural background. Furthermore, a separate post-processing algorithm was applied to track contrail cirrus clouds in the vicinity of linear contrails found by the contrail detection algorithm. As a result, they estimated that total contrail cirrus coverage visible in the MODIS imagery may be 3 to 4 times larger than the previously detected linear contrail coverage. The authors also found that the normalized contrail RF in 2012 was approximated at 20% lower than in 2006, based on satellite observation. This decrease is partially attributed to changes in optical properties such as reduced average cloud optical depth and ice particle effective diameters; however, further investigation is needed to verify this trend.

Google researchers have released a publicly accessible dataset of geostationary satellite images, called OpenContrails, that are annotated with human-labelled linear contrails. The goal of this dataset is to provide a standard benchmark for comparing the performance of detection algorithms. The dataset is built using GOES-16 Advanced Baseline Imager (ABI) imagery, which has a temporal resolution of 10 minutes and a spatial resolution of 2km by 2km. Next, they developed a supervised neural network algorithm to detect contrail pixels in the images. To evaluate the algorithm's performance, they selected two metrics:
1. Pixel-accuracy, which measures how accurately the algorithm identifies contrail pixels.
2. Linear shape accuracy, which assesses how well the algorithm detects and extracts the linear structure of contrails.

A similar work was conducted by MIT researchers to detect linear contrails using a supervised neural network algorithm on GOES-16 ABI imagery [29]. They applied the algorithm to analyze annual contrail coverage over the entire continental United States and found that total contrail cloud coverage decreased by 22% from 2019 to 2020, whereas total flight distance decreased by 36% due to the COVID-19 pandemic. Their nonlinear relationship is for further research.

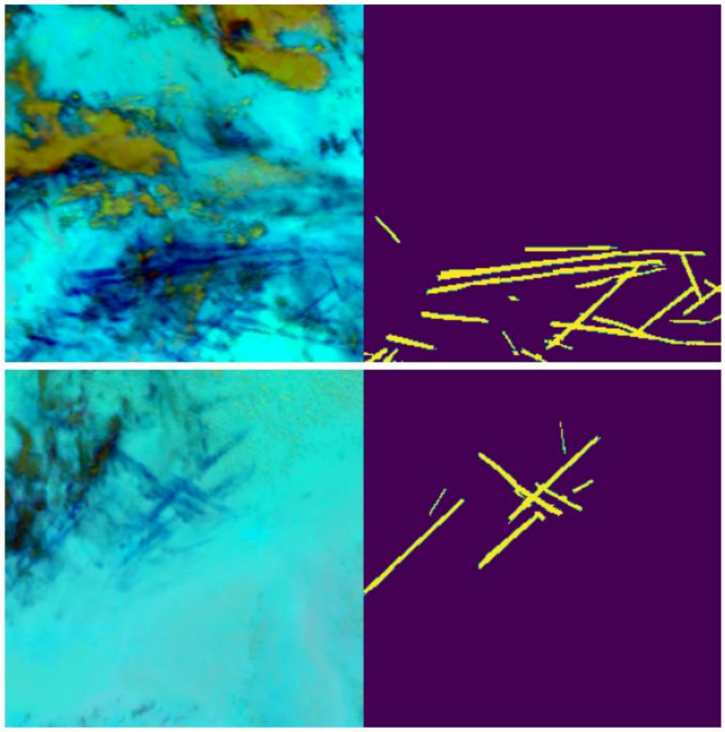

Figure 6 Sample images and labels in the OpenContrails dataset (original source [29])

In the OpenContrails dataset as shown in Figure 6, only young-aged linear contrail can be labelled by humans. Contrails in their initial formation stage and later contrail cirrus stage are not labelled. While the OpenContrails dataset could improve algorithm performance for detecting linear clouds in satellite imagery, using human-labelled data as a benchmark to verify and validate contrail models is questionable for several reasons:

1. As previously discussed, the detectable contrails only represent a fraction of contrail lifespan.
2. Human labelers cannot effectively differentiate between aviation-induced contrail cirrus clouds and natural cirrus clouds.
3. While location and geometric shape provide useful information, they are not crucial for evaluating the climate impact of contrails. Cloud properties such as optical depth, which are directly linked to RF, are not included in the OpenContrails dataset.

As a result, the dataset underestimates the overall impact of contrail. Furthermore, the geostationary satellite collects images regionally but not globally because of its fixed position relative to earth. For example, GOES-16 is positioned near the east coast of the United States and GOES-18 is positioned near the west coast of the United States. Although sensors like ABI on GOES-16 have a wide field of view to cover the entire continental U.S., the image of the west coast is not as accurate as the image from GOES-18, because GOES-18 is positioned over that region. Because of these discrepancies, data fusion is suggested for global coverage and improved accuracy.

2.6 In situ observations and other works

In situ aircraft observations or measurements provide direct, localized values of key parameters to assimilate and validate physics-based contrail prediction models. Researchers at Boeing have made progress using aircraft as a sensing platform to report near-real-time observations in complement to numerical weather prediction [30]. In addition to the atmospheric parameters related to contrails, they categorized the progress of winds, temperature, and icing in situ observation as “mature and evolving”, whereas water vapor in situ observation was labeled “restarting”, and aerosol in situ observation was categorized as “research needed”. NASA and Boeing have also conducted a series of flight tests to evaluate how using SAF could reduce aerosol and thus reduce persistent contrail formation [31].

3. Contrail Prediction Tools

3.1 Physics-based Contrail Prediction Tool

3.1.1 Contrail Cirrus Prediction Tool

The CoCiP, originally developed by Schumann at DLR in early 2010, is a state-of-the-art physics-based tool widely used for contrail prediction and climate impact analysis [16]. In CoCiP, the contrail lifecycle is divided into multiple stages: formation, initial development, advection, evolution, and dissipation. Each stage is governed by physics models.

Table 3: Contrail Stages and Physics Models in CoCiP

Category	Main physics model	Cloud form	Detectability by Satellite
Persistent contrail formation	Schmidt-Appleman Criterion	Ice crystal particles	Not detectable
Initial development (early age)	Parametric models for wake vortices process	Ice crystal particles and linear contrails	Not detectable
Advection and evolution (young to mid age)	Lagrangian Gaussian plume model	Linear contrails and Contrail cirrus	Partially detectable
Dissipation (late age)	Cloud microphysics (ice particle sublimation or precipitation)	Contrail cirrus	Not detectable

Contrail detectability primarily depends on clouds' optical depth, but it is also influenced by factors such as instrument specifications, Earth's surface background, and ambient atmospheric conditions. Clouds with an optical depth of less than 0.1 are generally considered "not detectable".

A key assumption of CoCiP is that contrails remain a Gaussian plume shape throughout their lifecycle. Consequently, a single plume model has been used to simulate the entire lifecycle. CoCiP uses various parametric models for simplicity, such as the wake vortex downwash process and assessing climate impact. CoCiP model parameter values are selected based on observations or experience. CoCiP also assumes the initial number of ice particles is linearly proportional to the number of soot particles emitted by the engine, without considering nanosized ultrafine aqueous particles (see Figure 2 and the discussion in Section 2.1). The ratio, known as survival factor, is directly derived from ice mass change. CoCiP does not consider ice crystal habitat and size distribution due to lack of observation data. Furthermore, direct interaction between contrail cirrus and natural cirrus has not been modelled in CoCiP. In the Burkhardt and Karcher model [32], contrail cirrus and natural cirrus interact by competing for available water vapor. Figure 8 depicts that critical relative humidity value for natural cirrus formation r_{ci} is larger than that of potential contrail formation r_{cc}.

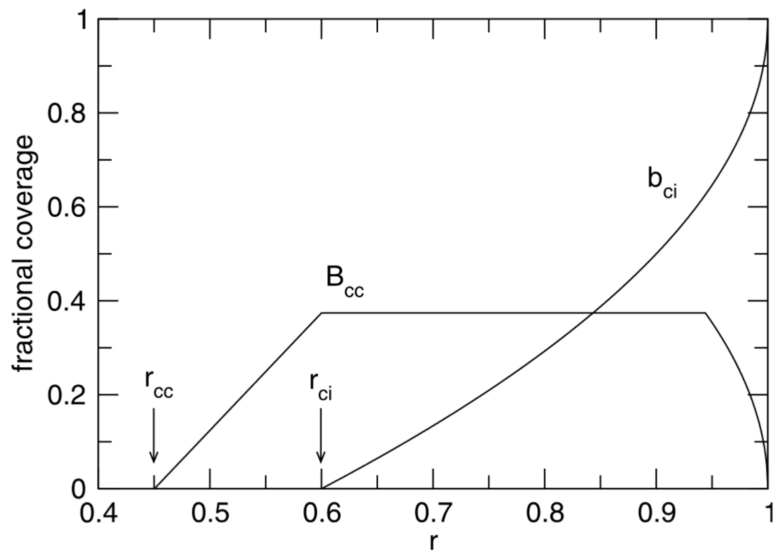

Figure 7 Fractional potential contrail cirrus coverage B_cc and natural cirrus coverage b_ci interact by competing for water vapor and by changing the relative humidity (original source [36])

3.1.2 Python library for modeling aviation climate impact

Pycontrails is an open-source Python package for predicting aircraft contrails [33], based on the CoCiP model. According to the latest software release notes, there are a few key differences between pycontrails and original CoCiP models. The pycontrails model sets the initial ice particle activation rate to be a function of the difference between the ambient temperature and the critical SAC threshold temperature. In comparison, the original CoCiP model uses a constant value of specific heat capacity, whereas the pycontrails model calculates isobaric heat capacity as a function of specific humidity. Additionally, the original algorithm uses top incident solar radiation as solar direct radiation value. Pycontrails implementation calculates the theoretical direct solar radiation at any arbitrary point in the atmosphere. Although we haven't found any published work formally validating Pycontrails with CoCiP, it is regarded as a formal implementation of the CoCiP model.

4. Enhancing the Ames Contrail Simulation Model

4.1 Ames contrail simulation model overview

The ACSM is a physics-based contrail model originally developed at NASA Ames Research Center [17] mainly for internal contrail climate impact assessment and mitigation research. ACSM is generally designed to share properties with CoCiP [13], such as model parameters and cloud climate model, but with reasonable modifications and simplifications. Like the original CoCiP tool, which is written in legacy Fortran, the original ACSM tool was also developed using a mixture of Fortran and MATLAB. A modern implementation of the original ACSM model using modular architecture, open-source programming languages is currently underway. In future work, we will compare the two new implementations.

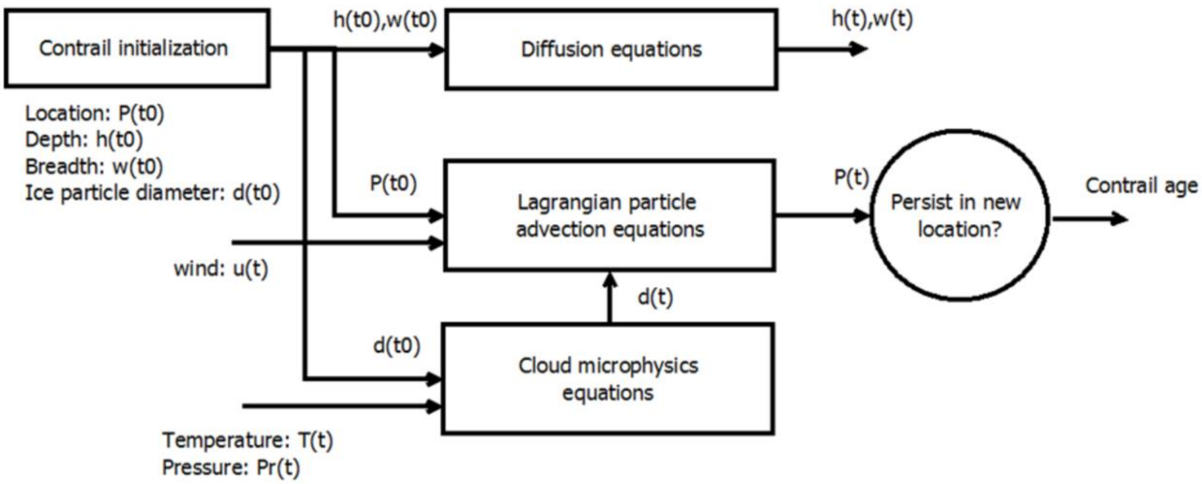

Figure 8 Ames Contrail Simulation Model (ACSM) structure (original source [16])

Table 4: Commonalities and differences between CoCiP and ACSM tool

Age / Phase	CoCiP	ACSM
All ages	Gaussian plume model	Uniform plume model without considering windshear induced inclination
Radiative forcing	Parametric model developed by Schumann	
Early age - wake vortices phase	Parametric model to determine initial cloud coverage shape (width, depth) and displacement (vertical)	Assume constant cloud shape and ignore vertical displacement
Mid age - cirrus diffusivity	Parametric model to determine diffusivity parameters	Assume constant diffusivity parameters
Contrail cloud cover	Detectable cloud cover depends on optical depth; overlapping contrail cirrus cloud and natural cirrus are aggregated to calculate local optical depth	Detectability not considered to calculate the contrail cloud cover; cloud overlapping is not considered
Ice crystal effective radius	Model total ice mass mixing ratio change	Model single ice particle growth
Ice particle loss	Parametric particle loss model	Not considered
Cloud optical depth	Parametric model	Assume constant optical depth
Late age – lifetime of contrail	The contrail lifetime ends when ambient humidity condition falls below ice supersaturation.	

The two key parameters for contrails are relative humidity over ice RH_i, and optical depth $\boldsymbol{\tau}$**.** RH_i determines the formation of persistent contrails and τ directly affects RF. It is widely recognized that RH_i predicted by current weather forecast models is not accurate enough for effective aircraft mitigation operations. However, AI-enhanced weather forecast models [34] and in situ sensor measurements [35] are expected to improve water vapor and ice humidity predictions. Optical depth is better understood by the research community. While there are some research to extract optical depth directly from satellite data, cloud microphysics models are needed to enhance prediction accuracy.

4.2 Recommended improvements

4.2.1 Enhancing physics-based models:

1. It is suggested to add a particle loss model to ACSM, as particle loss can significantly affect the contrail lifetime, as shown in Figure 9. Ignoring particle loss can lead to overestimating the average size of ice crystals, which in turn prolongs the estimated contrail lifespan.

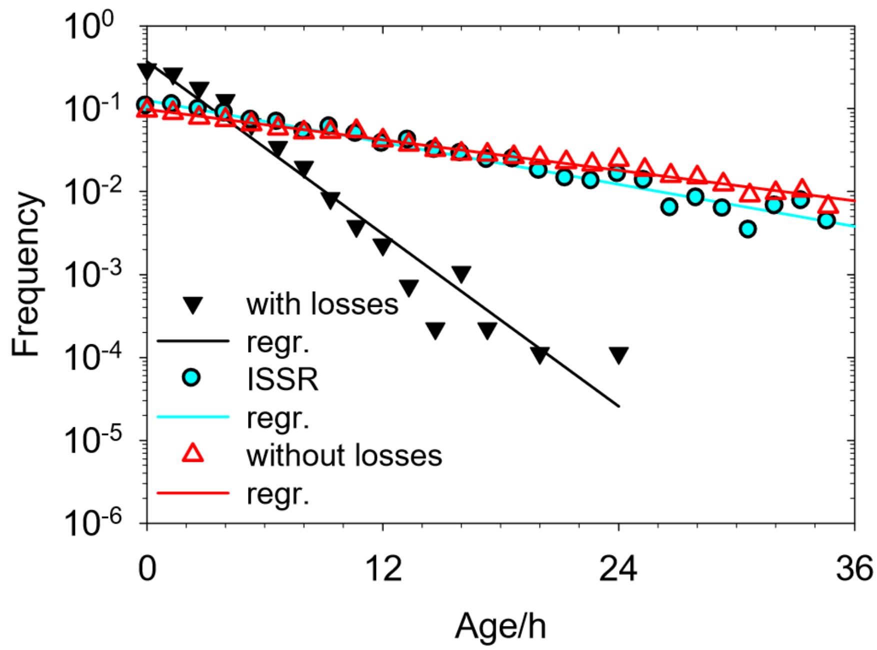

Figure 9 Contrail lifetime or age with and without particle loss (original source [12])

2. Due to the large time step size, it is necessary to apply the Runge-Kutta method to the discretized advection equations to improve numerical stability and accuracy in ACSM. Additionally, using two endpoint positions instead of the midpoint position of a contrail segment for advection calculation may be considered, which results in a varying contrail length.
3. To calculate ice crystal growth, CoCiP and ACSM took different approaches. Specifically, CoCiP took a top-down approach that tracks the total ice mass or ice mass mixing ratio. ACSM took a bottom-up approach that tracks single crystal growth though a Bourgeon process, which is the process of ice particle growth due to supercooled water content deposited on the ice particle surfaces. Future comparisons of the two approaches are recommended as part of follow-on work.
4. Vertical wind shear, when present, should be added to the diffusion model in addition to turbulence diffusion. Vertical wind shear, which is the vertical gradient of horizontal wind velocity, plays a

dominant role in contrail spreading. Without considering vertical wind shear, the original ACSM may underestimate the extent of cloud coverage.

$$\frac{dh(t)}{dt} = \frac{D_v}{h} + c\frac{\partial u_s}{\partial z}$$
$$\frac{dw(t)}{dt} = \frac{D_h}{w} + c\frac{\partial u_s}{\partial z}$$

where u_s represents vertical wind shear, and c is a constant spreading factor with suggested value in the range 0.72-1.0 [32].

5. A dynamic optical depth model is suggested to improve RF prediction in ACSM. Optical depth can be parameterized as a function of ice water mass mixing ratio or ice water content, as suggested in Burkhardt and Karcher [32] and Schumann et al. [13]. Optical depth can also be derived from satellite imagery [27], although further validation is needed.

4.2.2 Developing hybrid models

The emerging Machine Learning (ML) models, such as Google's NeuroGCM model [34], have shown potentially groundbreaking results in weather and climate prediction. ML models generally fall into two categories, as shown in Figure 10:

1. Full model ML emulator: train on complete input and output of established physics-based models to replicate its results.

2. Hybrid ML model: integrate ML approaches with traditional physics-based models, such as replacing physics parameters with features.

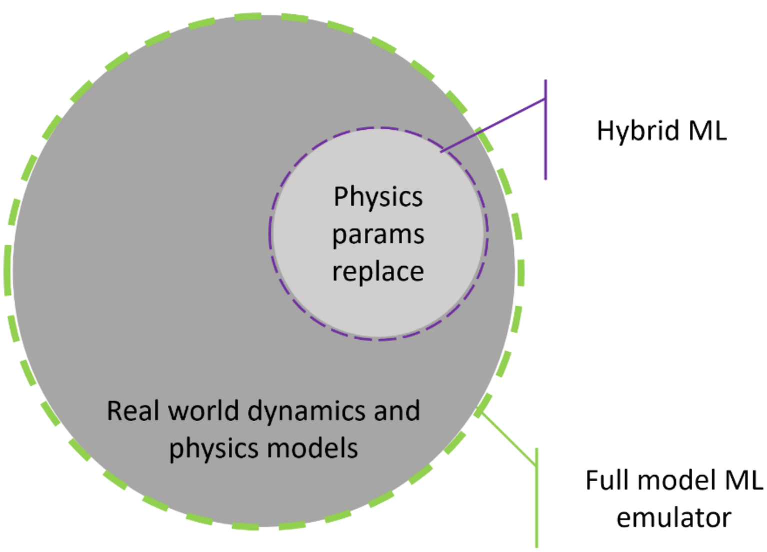

Figure 10 Physics and machine learning (ML) models.

Hybrid ML models can improve contrail prediction by replacing the physics parameter values with feature values extracted from satellite imagery and in situ measurements and can improve input reliability by using real-time data fusion techniques, as shown in Figure 11.

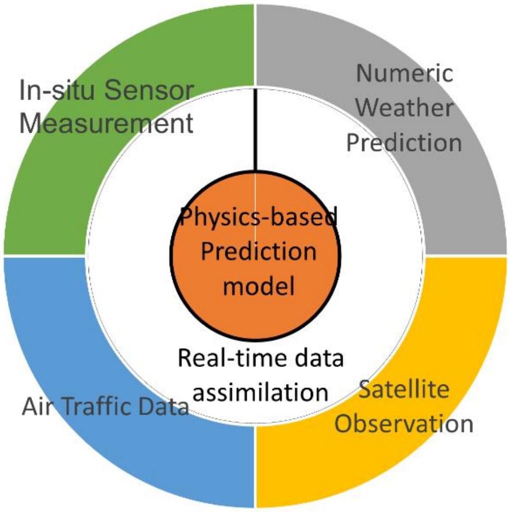

Figure 11 Diagram of real-time data fusion for the hybrid contrail prediction model

5. Conclusion and Future Work

This report provides a comprehensive review of key findings in aviation contrail research over the past decade. It highlights the current gaps and challenges in predicting contrails for operational mitigation and discusses new technologies for identifying contrails using machine learning methods. Finally, it proposes improvements to NASA's contrail simulation model, the Ames Contrail Simulation Model (ACSM).

A fully redesigned contrail prediction tool based on ACSM is currently in development supported by NASA Langley's Internal Research and Development (IR&D) program. Future work includes comparing the results with pycontrails and integrating the prediction model with NASA's satellite platform to predict and validate contrails in an end-to-end system.

Appendix A

Acronyms

ABI	Advanced Baseline Imager
ACSM	Ames Contrail Simulation Model
ADS-B	Automatic Dependent Surveillance - Broadcast
AIC	Aviation-Induced Contrail
ATCA	Automatic Tracking Contrail Algorithm
CDA	Contrail Detection Algorithm
CICONIA	Climate Effects Reduced by Innovative Concept of Operations Needs and Impacts Assessment
CoCiP	Contrail Cirrus Prediction Tool
DLR	German Aerospace Center
ERF	Effective Radiative Forcing
EU	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
GFS	Global Forecast System
GEO	Geostationary Satellite
GHG	Greenhous Gas
GTP	Global Temperature Potential

GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IR&D	Internal Research and Development
ISSR	Ice Supersaturation Regions
IWC	Ice Water Content
IWP	Ice Water Path
LEO	Low Earth Orbit Satellite
ML	Machine Learning
MODIS	Moderate-resolution Imaging Spectroradiometer
RAP	Rapid Refresh
RF	Radiative Forcing
SAC	Schmidt-Appleman Criterion
SAF	Sustainable Alternative Fuels
SEVIRI	Spinning Enhanced Visible and Infrared Imager

Appendix B

Corrections on NASA/TM "Ames Contrail Simulation Model"
The original ACSM report [17], "Ames Contrail Simulation Model: Modeling Aviation Induced Contrails and the Computation of Contrail Radiative Forcing Using Air Traffic Data", contains several typos and inaccuracies. The corrections are provided below.

On page 11, Equation (5): Replace the expression for saturation vapor pressure over water with $e_{sat}^{liq}(T) = 6.112 \times 100 \exp\left(\frac{17.625(T-273.15)}{T-273.15+243.12}\right)$ in Pascal using the Magnus-Tetens formula, where temperature T is in Kelvin.
Update the value of Q to 43×10^6 J/kg.
Update Equation (3) to $RH_i = RH_w \frac{e_{sat}^{liq}(T)}{e_{sat}^{ice}(T)}$, where
T is in Kelvin and $e_{sat}^{ice}(T) = \exp\,(9.55 - \frac{5723.265}{T} + 3.53\ln(T) - 0.0073T)$ in Pascal.
On page 19: The unit of d_i in equation (21) is meter (m).
On page 22: Update the value of m_air to 0.029 kg/mol and R to 8.314 J/K/mol.
In Equation (28), the value of deposition coefficient α is 0.036.
In Equation (29), the unit of κ_a is watt per meter Kelvin (watt/mK)
In Equation (33), the unit of mass diffusional growth rate $\dot{m}(t)$ is Kg per second (Kg/s).
On Page 27: Replace Equation (40) with $E_{LW}(\tau_c) = \exp\{-\delta_{lc}\tau_c\}$
Replace Equation (42) with $E_{SW}(\mu, \tau_c) = \exp\{\delta_{sc}\tau_c - \delta'_{sc}\tau_c/\mu\}$
τ_c represents the optical depth of existing cloud above contrail cirrus cloud.

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