Contrails Research Roadmap

Federal Aviation Administration (FAA)

National Aeronautics and Space Administration (NASA)

National Oceanic and Atmospheric Administration (NOAA)

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Executive Summary

United States government agencies have come together to advance the understanding of persistent contrails and their impacts to inform future decision making. Current models indicate that persistent spreading contrail cirrus has a significant net warming impact on the global climate; however, the magnitude of this impact is uncertain. Research is needed to improve scientific understanding, reduce process-level uncertainties, develop integrated decision support tools and mitigation strategies, and demonstrate and assess prediction and operational capabilities. Improved understanding will allow the U.S. to make informed decisions that will ensure U.S. competitiveness in the aerospace sector while managing the impacts of civil aviation in a cost-effective manner.

Our long-term vision is to achieve effective, routine, system-wide contrail management that incorporates climate impacts and economic tradeoffs by 2050. This will require sustained investment in research and development activities and progress is subject to availability of appropriated funds. Through 2030, the research community must continue to evaluate and understand the potential contrail reduction benefits from low-emitting engine technologies and novel sustainable aviation fuel (SAF) formulations. This will inform policymakers and operators on how best to strategically deploy these measures across the fleet, as current research indicates that only a small percentage of flights cause the majority of contrail-induced warming. In addition, we must demonstrate technology and predictive tools that achieve an acceptable level of confidence for economic and operational tradeoffs to be considered. By 2040, it is assumed that model fidelity and operational decision support tools have been demonstrated, validated, and are being used at some level to manage contrail cirrus climate impacts. The 2050 vision and interim goals require effective, complementary, and coordinated research efforts.

This document identifies initial high-level goals and research needs in four research areas: Atmospheric Science, Weather Prediction, Cruise Emissions, and Operational Management. Collaboration between government agencies and the U.S. Aviation industry will be critical to meeting these goals. The U.S. government agencies contributing to this document include the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA). Key stakeholders include research organizations, aircraft and engine manufacturers, airlines and operators, and associated customers and shareholders.

The next step will be to collaborate with key stakeholders to further develop our vision and refine this initial research roadmap. This document will be updated regularly as the research progresses.

I. Introduction

This document describes the joint goals of multiple United States government agencies—the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA)—to improve scientific understanding of contrails and inform decision-making to address their impacts. It is understood that persistent spreading contrail cirrus (hereafter referred to as “contrail cirrus”) has a net warming impact on the climate; however, more research is needed to fully understand these impacts and develop mitigation tools and strategies. The intent of this document is to identify areas of research requiring action and coordination across government, industry, and academia to lower uncertainties and develop mitigation solutions. The aviation sector recognizes these impacts must be addressed to achieve a sustainable aviation future and that addressing these impacts will require collaboration between government agencies and the global aviation industry.

The document first provides an overview on contrail lifecycle and impacts. This is followed by a discussion on collaboration, roles and responsibilities to support effective, complementary, and coordinated research efforts. The main focus of the document is the research activities and goals, which are divided into four research areas: Atmospheric Science, Weather Prediction, Cruise Emissions, and Operational Management. Each of these sections describe the research needs and milestones to achieve the long-term vision of effective, routine, system-wide contrail management that incorporates climate impacts and economic tradeoffs by 2050. The proposed activities encompass years-to-decades of research that will span the evolution of fuel sources, aircraft and engine technologies, and operational management within civil aviation.

Improved understanding of contrails and their impacts is essential to make informed decisions that will ensure U.S. economic competitiveness in the aerospace sector, maintain the safety and efficiency of the airspace system, and harmonize global strategies. Moving forward, these goals will be prioritized, regularly reviewed, and revised as contrails research advances. This allows for adjustments to be made guided by the latest research findings and ensures collaboration with key stakeholders to further refine our vision and update the contrails research roadmap.

II. Contrail Lifecycle and Impacts

Condensation trails (contrails) are ice clouds formed from the condensation of aircraft engine exhaust water vapor onto both co-emitted and naturally occurring particles at cruise altitudes. Some linear contrails develop into longer-lasting, persistent contrails and diffuse contrail cirrus clouds, which together comprise Aviation Induced Cloudiness (AIC) (Karcher et al., 2018). Contrail cirrus formation and persistence depend on the aircraft engine exhaust composition, which is impacted by engine technology and fuel chemistry, as well as local atmospheric conditions (for example, temperature and relative humidity). Contrails are more likely to form and persist when the ambient air is cold and humid.

Contrails vary in their persistence and impact and can be broadly classified into three types: short-lived contrails, persistent non-spreading contrails, and persistent spreading contrail cirrus.

Short-Lived Contrails

Short-lived contrails, as their name implies, disappear within minutes of their formation. These contrails form and dissipate quickly because the atmosphere is too dry to sustain them. Because of their short lifetime, these contrails typically have a minimal impact on the atmosphere.

Persistent Non-Spreading Contrails

Persistent non-spreading contrails can remain visible and retain their linear features for hours to days. These contrails form in ice supersaturated regions of the atmosphere and are likely to be more impactful than short-lived contrails. Persistent non-spreading contrails are easily identified from the ground and satellites as being formed from aviation activity.

Persistent Spreading Contrail Cirrus

Persistent spreading contrail cirrus, like persistent non-spreading contrails, form in ice supersaturated regions of the atmosphere and can last for hours to days. They are characterized by their tendency to widen and spread, eventually covering areas that can span several hundred kilometers. Because of their longer lifetime and wider geographical extent, contrail cirrus are likely to have the most significant impact on the atmosphere. Contrail cirrus can be difficult to distinguish from naturally occurring cirrus clouds.

Of the three types, persistent non-spreading contrails and persistent spreading contrail cirrus are the most significant in terms of their potential impact and thus are the focus of our research. **Figure 1** provides an overview of the processes by which aviation effects the climate system and contextualizes how contrails fit within the spectrum of these impacts (Lee et al., 2021).

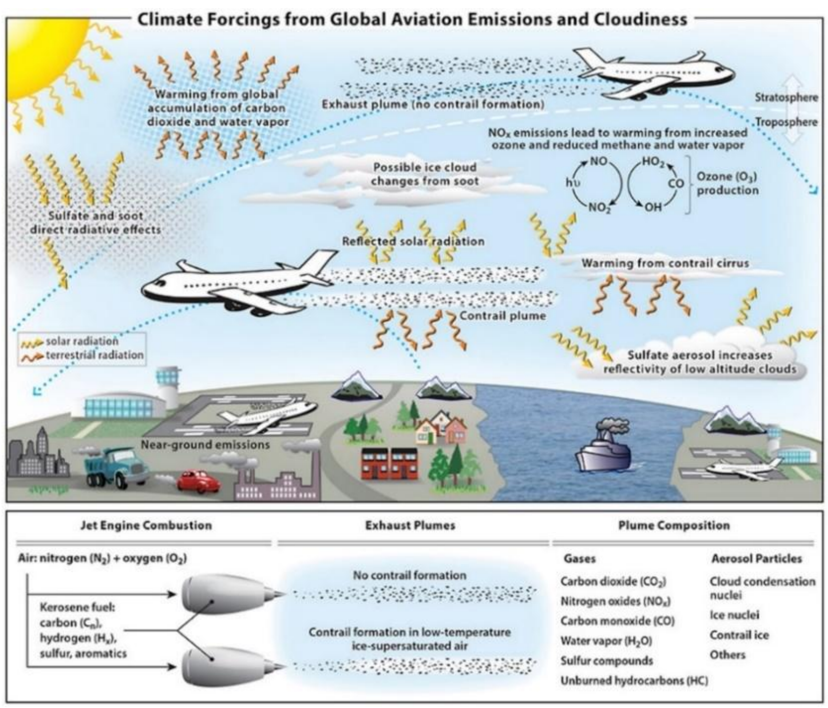


Figure 1: Climate Forcing from Global Aviation Emissions and Cloudiness (Lee et al., 2021)

Current global models tell us that persistent contrail cirrus clouds have a measurable effect on the Earth's energy balance, exerting what is referred to as an effective radiative forcing (ERF) on the planet. This is because they reflect incoming sunlight back to space (negative ERF) and trap outgoing heat radiation within the atmosphere (positive ERF). The balance between these negative and positive effects can vary for individual contrails depending on the time of day, as well as other surface and atmospheric properties. Over the course of their lifetimes, some contrails have a net negative ERF, while others are net positive. Overall, current global models tell us that the global net ERF for contrail cirrus clouds today is positive and of a similar magnitude to that from the cumulative emissions of aviation carbon dioxide (CO_2), though the precise value is very uncertain, as shown in **Figure 2**. The uncertainty bounds on the net radiative impact of contrail cirrus clouds from today's models do not indicate that the impact could be zero or cooling (Lee et al., 2021).

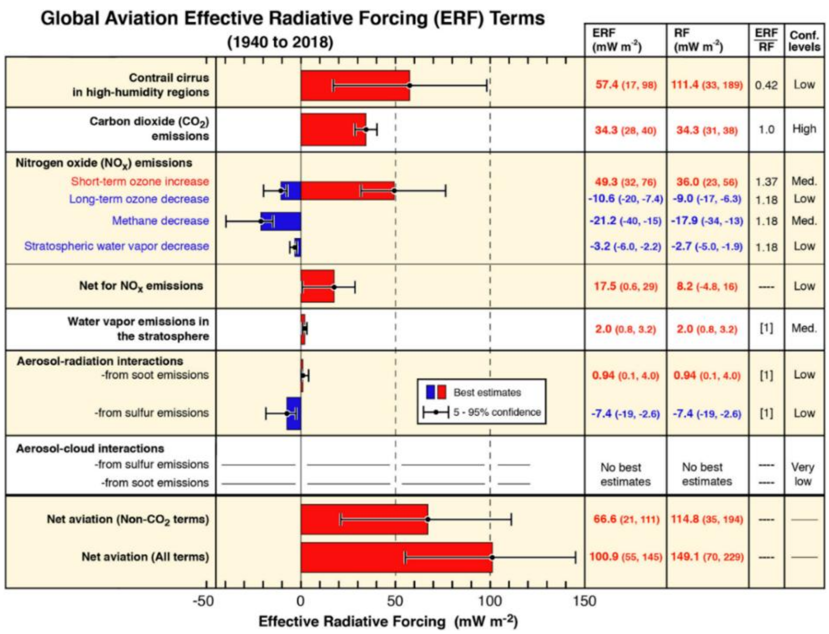


Figure 2: Global Aviation Effective Radiative Forcing (ERF) Terms (1940 to 2018) (Lee et al., 2021)

Scientists can confidently say that the net global impact of contrail cirrus clouds today is warming and significant relative to the warming from aviation carbon emissions. However, quantifying the net impact of individual contrails (that can be either warming or cooling) is much more uncertain. More research will improve confidence contrail prediction at regional-to-continental scales and will provide the best ways to improve, advance, and strategically deploy these capabilities across the aviation section in the near-, mid-, and long-term (Lee et al., 2021; Lee et al., 2023).

III. Collaboration, Roles, and Responsibilities

Contrail cirrus management requires a solid foundational understanding of atmospheric chemistry and physics, aircraft emissions, weather prediction, and operational management. At present, there is low confidence in the accuracy of contrail cirrus climate predictions, which motivates improving and advancing modeling capabilities, as well as developing robust methods for environmental monitoring, data collection, and validation. Similarly, we have a limited understanding of the potential disruptions to the national airspace caused by contrail cirrus management or the long-term climate and economic impacts of effective management. Due to the breadth of research needs to reduce uncertainties and develop mitigation solutions, collaboration among impacted stakeholders is crucial. Various U.S. government agencies, industry stakeholders, researchers, and scientists all play key roles in contrail research efforts.

Fortunately, stakeholders have already begun discussions, partnerships, and programs to advance contrail cirrus management. Defining additional clear roles and responsibilities will enhance the coordination needed to push contrail research and mitigation strategies forward effectively. Given the global nature of this issue—and considerable research being performed outside of the U.S.—it will also be critical to continue our collaboration with stakeholders around the world to support effective, complementary, and coordinated research efforts.

IV. Research Areas

Scientists can confidently say that the net global impact of contrail cirrus clouds today is warming and significant relative to the warming from aviation carbon emissions. However, quantifying the net impact of individual contrails is much more uncertain. More research is needed to understand the capability of contrail prediction models at regional-to-global scales in order to inform potential efforts to avoid or mitigate persistent contrail formation. In addition, there is a continuing need to incorporate new global model simulations and observational estimates into assessments of the net global warming potential from contrail cirrus clouds. Finally, advanced aircraft engine technologies, sustainable aviation fuels, and operational re-routing promise to be important tools for contrail cirrus management. Research is needed to understand the best ways to improve, advance, and strategically deploy these capabilities across the aviation sector in the near-, mid-, and long-term.

A robust national contrails research program addresses how contrails form, persist, and impact the environment. Contrail management solutions will be informed by research activities in the following four research areas:

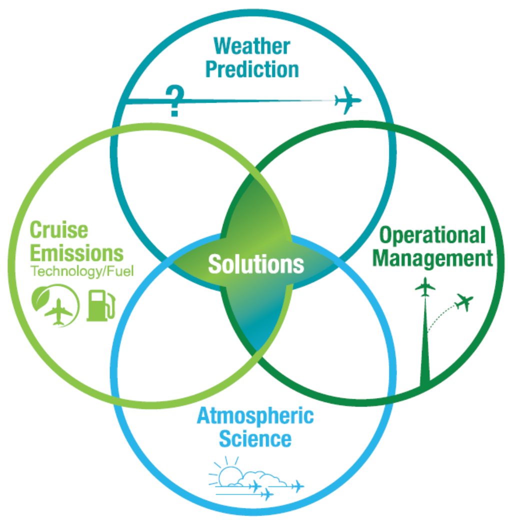


Figure 3: Contrail Research Areas

- **Atmospheric Science:** Process-level scientific understanding of how aviation emissions evolve and interact with Earth's atmosphere and radiation budget across local, regional, and global spatial scales and over daily, annual, and centennial timescales.
- **Weather Prediction:** Ability to forecast/nowcast ice supersaturated regions of the atmosphere, persistent contrail formation, and contrail cirrus radiative impact over hours to days.
- **Cruise Emissions:** Fundamental understanding of how advanced engine technologies, sustainable aviation fuel (SAF), and other alternative fuels (e.g., hydrogen) impact aircraft emissions and contrails.
- **Operational Management:** Ability to make effective and efficient operational decisions impacting contrails and the national airspace that balance economics, environmental impacts, and societal needs all without compromising safety.

The following sections provide more details on the envisioned goals and research activities in each of these research areas.

1. Atmospheric Science

Current research centers on improving our understanding of the atmospheric conditions and cruise emissions that contribute to contrail cirrus formation, persistence, and environmental impact. Relevant contrail microphysical properties include the number of ice crystals and their size distribution, while macrophysical properties include the contrail optical depth, light extinction and scattering, and the spatiotemporal extent of the cloud. The same atmospheric conditions that allow for persistent contrails also tend to promote the formation of natural cirrus clouds, and the current understanding of how contrail cirrus and natural cirrus interact remains primitive. Atmospheric science intersects with weather prediction through the use of numerical weather prediction models and satellite and in situ observations to identify ice supersaturated regions (ISSRs) and to forecast/nowcast formation, persistence, and climate impact as well as counterfactual cases (i.e., what would the atmosphere look like if the aircraft altered its trajectory?). Atmospheric science intersects with cruise emissions through the causal link between fuel- and combustor-dependent aircraft engine particle emissions that determine contrail ice microphysical properties. Atmospheric science intersects with operational management by allowing decisionmakers to optimize environmental, economic, and societal benefits while working with uncertain information.

Technological advancements play a critical role in this research. Remote sensing tools such as space- and ground-based imagers, lidars, and spectrometers, as well as in situ sensors aboard aircraft, provide crucial data for observing contrail formation and evolution. Observations help track contrails in real time and can provide quantitative estimates of contrail-induced radiative forcing, while atmospheric models simulate contrail behavior and their broader effects. However, these models have limitations: global models struggle with real-time predictions, while ice microphysics models are efficient but approximate and can miss broader climate interactions. Goals of atmospheric science research include:

A-1. Characterization of atmospheric temperature, water vapor, and particles relevant for contrail cirrus and natural cirrus clouds

Observations and modeling studies are needed to understand the spatial and temporal distribution of the key atmospheric parameters for determining the Schmidt-Appleman criterion for contrail formation and persistence as well as constraining aerosol-cloud interactions related to natural cirrus. Some important scientific questions include: 1) to what extent are ISSRs horizontally wide and vertically shallow; 2) how does the contrail formation alter natural cirrus and the upper tropospheric water budget; 3) do aviation particle emissions act as ice nucleating particles for natural cirrus; and 4) do ambient particles act as cloud condensation nuclei in forming contrails behind low-soot engines?

A-2. Improved understanding of contrail cirrus persistence and evolution over time

Despite the central importance of contrail cirrus, most recent airborne studies have concentrated on studying the properties of newly formed linear contrails that are only seconds to minutes old. New research is needed that extends these timescales out further to capture the evolution of linear contrails into diffuse contrail cirrus. Such work would be well complemented by satellite and ground-based remote sensors.

A-3. Improved predictability of the environmental impact from individual flights

Operational interventions to manage contrail warming will take place on a per flight trajectory or regional domain basis, which necessitates improving our understanding of how the formation of persistent contrails behind one or more aircraft interact to produce a radiative forcing. Large uncertainties in radiative forcing remain at the global level, and it is expected that the uncertainties at smaller scales are likely to be much greater. Scientific studies are needed to understand under what conditions, locations, and times there is sufficient confidence in predictions of the warming impact from individual flights to allow for interventions. The contribution of information from in situ sensors onboard the aircraft should also be considered.

A-4. Linking ground-based and in-flight emissions measurements and understanding how emissions at cruise determine contrail microphysical properties

Extensive information about aircraft engine emissions at sea level static pressures are available through the International Civil Aviation Organization (ICAO) Emissions Databank and are thought to be broadly representative of aircraft engine emissions throughout the landing and takeoff (LTO) cycle. However, engine operation and emissions at cruise altitudes are likely to be different than those at LTO. Research is needed to understand how engine emissions scale with altitude in order to develop and improve model parameterizations of engine soot and volatile particle emissions for different combustor types and engine families. Novel particle sources may impact contrail formation and properties such as the recent awareness of lubrication oil vapor as a source of volatile aerosols that may be relevant for contrail formation behind low-soot aircraft engines.

A-5. Improved understanding of contrail effective radiative forcing and climate impact

Recent global climate model assessments conclude that the global effective radiative forcing from contrail cirrus is likely to be significantly positive (i.e., warming) and of a similar magnitude to that from aviation carbon dioxide emissions since the dawn of the jet age. Yet, the precise magnitude of this global net effective radiative forcing remains highly uncertain. The uncertainties are even greater for individual flight trajectories; although, this is the level at which contrail avoidance and management efforts will be implemented. Research on these radiative impacts is needed to reduce these uncertainties and to better constrain the model representation of rapid adjustments that are used to convert from the initial radiative forcing to the effective radiative forcing. For example, satellite-derived radiation estimates due to contrails on various time scales are also being developed.

A-6. Satellite observations for contrails

Current high-spatial and temporal resolution, polar-orbiting, and geostationary satellite images are effective tools for identifying persistent linear contrail features. Research in this area has been on-going for decades and has resulted in advancements in discriminating aviation-induced cloud features from naturally occurring line-shaped cloud features caused by gravity waves, coastlines, and frontal systems. Recent work has incorporated artificial intelligence and machine learning algorithms, which show gains in processing efficiency and throughput, albeit with more modest improvements in feature discrimination. New research studies are needed to advance satellite retrieval algorithms and to improve the ability to resolve diffuse contrail cirrus for monitoring and validation. In addition, new concept studies are needed to define the future of space-based remote sensing, which may include next generation geostationary satellites and constellations of small satellites in low Earth orbit that overcome the current poor time resolution of current polar-orbiters.

A-7. Understanding the atmospheric impacts and trade space of non-CO_2 versus CO_2 emissions

Understanding the long-term effects of contrail cirrus clouds and their interactions with Earth's radiation is a key goal. Researchers will need to work to predict how individual contrails contribute to global warming and how these impacts compare to other aviation radiative effects (e.g., CO_2, NOx, etc.).

2. Weather Prediction

Weather prediction is another necessary research area needed to mitigate and, eventually, predict contrail formation. Therefore, a key area of focus in contrail mitigation is enhancing weather prediction models to better capture atmospheric variables like temperature, wind speed, humidity, and background radiation, which significantly influence contrail formation. Increasing the volume of in situ data observations available will be crucial to help refine prediction models. This may be achieved by expanding the use of aircraft-based observations (ABO) and by improving the resolution of the data through new technologies. Improving the availability of high-resolution remote sensing data, such as through weather satellites, will also be a critical factor. By refining predictive models, researchers aim to improve the timeliness and accuracy of delivered data, allowing better informed flight operational decisions to be made and aiding in the real-time management of contrails to reduce their environmental impact. Goals of weather prediction research include:

W-1. Improved accuracy and timeliness of temperature and relative humidity at altitude

Near real time assimilation of all available atmospheric thermal and moisture observations (e.g., in situ, remote sensing) at altitude into numerical weather prediction models is crucial to improve model-based predictions of contrail formation and evolution at relevant flight levels.

W-2. Robust understanding of uncertainty and forecast levels of confidence

Understanding uncertainty is essential to advance and improve the reliability of contrail mitigation strategies. By characterizing the confidence levels forecasts can be effectively used to predict contrails and inform mitigation strategy plans. Additionally, understanding where uncertainty and improvements are needed can help inform future research.

W-3. Improved characterization of background atmospheric radiation environment

Accurately quantifying the warming and cooling contributions of contrails to the atmosphere requires a clear understanding of the background natural cirrus and radiation environment. Similarly, this understanding is required to accurately understand and predict contrail development and persistence (e.g., through satellite observations, as discussed in A-6). This knowledge is essential for improving climate models, forecasts, and fully understanding the effects of mitigation strategies.

W-4. Weather satellite launch and model prediction improvements

Adopting a forward-looking lens to contrail-related applications using future satellite remote sensing platforms will also be high priority activities that should be supported. Advocating for and demonstrating how to optimally harness observations from the next generation of weather-centric satellites that will provide both higher spatiotemporal sampling and improved estimates of atmospheric temperature and relative humidity profiles will also be necessary, especially for numerical weather prediction data assimilation applications.

W-5. Aircraft atmospheric sensor technology development and implementation

Real-time contrail detection systems offer the possibility of enabling pilots to avoid contrail-producing conditions during flight. Improved humidity and temperature sensors are one key step in the development of these systems. Sensor improvements also contribute to enhanced forecasting capabilities. These are needed to minimize uncertainties and boost the confidence levels of predictions, with a particular focus on atmospheric variables that influence contrail persistence, such as background radiation and humidity. By refining weather models, researchers aim to improve the timeliness and accuracy of data, aiding in better contrail management.

3. Cruise Emissions

Aircraft engines produce hot exhaust emissions during cruise that are particularly of concern when emitted at high altitudes where we observe the existence of ice supersaturation regions. The gases, liquids, and particles found in hot engine exhaust contribute significantly to contrail formation and persistence. These emissions include carbon dioxide (CO_2), water vapor, sulfur oxides (SO_x), nitrogen oxides (NO_x), and small carbon particles often referred to as soot or non-volatile particulate matter (nvPM). As hot engine exhaust cools in a humid environment, some of the gaseous pollutants condense into secondary particles that become good cloud condensation nuclei, thereby further contributing to the formation and persistence of contrails.

Aircraft engines also release small quantities of spent lube oil into the atmosphere during cruise. Spent lube oil emissions have been shown to emit volatile organic material and sulfur compounds known to interact with ice crystals in the atmosphere and impede their melting capabilities, leading to the formation of persistent spreading contrail cirrus.

Research on this topic involves characterizing and maturing advanced engine technologies that have been shown to severely limit or eliminate the release of gases, liquids, and particles that actively contribute to the formation of persistent warming contrails. Similarly, research can demonstrate cleaner fuels that lead to the same goal. A large part of the research efforts will involve accurately measuring engine exhaust pollutant emissions, both on the ground and at altitude. Research in this area will involve using industry best practices to characterize emissions based on a variety of modern combustion technologies and fuel formulations. The aim is to explore novel technologies that minimize or eliminate the formation of persistent warming contrails. Goals of cruise emissions research include:

C-1. Understanding emissions characteristic variations from current propulsion systems with current fuels

The aim of this effort is to characterize the emissions performance of different combustion technologies and fuel formulations to determine how pollutant levels at cruise contribute to the formation of persistent warming contrails. For example, modern combustors can offer low emissions performance, but this technology has not been fully characterized burning blended or neat sustainable aviation fuels (SAF). While SAFs offer the potential to reduce lifecycle carbon emissions and soot production, challenges remain in balancing fuel composition with engine compatibility and minimizing contrail production. The is one piece of research that can be accomplished in the near-term with proper collaboration between industry, airlines, and government.

C-2. Explore and characterize future fuel emissions and impacts

Emerging alternative fuels in the marketplace (e.g., hydrogen, liquid natural gas, cryogenic fuels, etc.) aim to significantly reduce CO_2 emissions from aviation. However, they also need to be assessed regarding their potential contribution to the formation of contrails.

C-3. Advance and enable technologies that reduce the formation of persistent warming contrails

As technology evolves, it will be important to characterize the emissions performance of new technologies and advance those that minimize the formation of persistent warming contrails. This includes new combustion technology as well as novel technologies outside of the combustor that address other engine impacts on contrails (e.g., spent lube oil). Public private partnerships can help support the advancement of the most promising technologies while reducing technological and economic risk.

4. Operational Management

Operational management of contrails consists of making adjustments to where aircraft fly to reduce the likelihood of formation of and the impacts from persistent warming contrails. While route adjustments are not a novel concept, there are multiple challenges to developing and implementing safe, efficient and effective operational contrail management strategies. Airspace is already highly constrained, with many interdependent factors to balance at once. Additional constraints or objectives may increase complexity, which potentially diminishes safety, capacity, and efficiency while also increasing workload for stakeholders (e.g., air traffic control, pilots, dispatch, etc.). Research is needed to develop contrail operational management decision support capabilities, concepts of operation (CONOPS), methods for verification of effectiveness, and protocols/mechanisms for contrail information connectivity across aviation systems. This work will need to be validated through large-scale demonstration activities to further mature the concepts and define stakeholder roles and responsibilities.

This research can support the overarching goal of seamless integration of contrail management decision-making into National Airspace System (NAS) operations. This future state does not entail adjusting every flight to avoid contrails. In fact, current research indicates that only a small percentage of flights cause the majority of contrail-induced warming (Teoh et al., 2024). Rather, the vision is to be able to make science-informed contrail management decisions for all flights in balance with other priorities. Goals of operational management research include:

O-1. Development of prototype decision support capabilities and initial CONOPS for contrail operational management

Developing decision support capabilities and CONOPS for contrail operational management first requires continued advancement in the other research areas discussed in this document to reduce uncertainty and improve prediction and modeling tools. The design and function of these tools needs to be informed by input from operational stakeholders such that information is presented in a manner that is understandable and actionable. Similarly, a broad selection of operational stakeholders should be engaged to define and evaluate different potential CONOPS. There are differing approaches under consideration for where the operational decision should originate, the timeline for decision-making/intervention, and the corresponding roles and responsibilities for various stakeholders. Lastly, consideration should be given to the extent to which existing or incoming operational systems (e.g., systems that enable route adjustments for other purposes) could be leveraged to integrate contrail operational management decision support capabilities. There may be opportunities to improve efficiency while also managing contrail impacts, so a decision support capability should look for synergies between contrail management and system efficiency.

O-2. Test/demonstration of decision support capabilities and CONOPS and iterative refinement

The capabilities and CONOPS developed under O-1 will require testing and demonstration to prove out the concepts and identify areas for improvement. This testing may occur through simulations of increasing complexity progressing into trials with live flight operations. The development work and stakeholder coordination that occurs under O-1 can help identify the needs and objectives of operational simulations and trials, i.e., by identifying the questions and issues that need to be resolved and the available methods and test infrastructure to resolve them. Based on the outcomes of the test and demonstration activities, as well as potential advancements in the science and modeling, the contrail operational management tools and CONOPS will likely need refinement. This may be an iterative process in which smaller scale bench testing or demonstration work is conducted to fine-tune the tools and protocols. Furthermore, these test and demonstration activities may serve as valuable sources of data to improve the science and modeling.

O-3. Large-scale test/demonstration of regionally integrated contrail management capability

Once the contrail operational management system is reasonably mature, there will likely be a need to conduct a large-scale trial (or trials) to fully vet the capabilities. This could differ from prior live flight trials in terms of scope and duration. Ideally, this testing would occur across multiple air route traffic control centers—and possibly multiple air navigation service providers—over an extended period of time, sufficiently long to validate the effectiveness of the contrail operational management system. This large-scale trial could include a validation component to provide confirmation that the contrail management capability is effective. Establishing a large cross-industry team—potentially to include global partners—to engage in all phases of this work, including planning, execution, and post-trial data analysis, can help ensure this work is successful.

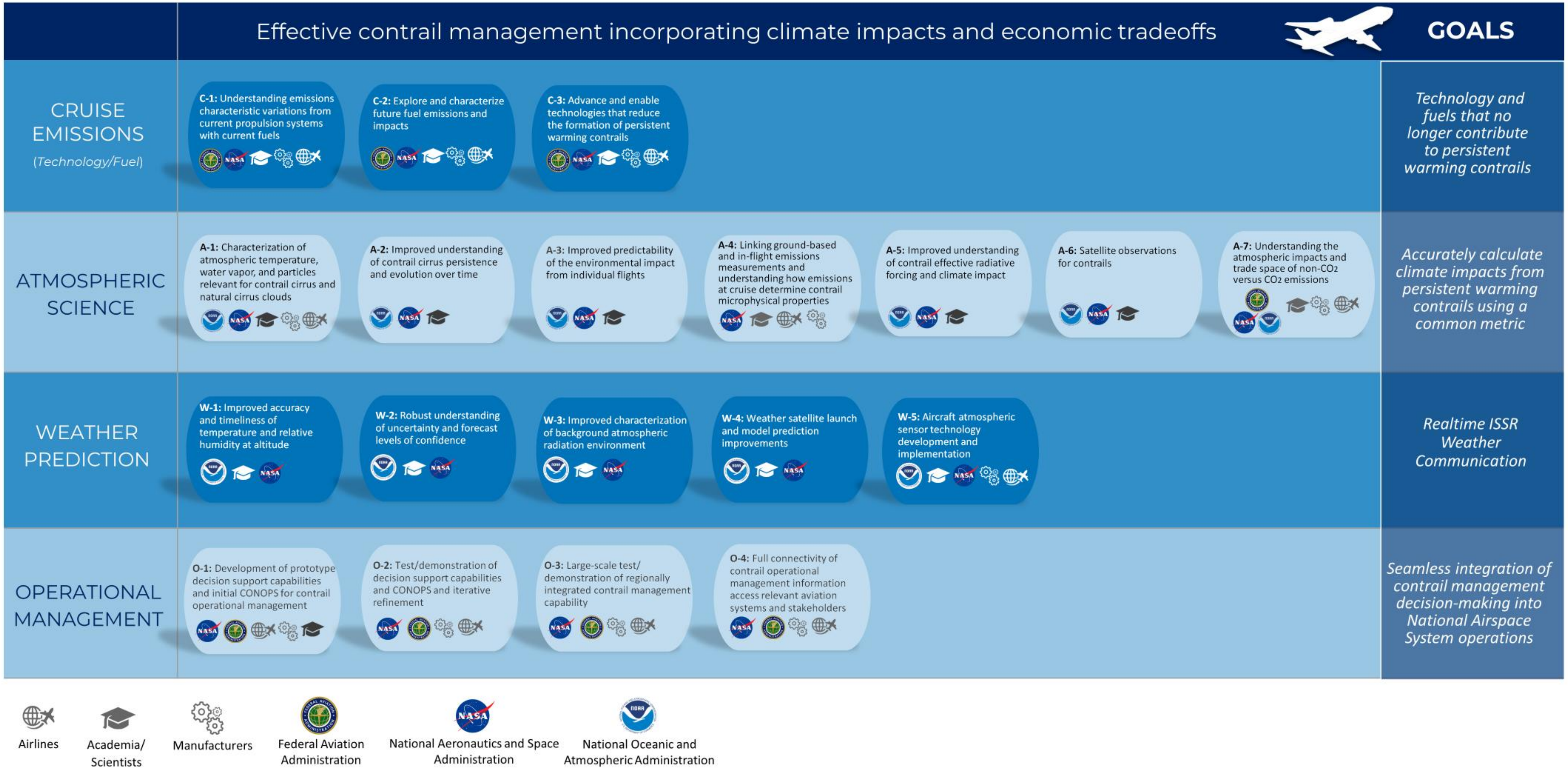
O-4. Full connectivity of contrail operational management information across relevant aviation systems and stakeholders

The prior research, development, and demonstration work could inform identification of the appropriate integration points in the airspace system for the contrail operational management capabilities. These capabilities will need to link contrail prediction and management information with flight planning, air traffic control, and cockpit systems such that all relevant operational stakeholders can participate in contrail-aware decision-making. Implementation may require modification of existing systems or the introduction of new systems into the NAS. In either approach, several steps are required to create an operationally fielded system. This includes establishing information exchange protocols, creating safety risk management plans, and developing training material, among others.

5. Contrails Research Activities

The Contrails Research Activities chart, **Figure 4**, depicts the aforementioned activities across a notional swim lane image. It seeks to identify both near- and long-term activities covering all four research areas, recognizing potential involvement across federal agencies and potential aviation stakeholders. Some activities, such as *A-4: Contrail Microphysics…* and *C-1: Propulsion Systems and Fuels…*, may occur simultaneously. Others, such as *O-1: Development of Decision Support Capabilities/CONOPS…* and *O2: Test/Demonstration of Capabilities/CONOPS…*, follow a more sequential path. The chart is meant to be fluid as some activities may span across swim lanes but are shown in their core research category. For example, *A-4: Contrail Microphysics…* is a research activity that spans across Atmospheric Science and Cruise Emissions but is primarily set in the Atmospheric Science category and included there as a result. In the chart, each research activity includes icons representing various federal agencies and potential aviation stakeholders where we welcome collaboration. The research activities identified in the figure will evolve as we learn more in partnership with our stakeholders.

Contrails Research Activities



V. Going Forward

Progress in the research areas outlined in this document provides a pathway toward achieving our vision of effective, routine, system-wide contrail management that incorporates climate impacts and economic tradeoffs by 2050. This document provides a starting point for advancing our understanding of contrails and their impacts in order to advance sustainable aviation. It is envisioned that earlier activities through the 2030s will support development, demonstration, and validation of models and tools. Beyond the 2030s, these research results may support subsequent activities to effectively manage contrail cirrus climate impacts. As with all large research initiatives of this scope, we anticipate learning along the way. Therefore, this roadmap will evolve and additional activities will emerge based on the outcomes of our proposed research.

We will regularly take stock of how uncertainties have been lowered and collectively chart the course for the next round of priority research with each update of this document – considering discovered gaps and lessons learned. The cadence of updates to this document will be commensurate with the pace and success of accomplishing research activities identified in this document, as well as shared lessons learned from complementary research initiatives from others. The lessons learned and improvement in our scientific understanding of persistent, warming contrails are envisioned to be shared outward to global stakeholders who are also working in this space. Sharing can be done in many ways and all approaches are welcome, but primary focus will be on archival scientific journal publications to ensure a global scientific consensus is properly supported.

The flexible format of this roadmap allows for adjustments and updates to plans along the way due to funding and research findings. It also allows for the transparent progress to be noted from the broader research community focused on persistent, warming contrails. Specific U.S. investments and research activities are subject to the availability of funds.

VI. Acronyms

ABO	Aircraft-based Observations
AIC	Aviation-Induced Cloudiness
CONOPS	Concept of Operations
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
ISSR	Ice Supersaturated Region
LTO	Landing and Takeoff Cycle
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
nvPM	non-volatile Particulate Matter
SAF	Sustainable Aviation Fuels

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