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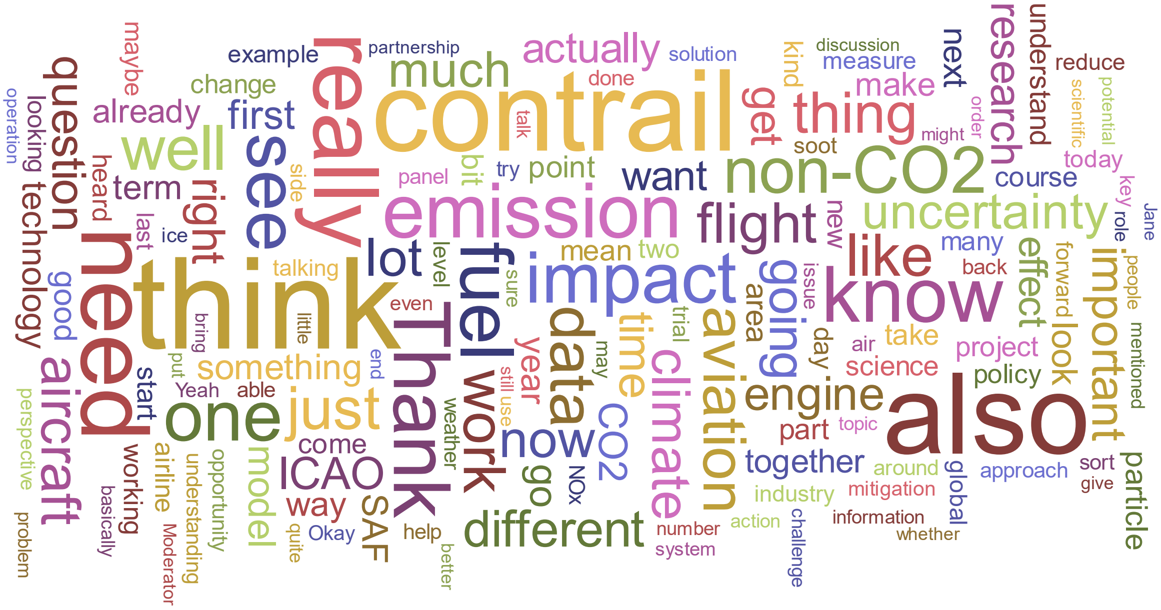
# SUMMARY OF THE ICAO SYMPOSIUM ON NON-CO$_2$ AVIATION EMISSIONS



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This report has been prepared to provide an overview of the current state of science, research priorities, and policy actions related to non-$CO_2$ emissions in aviation. The information contained herein is based on the discussions and presentations from the ICAO symposium and is intended for informational and educational purposes only.

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# ABOUT THE AUTHOR

Lukas Durdina is a seasoned aviation emissions expert with over a decade of hands-on experience in emissions characterization and prediction and sustainable aviation fuel (SAF). Lukas provides original research, specialized consultancy, and technology assessments, focusing on non-CO2 emissions and SAF. His work has had a significant impact on international aviation standards, with contributions to key projects for organizations such as the European Union Aviation Safety Agency (EASA) and the Swiss Federal Office of Civil Aviation (FOCA).

Lukas previously led the aviation emissions sub-group at the ZHAW Centre for Aviation, Switzerland, where he managed national and international research projects focusing on the environmental impact of aviation and led emissions certification test campaigns. He has actively contributed to emission measurement standards for SAE Aerospace and ICAO.

Lukas holds a PhD in Environmental Engineering from ETH Zürich, Switzerland, where he focused on particle emissions from turbofan engines and fuel composition effects, and a Master of Science in Mechanical Engineering from Brno University of Technology, Czechia. Lukas is passionate about reducing aviation's environmental footprint and advancing global sustainability through cutting-edge research and innovative solutions.

# ABSTRACT

This report provides a comprehensive summary of the ICAO Symposium on Non-CO2 Aviation Emissions, held in Montreal from September 16 to 18, 2024. The symposium brought together leading experts, researchers, policymakers, and industry stakeholders to address the critical role of non-CO2 emissions in aviation's climate impact. While CO2 emissions have been extensively studied, non-CO2 emissions and their effects, such as contrails, nitrogen oxides (NOx), and particulate matter (PM), may contribute significantly to aviation's short-term climate effects.

The report is divided into two parts. **Part 1** synthesizes the state of scientific knowledge on non-CO2 emissions, identifies knowledge gaps, and outlines ongoing research, policy actions, and technological developments aimed at mitigating their effects. Key areas covered include contrail formation and mitigation, NOx emissions, particulate matter emissions, the role of sustainable aviation fuels (SAF), hydrogen propulsion, and novel engine technologies. It also explores measurement, reporting, and verification (MRV) schemes for non-CO2 emissions, highlighting the growing importance of partnerships, data sharing, and international collaboration in developing effective mitigation strategies.

**Part 2** delves deeper into specific sessions from the symposium, providing detailed summaries of expert presentations and discussions. These summaries capture the insights shared by leading researchers and policymakers on topics such as contrail avoidance techniques, advancements in non-volatile and volatile particulate matter research, and the integration of non-CO2 effects into international aviation policies. The discussions also highlight the importance of advancing measurement technologies, refining emissions models, and fostering cross-sector partnerships to accelerate the development and implementation of sustainable solutions for aviation.

This report serves as both a summary of the symposium’s key findings and a forward-looking analysis of future research and policy directions needed to address the challenges posed by non-CO2 emissions in the aviation sector.

This report was created exclusively using recorded sessions from the event available online: https://www.icao.tv/icao-symposium-on-non-co-aviation-emissions.

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# PART 1 – OVERVIEW OF SCIENTIFIC ADVANCES, POLICY ACTIONS, AND TECHNOLOGICAL INNOVATIONS IN NON-CO2 EMISSIONS

## 1. INTRODUCTION

The ICAO Symposium on Non-$CO_2$ Aviation Emissions, held in Montreal from September 16 to 18, 2024, brought together experts, researchers, industry leaders, and policymakers to explore the complex challenges of aviation's non-$CO_2$ emissions. While $CO_2$ emissions have long been the focal point of climate discussions, non-$CO_2$ emissions and their effects—such as contrails, nitrogen oxides (NOx), and particulate matter (PM)—are increasingly recognized as critical contributors to aviation's overall climate impact. These emissions often have greater warming potential in the short term than $CO_2$.

This overview synthesizes the state of scientific knowledge, highlights knowledge gaps, and outlines research, development, and policy actions on contrails, NOx, particulate matter (nvPM and vPM), sustainable aviation fuels (SAF), hydrogen propulsion, and non-$CO_2$ emissions reporting mechanisms (MRV schemes). Additionally, it addresses concerns, blind spots, and the role of economics in the broader discussion.

## 2. CONTRAILS

### 2.1. FORMATION AND CLIMATE EFFECTS

Contrails, or condensation trails, are line-shaped clouds that form when hot, humid exhaust from aircraft engines mixes with the cold, ambient air at high altitudes. The process begins when water vapor in the exhaust cools and condenses onto particles emitted by the engine, such as soot and aerosols. These particles act as condensation nuclei, allowing water vapor to transition into liquid droplets. If the ambient temperature is below the ice frost point, ice crystals form within these droplets and grow as they take up more water vapor from the surrounding atmosphere. The **Schmidt-Appleman criterion** states that contrails form when the cooling exhaust plume becomes supersaturated with respect to liquid water, meaning the relative humidity with respect to water exceeds 100%.

Whether contrails persist long enough to have a climate impact depends not only on environmental conditions like atmospheric temperature, pressure, and humidity but also on the properties of the aircraft exhaust. The amount and type of particles in the exhaust, which is influenced by factors like fuel type and engine design, play a crucial role in determining the number and size of ice crystals that form.

Persistent contrails typically form in regions of the atmosphere that are cold and humid enough to sustain ice crystal growth. These **ice-supersaturated regions (ISSRs)** are often found near the tropopause, particularly over the North Atlantic and Europe where air traffic is heavy.

Contrails impact the climate by trapping outgoing longwave radiation from the Earth's surface, creating a warming effect similar to that of greenhouse gases. However, they can also reflect incoming solar radiation, leading to a cooling effect. The net climate impact of contrails depends on various factors, including their altitude, thickness, and coverage, as well as the time of day and underlying surface properties. While the precise climate impact of contrails is still subject to significant uncertainties, studies suggest that contrails could be as important to aviation's climate impact as all the CO2 emitted by aircraft since the dawn of aviation. One study estimates that contrails contribute to around 30% of aviation's total climate impact, with the remaining 70% attributed to CO2 emissions. However, this ratio can vary significantly depending on how contrail impacts are modeled and evaluated.

Several factors contribute to the **uncertainty surrounding the climate impact of contrails**. These include:

- Limited understanding of how contrails form and evolve
- Difficulties in accurately modeling and predicting atmospheric conditions at high altitudes, such as temperature, humidity, and wind patterns.
- Challenges in measuring the radiative properties of contrails and their interactions with other atmospheric components, such as natural cirrus clouds.

## 2.2. MITIGATION STRATEGIES FOR CONTRAIL-INDUCED CLIMATE IMPACTS

Several mitigation measures are being explored to reduce the climate impact of contrails. One promising approach is **contrail avoidance**, which involves rerouting flights to avoid areas where contrails are likely to form and persist. This can involve flying at different altitudes or slightly adjusting flight paths to steer clear of ISSRs. Studies indicate that rerouting a small percentage of flights (5-20%) could significantly reduce the warming effects of contrails.

**Engine technology** advancements can also contribute to mitigating contrail formation. By optimizing combustion processes and employing advanced engine designs, aircraft manufacturers aim to reduce the number of soot particles and volatile particulate matter (vPM) emitted in the exhaust. Reducing these particles can lead to fewer but larger ice crystals in contrails, potentially decreasing their climate impact.

**Fuel properties**, particularly the use of sustainable aviation fuels (SAFs), offer another avenue for mitigating contrails. SAFs typically have lower aromatic content compared to conventional jet fuel, resulting in reduced soot particle emissions. This reduction in soot particles can lead to changes in contrail properties, potentially diminishing their warming effect. However, it is crucial to note that SAFs will not eliminate contrails entirely.

## 2.3. CONTRAIL AVOIDANCE MEASURES AND TRIALS IN DETAIL

Contrail avoidance as the primary method for mitigating the climate impact of contrails involves adjusting flight paths to circumvent areas prone to their formation. Numerous research projects and trials are underway in Europe and North America to address these challenges and assess the viability of contrail avoidance as a mitigation strategy.

- **Germany:** The German government has supported initiatives like the 100-flights trial to demonstrate the feasibility of contrail avoidance. The D-KULT trial is another German initiative exploring contrail avoidance.

- **SESAR (Single European Sky ATM Research):**
  - **CICONIA:** This project focuses on developing climate-optimized trajectories and has conducted simulations and analyses of flight data to assess the potential of contrail avoidance. Preliminary results indicate that a significant reduction in contrail climate impact (around 80%) could be achieved with a relatively small increase in fuel consumption (approximately 1%).
  - **CONCERTO:** This project aims to optimize traffic flows to mitigate non-CO2 effects from aviation, focusing on the collaborative role of airlines and Air Navigation Service Providers (ANSPs) in contrail avoidance. The project is developing an optimization tool to identify climate-sensitive areas and provide mitigation suggestions.
- **Other European Projects:**
  - **AEROPLANE:** This exploratory research project investigates the climate impact of aviation, including the effects of aircraft flying through existing cirrus clouds (embedded contrails). It aims to identify suitable metrics for assessing climate change and developing mitigation strategies.
  - **E-CONTRAIL:** This project utilizes advanced AI technology for contrail detection and prediction, aiming to reduce uncertainties in forecasting contrail formation.
  - **ECHOES:** This project utilizes low-orbit satellites to provide VHF communication data from aircraft, supporting the forecasting of ISSRs.
  - **IAGOS:** a European research infrastructure for global observations of atmospheric composition from commercial aircraft during regular flights. This data, including measurements of water vapor, NOx, and ozone, is openly accessible to scientists worldwide. This open data policy enables researchers to study various atmospheric phenomena, particularly the formation and persistence of contrails. The comprehensive atmospheric measurements, especially of water vapor, could potentially contribute to improving weather models and predicting areas where contrails are likely to form. This information could be valuable for developing contrail avoidance strategies in the future.
- **North America:**
  - **Pre-Trails:** This program, supported by the U.S. Department of Energy, focuses on improving the prediction of persistent contrail cirrus clouds. Several teams are involved, including Boeing, Raytheon Technologies, Northrop Grumman, JPL, and GE Aerospace, each developing and testing new technologies and models for contrail prediction.
  - **Canada:** Transport Canada is actively involved in research and development related to contrail avoidance, including developing a dedicated contrail avoidance tool.
  - **EcoDemonstrator:** Boeing and United Airlines collaborated on a project using a 737 MAX as a flying testbed to gather data on contrail formation and the effects of engine design, fuel properties, and other factors on contrail properties.

### 2.3.1. KEY FINDINGS AND OBSERVATIONS FROM TRIALS

- **Significant Potential but Limited Real-World Application:** While simulations suggest substantial reductions in contrail climate impact are achievable, translating this potential into real-world operations is challenging.
- **Automation is Crucial:** Managing contrail avoidance maneuvers solely through human input (pilots and air traffic controllers) is unsustainable. Automated systems integrated into flight planning and air traffic management tools are essential for efficient and scalable implementation.
- **Data Gaps and Uncertainties:** A lack of comprehensive, high-quality data on atmospheric conditions, contrail formation, and persistence remains a significant obstacle. Continued research, data collection, and model refinement are necessary to improve forecasting accuracy and support decision-making.
- **Collaboration is Key:** Addressing the complex challenges of contrail avoidance necessitates collaboration between various stakeholders, including airlines, ANSPs, aircraft and engine manufacturers, researchers, and policymakers. Sharing data, expertise, and resources is essential for developing effective solutions.
- **Focus on High-Impact Flights:** Given the complexities and potential trade-offs, prioritizing contrail avoidance for flights identified as having the most significant climate impact could offer the most efficient approach.

### 2.3.2. SOFTWARE TOOLS

Several companies have developed software tools and platforms to support contrail avoidance research and trials:

- **Google:** Google has developed an AI-based contrail forecasting model and provides a free API (Contrails API) that offers access to these predictions. This API allows airlines, researchers, and other stakeholders to integrate contrail forecasts into their own systems and develop applications for contrail avoidance.
- **FlightKeys:** This Austrian company specializes in flight planning and has integrated contrail avoidance functionality into its software, including its electronic flight bag application, Loretta. FlightKeys' system allows for the visualization of contrail-forming areas and the optimization of flight profiles to minimize contrail formation while considering fuel efficiency.
- **Breakthrough Energy:** This organization is actively involved in contrail avoidance research and has partnered with various stakeholders, including Google and FlightKeys, to develop solutions for contrail mitigation. They offer tools and services to support airlines in implementing contrail avoidance strategies.
- **Satavia:** While not extensively detailed in the provided sources, Satavia is mentioned as being active in contrail avoidance trials, particularly in the U.S. They are known for their DECISIONX platform, which provides atmospheric modeling and flight optimization services, including contrail avoidance.

## 2.4. CHALLENGES OF CONTRAIL AVOIDANCE

### 2.4.1. PREDICTING ISSRS AND PERSISTENT CONTRAILS

Accurately predicting the formation and persistence of contrails is crucial for effective contrail avoidance, but it is a complex task fraught with uncertainties. These uncertainties stem from various factors:

- **Complex Atmospheric Processes:** Contrail formation depends on a delicate balance of atmospheric conditions, including temperature, humidity, wind shear, and atmospheric turbulence. These parameters can vary significantly over short distances and time scales, making accurate prediction challenging. Current climate models often lack the spatial and temporal resolution to represent these fine-scale variations accurately.
- **Limited Understanding of Ice Supersaturation:** While the Schmidt-Appleman criterion provides a basic understanding of contrail formation, predicting the precise conditions leading to ice supersaturation and persistent contrails require more sophisticated modeling and data.
- **Variable Aircraft Emissions:** The composition of aircraft exhaust, particularly the presence of soot and other particles that act as ice nuclei, significantly influences contrail formation and varies between engine types. The use of sustainable aviation fuels, while potentially reducing soot, can also alter other emissions, impacting contrail formation in complex ways.
- **Lack of Real-Time Observations:** Current contrail forecasting often relies on global weather models that may not accurately reflect real-time atmospheric conditions at cruise altitudes. Limited availability of real-time observations of humidity and temperature in the upper atmosphere hinders accurate contrail prediction.

### 2.4.2. OPERATIONAL FEASIBILITY

Even with accurate contrail predictions, implementing contrail avoidance maneuvers on a large scale faces significant operational challenges:

- **Airspace Complexity and Congestion:** Modern airspace, especially over Europe and North America, is highly congested, with aircraft operating under tight schedules and strict air traffic control procedures. Implementing contrail avoidance maneuvers requires coordinating altitude and route changes for numerous aircraft simultaneously, posing significant challenges for air traffic management systems and potentially disrupting existing traffic flows.
- **Pilot Workload and Tactical Decision-Making:** Contrail avoidance often necessitates real-time adjustments to flight paths, potentially increasing pilot workload and requiring additional communication with air traffic control. Balancing contrail avoidance with other operational priorities, such as fuel efficiency and passenger comfort, can create complex decision-making scenarios for pilots.
- **Variability in Airline and ANSP Adoption:** The successful implementation of contrail avoidance relies on the willingness and capability of airlines and ANSPs to incorporate contrail mitigation strategies into their operations. Varying levels of awareness, resources, and infrastructure across different stakeholders can create inconsistencies and hinder widespread adoption.

#### 2.4.3. FUEL BURN AND CO2 EMISSIONS TRADEOFF

A fundamental challenge in contrail avoidance is the potential tradeoff between reducing contrails and increasing fuel burn and associated CO2 emissions.

- **Suboptimal Trajectories:** Avoiding ISSRs often necessitates deviating from optimal flight paths, leading to increased flight distances or less fuel-efficient altitudes. This can result in higher fuel consumption and, consequently, greater CO2 emissions.
- **Quantifying the Tradeoff:** Accurately assessing the climate benefit of contrail avoidance requires quantifying the CO2 impact of altered flight paths against the reduced warming effect of avoided contrails. This requires reliable metrics for evaluating the climate impact of both CO2 and contrails over relevant timescales.

#### 2.4.4. COST

Implementing contrail avoidance measures involves various costs:

- **Research and Development:** Developing accurate contrail prediction models, advanced sensing technologies, and sophisticated air traffic management tools requires significant investment in research and development.
- **Operational Costs:** Implementing contrail avoidance strategies can lead to increased operational costs for airlines, including:
    - **Higher Fuel Consumption:** As mentioned above, deviating from optimal flight paths to avoid ISSRs can result in increased fuel burn.
    - **Longer Flight Times:** Altered flight paths can lead to slightly longer flight durations, potentially impacting airline schedules and increasing operating costs.
    - **Air Traffic Management System Upgrades:** Implementing contrail avoidance strategies effectively may necessitate upgrades to existing air traffic management systems and procedures, incurring additional costs

### 2.5. FUTURE PLANS FOR CONTRAIL AVOIDANCE IMPLEMENTATION

#### 2.5.1. NECESSARY STEPS FOR FLEET-WIDE IMPLEMENTATION

Implementing contrail avoidance strategies across the entire aviation industry requires a multifaceted approach that addresses technological, operational, and policy-related challenges:

- **Improved Weather Forecasting:** A recurring theme throughout the symposium was the need for more accurate and higher-resolution weather forecasts, particularly concerning humidity and temperature at cruise altitudes.
    - Stakeholders emphasized the importance of developing better humidity sensors and incorporating data from infrared sounders to enhance the accuracy of weather models, particularly in predicting ISSRs where contrails are likely to form.
    - Real-time or near-real-time data is crucial for enabling both pre-flight planning and in-flight tactical adjustments to avoid these regions.

- **Standardized Climate Impact Metrics:** A significant barrier to widespread adoption of contrail avoidance is the lack of globally agreed-upon metrics for measuring the climate impact of both contrails and CO2 emissions.
    - Stakeholders highlighted the need for a standardized framework to evaluate the effectiveness of contrail avoidance strategies and enable meaningful comparisons of different mitigation options.
    - This framework should consider various factors, including Radiative Forcing (RF), Effective Radiative Forcing (ERF), Global Warming Potential (GWP), and Global Temperature Change Potential (GTP).
- **Enhanced Air Traffic Management (ATM) Systems and Procedures:** Integrating contrail avoidance into routine flight operations requires significant adjustments to existing ATM systems and procedures.
    - Stakeholders emphasized the need to develop new concepts of operations that consider contrail avoidance on a system-wide level, rather than relying solely on individual flight-by-flight decisions.
    - This includes exploring various strategies, such as tactical and pre-tactical adjustments, controller and pilot-initiated maneuvers, and the role of dispatch in decision-making.
- **Collaboration and Data Sharing:** Successful implementation of contrail avoidance necessitates unprecedented levels of collaboration and data sharing across the aviation industry.
    - The symposium highlighted the importance of sharing data on contrail observations, weather forecasts, aircraft emissions, and flight trajectories to improve prediction models, develop effective mitigation strategies, and track progress.
    - Collaborative initiatives like ContrailNet, spearheaded by Eurocontrol, aim to facilitate data sharing and promote the development of standardized tools and methodologies for contrail observation and analysis.
- **Addressing Cost and Operational Challenges:** Implementing contrail avoidance strategies at scale requires addressing the associated costs and operational complexities.
    - Stakeholders acknowledged the potential increase in fuel burn and flight times associated with contrail avoidance maneuvers and emphasized the need to develop solutions that minimize these impacts while maximizing climate benefits.
    - Exploring innovative financing mechanisms, such as green loan books and carbon offsetting programs, could help mitigate the financial burden on airlines and encourage wider adoption.

#### 2.5.2. MISSING DATA

Several critical data gaps hinder the development and implementation of accurate and effective contrail avoidance strategies:

- **Volatile Particulate Matter (vPM) Emissions:** While regulations on non-volatile particulate matter (nvPM) have led to reduced soot emissions, volatile particulate matter, which also contributes to contrail formation, remains largely unregulated and understudied.

    - Research is needed to understand the relationship between vPM emissions, fuel composition, and contrail properties to develop effective mitigation strategies targeting this emission source.

- **Comprehensive In-Flight Measurements:** Limited availability of real-time, in-flight measurements of atmospheric conditions, aircraft emissions, and contrail properties poses a significant challenge.
    - Stakeholders emphasized the need to equip more aircraft with humidity sensors and other instruments to collect data on ice supersaturation, contrail formation, and persistence.
    - This data is essential for validating and improving prediction models and for assessing the effectiveness of mitigation strategies.
- **Long-Term Climate Impacts of Contrails:** While significant progress has been made in understanding the short-term radiative forcing of contrails, more research is needed to quantify their long-term climate impacts accurately.
    - This includes investigating the role of contrails in cloud formation, their impact on atmospheric chemistry, and their contribution to global warming over different timescales.

### 2.5.3. GOALS

The symposium highlighted several key goals related to contrail avoidance:

- **Developing a Globally Harmonized Approach:** Stakeholders emphasized the need for a globally harmonized approach to contrail avoidance, including standardized metrics, regulations, and mitigation strategies.
    - This will help ensure fairness, prevent market distortions, and maximize the environmental benefits of mitigation efforts.
- **Enabling Informed Decision-Making:** A key goal is to develop tools and provide information that empowers stakeholders across the aviation industry to make informed decisions about contrail avoidance.
    - This includes providing airlines with accurate contrail forecasts, equipping pilots with real-time information for tactical decision-making, and supporting ANSPs in developing efficient traffic management strategies.

# 3. NOX EMISSIONS

## 3.1. ROLE OF NOX IN AVIATION NON-$CO_2$

NOx refers to nitrogen oxides, primarily nitric oxide (NO) and nitrogen dioxide (NO2). These gases are produced during the high-temperature combustion of fuels and within the specification of commercial jet fuel NOx is practically independent of fuel composition. The role of NOx in aviation's climate impact is complex. These emissions, while not a direct radiative forcing agent like $CO_2$, contribute to climate change through intricate atmospheric chemical reactions.

**Ozone Formation and Methane Destruction:** NOx emissions from aircraft engines, primarily released at high altitudes, play a significant role in atmospheric chemistry. They contribute to the formation of ozone ($O_3$) in the troposphere. Ozone is a potent greenhouse gas and air pollutant, contributing to both warming and respiratory problems. However, NOx is also involved in reactions that destroy methane ($CH_4$), another potent greenhouse gas. This dual role of NOx, contributing to ozone formation while also mitigating methane's warming effect, creates complexity in assessing its net climate impact. The net radiative forcing of NOx from current aviation fleets is considered small due to these counteracting effects.

**Impact Dependent on Altitude and Atmospheric Conditions:** The climate impact of NOx is highly dependent on the altitude at which it's emitted and the prevailing atmospheric conditions. NOx emitted at higher altitudes, where aviation operates, generally has a longer atmospheric lifetime, allowing it to participate in more chemical reactions and potentially leading to a greater climate impact.

## 3.2. MODEL PREDICTIONS AND ACCURACY

**Model Discrepancies and Uncertainties:** There are significant uncertainties and discrepancies in model predictions regarding the climate impact of aviation NOx. Several factors contribute to these uncertainties:

- **Complex Chemical Interactions:** The intricate and interconnected nature of atmospheric chemistry, with NOx participating in multiple competing reactions, makes it challenging to model its impact accurately.
- **Spatial and Temporal Variability:** The atmospheric concentration of NOx and other reactive species varies greatly with location, altitude, and time, making it difficult to represent these variations in global climate models, which typically use coarse spatial and temporal resolutions.
- **Background NOx Concentrations:** Accounting for background NOx concentrations from sources other than aviation is challenging. These background concentrations vary significantly across space and time, making it difficult to isolate and accurately assess the specific impact of aviation-emitted NOx.
- **Long-Term Impacts and Metrics:** The climate impact of NOx emissions can vary significantly depending on the time horizon considered and the metrics used for evaluation. This is because NOx is a short-lived climate forcer, with effects lasting for years to decades, while CO2 is a long-lived climate forcer, with effects persisting for centuries.
- **Limited Understanding of Some Reactions:** Current models may not fully account for all relevant chemical reactions involving NOx, particularly those occurring within the engine plume or in the presence of aerosols, leading to potential inaccuracies in impact assessments.

**Efforts to Improve Model Accuracy:** Despite these challenges, research efforts are underway to improve the accuracy and reliability of model predictions. These efforts include:

- **Refining Chemical Mechanisms:** Researchers are working to incorporate a more comprehensive understanding of NOx chemistry into climate models, including reactions occurring within engine plumes and interactions with aerosols.
- **Increasing Model Resolution:** Enhancing the spatial and temporal resolution of climate models can help better represent the variability of NOx concentrations and their impact on ozone formation and methane destruction.
- **Improved Emission Inventories:** We need more accurate and comprehensive emission inventories, particularly for NOx emitted during cruise at high altitudes. This is crucial since 90% of global aviation NOx emissions occur at high altitudes.
- **Model Intercomparison and Validation:** Comparing the results from different climate models and validating them against observational data from atmospheric measurement campaigns, such as those conducted by IAGOS (In-service Aircraft for a Global Observing System), can help identify model biases and improve their overall accuracy.

## 3.3. MITIGATION MEASURES

**Engine Technology Advancements:** Given the complexities and uncertainties surrounding the net climate impact of NOx, the experts generally favor a precautionary approach. This involves focusing on reducing NOx emissions at the source through technological advancements in engine design and combustion technologies:

- **Lean-Burn Combustion:** Modern engines increasingly use lean-burn combustion technology, which operates with a higher air-to-fuel ratio compared to traditional rich-burn engines. This reduces peak combustion temperatures, leading to lower NOx formation.
- **Post-Combustion Treatment Systems:** While more common in ground-based applications, research is exploring the feasibility of incorporating post-combustion treatment systems, such as catalytic converters, in aircraft engines to further reduce NOx emissions.

**Operational Optimizations:** While less effective than engine technology advancements, optimizing aircraft operations can play a role in minimizing NOx emissions:

- **Flight Level Optimization:** Similar to mitigating contrail formation, adjusting flight paths and altitudes can help minimize NOx emissions in specific regions or atmospheric conditions. However, the effectiveness of this approach for NOx reduction is still under investigation.

## 3.4. KNOWLEDGE GAPS AND POLICY CONSIDERATIONS

- **Local Air Quality vs. Climate Impact:** There is a potential conflict between optimizing for local air quality addressed through ICAO regulations on NOx emissions during take-off and landing and minimizing overall climate impact, which requires a focus on NOx emissions at cruise altitudes. An engine optimized for low NOx emissions during the landing and take-off cycle might not be as efficient at reducing NOx at higher altitudes.

- **Trade-off between NOx and CO2:** NOx emissions are largely a function of combustion temperature—higher temperatures lead to increased NOx formation, but lowering combustion temperatures to reduce NOx can decrease engine efficiency and increase fuel consumption.
- **Cruise NOx Metric:** ICAO's CAEP is exploring a metric based on emissions measured at 85% takeoff thrust (at standard sea level), a point already used in existing certification procedures. Preliminary data suggests that this metric can effectively differentiate between engines with varying NOx emission profiles at cruise conditions.

# 4. PARTICULATE MATTER EMISSIONS

## 4.1. ROLE OF PARTICULATE MATTER IN AVIATION NON-CO2 EFFECTS

Non-volatile PM (nvPM) and volatile PM (vPM), despite their small size, play significant roles in aviation's non-$CO_2$ effects, primarily through their influence on contrail formation and persistence.

nvPM is primarily composed of soot particles formed during incomplete combustion. These particles are solid at high temperatures typical for engine exhaust, hence the term "non-volatile".

nvPM affects the climate system through several pathways:

- **Direct Radiative Forcing:** nvPM, being dark in color, absorbs sunlight and contributes directly to atmospheric warming (overall a negligible effect).
- **Contrail Formation:** nvPM plays a critical role in forming contrails, acting as condensation nuclei for water vapor to condense and freeze at altitudes where conditions would not typically support ice crystal formation. Each nvPM particle can act as a site for an ice crystal to form, influencing the initial number and size distribution of ice crystals in the contrail.
- **Contrail Cirrus:** The characteristics of the initial contrail, influenced by nvPM, can impact the formation, properties, and lifespan of contrail cirrus.
- **Aerosol-Cloud Interactions:** The broader scientific literature acknowledges that aerosols, including soot particles, can interact with existing cloud formations. These interactions can alter cloud properties, such as cloud droplet size and cloud lifetime, potentially influencing precipitation patterns and overall radiative balance.

Unlike nvPM, vPM comprises organic and inorganic compounds that can exist in gaseous or particulate form depending on temperature and pressure. The sources of vPM are unburned hydrocarbons from incomplete combustion, sulfur present in aviation fuel oxidized during combustion to form sulfuric acid, which can condense into particles, and engine oil.

The understanding of vPM's role in climate effects is evolving, particularly in the context of increasingly cleaner aircraft engines:

- **Impact on Soot:** vPM can condense onto existing soot particles, forming coatings that can alter their properties and behavior in the atmosphere. These coatings can influence how readily soot particles act as condensation nuclei for contrail formation.
- **Contrail Formation in Soot-Poor Conditions:** As engine technologies advance and nvPM emissions decrease, vPM might play a more significant role in contrail formation. In engines emitting very low soot levels, vPM could become the dominant source of condensation nuclei for contrail ice crystal formation.
- **Sulfur's Role in Contrail Formation:** Sulfur, often present in vPM as sulfuric acid, could have a notable impact on contrail formation, potentially counteracting the intended benefits of reducing nvPM emissions through cleaner engine technologies.

## 4.2. MITIGATION MEASURES

### 4.2.1. TECHNOLOGICAL ADVANCEMENTS

**Lean-Burn Combustion Technology:** Lean-burn engines, primarily developed to reduce NOx emissions, operate with a higher primary zone air-to-fuel ratio than traditional rich-burn engines. This lower flame temperature reduces the formation of NOx, but it also reduces nvPM by orders of magnitude. Lean-burn technology is already implemented in modern engines from GE Aviation and CFM International, with the 3rd generation being introduced in the new GE9X engine.

**Post-Emission Treatment Systems:** Optimizing oil venting systems, and potentially exploring oil-specific mitigation technologies, such as catalytic converters for oil vapors, warrant further research.

### 4.2.2. FUEL COMPOSITION AND SAF

**Reducing Aromatic Content:** Conventional jet fuel contains aromatic compounds contributing to soot formation. Utilizing SAFs with lower or zero aromatic content has shown potential in reducing both nvPM emissions and contrail formation. However, it's crucial to recognize that not all SAFs are created equal, and their effectiveness in mitigating non-$CO_2$ impacts depends on their specific chemical composition.

**Reducing Sulfur:** Sulfur in jet fuel is a direct precursor to sulfuric acid, a major component of vPM. Reducing sulfur content consequently leads to a decrease in sulfuric acid formation in the engine exhaust, thus lowering overall vPM mass.

## 4.3. KNOWLEDGE GAPS AND POLICY CONSIDERATIONS

**Understanding the Role of vPM in a Low-Soot Future:** As aviation transitions towards cleaner-burning engines and SAFs that significantly reduce soot emissions, the role of vPM in contrail formation is likely to become more significant. Research is needed to better quantify the contribution of different vPM components to contrail formation, their atmospheric behavior, and potential mitigation strategies in a low-soot exhaust.

**Uncertainties in Impact Assessment and Metrics:** Despite advancements in atmospheric modeling, significant uncertainties remain in accurately quantifying the climate impacts of nvPM and vPM, particularly concerning the long-term effects of contrails and their interaction with atmospheric processes.

**New Reporting Points for nvPM Emissions Certification Data:** Recognizing that the traditional four reporting points for the landing and take-off (LTO) do not fully capture nvPM emission characteristics in the range of operating conditions relevant for cruise emissions modeling, new voluntary reporting points have been introduced. This includes reporting nvPM emissions at 57.5% thrust and the thrust setting where maximum nvPM emissions occur, allowing more accurate interpolation and correction of the ground-based certification data to cruise conditions.

### 4.4. PROJECTS FOCUSING ON IN-FLIGHT CHARACTERIZATION OF NVPM

- **ECLIF (Emission and Climate Impact of alternative Fuels):** ECLIF campaigns, were significant efforts to quantify the impact of SAF (up to 100% SAF) on nvPM emissions and ice crystal formation in contrails. These campaigns involved flight tests using chase aircraft to measure emissions and contrail properties.
- **VOLCAN**: This project, funded by the French DGAC and German agencies, focuses on understanding the link between fuel composition and aircraft emissions, including nvPM and vPM, and contrail formation in lean-burn engines.
- **UNIC (Understanding of Non-CO2 Impacts for Decarbonized Aviation):** This four-year European project involves over ten universities and research institutes. UNIC focuses on measuring and characterizing particulate matter, both nvPM and vPM, at the engine exit plane of research aircraft on the ground and in-flight, providing important data for validating ground-to-cruise corrections methodologies.

## 5. SUSTAINABLE AVIATION FUEL AND FOSSIL FUEL COMPOSITION

### 5.1. SAF ROLE IN AVIATION NON-CO2 EMISSIONS

While widely recognized for their potential to reduce $CO_2$ emissions, the symposium revealed that the role of SAFs in mitigating non-$CO_2$ effects is more nuanced and depends heavily on their specific chemical composition.

Fuel composition plays a crucial role in mitigating the non-CO2 emissions from aviation, particularly the formation of nvPM and vPM. Aromatic compounds and sulfur content in jet fuels are key factors influencing the formation of these emissions.

**Role of Aromatics in Soot Formation**

Aromatic hydrocarbons, characterized by their ring-shaped molecular structure, are a significant constituent of conventional jet fuels, comprising up to 25% of the total volume. The presence of double bonds within these aromatic rings makes them slower to burn compared to other hydrocarbon types, making them precursors to soot formation.

Sustainable aviation fuels, especially those derived from HEFA (Hydroprocessed Esters and Fatty Acids) technology like HEFA-SPK, offer a significant advantage in this regard. These fuels are largely paraffinic, meaning they are virtually free of aromatic compounds. Consequently, they burn more cleanly, resulting in substantially lower soot emissions. Research conducted during the ECLIF (Emission and Climate Impact of alternative Fuels) campaigns, which involved testing 100% SAF blends, consistently demonstrated a strong correlation between lower aromatic content and reduced soot emissions, subsequently leading to a decrease in ice crystal formation within contrails.

However, it's crucial to recognize that not all SAFs are created equal. While HEFA-SPK fuels are inherently low in aromatics, other emerging SAF pathways might produce fuels with varying levels of aromatics. For instance, SAK (Synthetic Aromatic Kerosene), a new type of SAF, is characterized by its high aromatic content. However, even in this case, the aromatic compounds in SAK are primarily mono-aromatics, which are considered less problematic in terms of soot formation compared to the di-aromatics found in conventional jet fuel. This difference highlights the need for a nuanced understanding of SAF composition and its implications for non-CO2 emissions.

**Sulfur Content and Volatile Particulate Matter (vPM)**

During combustion, sulfur in fuel is oxidized to form sulfur dioxide (SO2), which can further react in the atmosphere to form sulfuric acid (H2SO4). Sulfuric acid is highly hygroscopic, meaning it readily absorbs water vapor from the atmosphere. This process leads to the formation of vPM, which can contribute to cloud formation and growth, potentially impacting the radiative properties of clouds and affecting the climate.

Sustainable aviation fuel blends typically have a significantly lower sulfur content than conventional jet fuels. This reduction in sulfur content contributes to cleaner combustion, resulting in lower SO2 emissions and, consequently, reduced sulfuric acid formation and vPM. The lower vPM levels associated with SAFs can potentially lead to a decrease in contrail cirrus formation, as vPM can act as condensation nuclei for ice crystals, influencing contrail properties.

## 5.2. OPTIMIZING FOSSIL FUEL COMPOSITION

While the long-term goal is to transition away from fossil fuels, the symposium recognized that optimizing the composition of conventional jet fuel can offer near-term opportunities to reduce non-$CO_2$ impacts. This includes researching and implementing methods to reduce both aromatic and sulfur content.

**Benefits of optimizing fossil fuels:**

- **Reduced Soot and vPM Emissions:** Lowering aromatic content through refining processes like hydro-treating can significantly reduce soot formation, similar to the benefits observed with paraffinic SAFs. Reducing sulfur content through hydro-desulfurization can minimize vPM formation, contributing to cleaner combustion.

- **Potential for Immediate Impact:** Optimizing fossil jet fuel composition offers a more immediate pathway to reducing non-CO2 emissions compared to the longer-term transition to SAFs, which are currently limited in production capacity.

**Challenges associated with optimizing fossil fuels:**

- **Impact on Fuel Properties:** Significantly altering aromatic and sulfur content can impact other crucial fuel properties, such as density, combustion characteristics, and stability.
- **Engine Compatibility:** Changes in fuel properties necessitate careful consideration of engine compatibility to avoid compromising performance and safety.
- **Increased Refinery CO2 Emissions:** The refining processes required to lower aromatics and sulfur content in fossil fuels are energy-intensive and can lead to increased CO2 emissions from refineries. Addressing this challenge requires incorporating carbon capture and storage (CCS) technologies within the refinery sector to mitigate these additional emissions.

A study funded by the UK Department for Transport investigated the impact of reducing aromatic content in fossil jet fuel. Experimental data from this study, conducted on an APU (Auxiliary Power Unit) engine, demonstrated a clear correlation between lower aromatic content and reduced particle number and mass emissions. Furthermore, the study indicated a slight improvement in fuel consumption, which could potentially translate to lower CO2 emissions per passenger. These findings underscore the potential of optimizing fossil fuel composition as a viable strategy to mitigate aviation's non-CO2 impact.

## 5.3. CHALLENGES AND TRADE-OFFS IN SAF ADOPTION

While SAFs hold significant promise for reducing aviation's environmental footprint, their widespread adoption faces several challenges:

- **Scaling Up Production:** The most pressing challenge is the limited production capacity of SAFs. Current production levels are insufficient to meet the increasing demand from the aviation industry. Addressing this challenge requires significant investment in new production facilities, technological advancements to improve production efficiency, and supportive policies to incentivize SAF production and uptake.
- **High Costs:** SAFs are currently more expensive to produce compared to conventional jet fuel, making them less economically attractive for airlines. Achieving cost parity with fossil fuels will be crucial for widespread adoption. This requires further research and development of more efficient production pathways and economies of scale in SAF production.
- **Engine Compatibility and Fuel Performance:** Although many SAFs are designed as "drop-in" fuels, meaning they can be used in existing aircraft engines without major modifications, changes in fuel composition can still impact engine performance and require rigorous testing to ensure compatibility and safety. Additionally, optimizing fuel composition for non-CO2 reduction should not compromise CO2 reduction goals.

# 6. NOVEL ENGINE TECHNOLOGIES

The symposium discussed several novel engine technologies with the potential to reduce non-$CO_2$ emissions, acknowledging the challenge of achieving this without compromising fuel efficiency and $CO_2$ reduction goals.

## 6.1. LEAN-BURN COMBUSTION TECHNOLOGY

**Technology:** Lean-burn combustion technology increases the ratio of air to fuel during combustion. In conventional "rich burn" engines, the fuel-air mixture in the primary zone is closer to the stoichiometric ratio, which is the ideal ratio for complete combustion. However, by leaning out the mixture, lean-burn engines can achieve lower combustion temperatures. This reduction in temperature inherently limits the formation of NOx.

Lean-burn combustion has evolved through several generations, with each iteration offering improvements in performance and emission reduction. For instance, General Electric (GE) Aerospace has developed three generations of lean-burning Twin Annular Pre-Swirl (TAPS) combustion systems. The GEnx engine incorporates Generation 1, the LEAP family of engines utilizes Generation 2, and Generation 3 will be employed in the GE9X engine.

**Benefits:**

- **Substantial nvPM Reduction:** Lean-burn technology can achieve multiple orders of magnitude reduction in nvPM emissions. This is significant as nvPM is a primary contributor to contrail formation.
- **NOx Control:** While not as drastic as nvPM reduction, lean-burn technology can control NOx and hold it down to levels that are significantly reduced compared to traditional rich-burn combustors in engines with the same pressure ratio.

**Challenges:**

- **Scaling Down for Future Engines:** A key challenge lies in adapting lean-burn technology to the smaller, more compact core designs anticipated for future aircraft engines, such as those being explored in GE and CFM International's RISE program.
- **Volatile Particulate Matter (vPM) Formation:** While effective in reducing nvPM, lean-burn technology can lead to increased formation of vPM, particularly in the soot-poor regime. Further research is needed to understand the climate impacts of vPM and explore mitigation strategies.
- **Long Development Timelines:** Developing new engine technologies, including advancements in lean-burn combustion, is a lengthy process. This extended timeframe can pose challenges in responding rapidly to evolving scientific understanding and potential regulatory changes.

## 6.2. HYBRID PROPULSION SYSTEMS

**Technology:** Hybrid propulsion systems combine traditional gas turbine engines with electric motors and batteries. This allows for optimized engine operation during specific phases of flight, potentially reducing both $CO_2$ and non-$CO_2$ emissions.

**Benefits:**

- **Reduced Engine Load:** During taxiing, take-off, and climb, hybrid systems can utilize electric power to supplement or even replace the gas turbine engine, significantly reducing emissions in these critical phases.
- **Improved Fuel Efficiency:** By optimizing engine operation throughout the flight profile, hybrid systems can contribute to overall fuel burn reduction, leading to lower $CO_2$ emissions.

**Challenges:**

- **Weight and Complexity:** Integrating electric motors, batteries, and associated systems into aircraft designs adds weight and complexity, potentially offsetting some of the efficiency gains.
- **Technology Maturity:** While hybrid propulsion is being actively researched and developed, its widespread implementation in commercial aviation is still some years away.

## 6.3. Open Rotor Technology

**Technology:** Open rotor engines, also known as unducted fan engines, feature large, unshrouded propellers driven by a gas turbine. Currently, such a design is under development in the CFM International's RISE program. This design offers significant fuel efficiency improvements compared to traditional turbofan engines, potentially leading to lower $CO_2$ and non-$CO_2$ emissions.

**Benefits:**

- **Fuel Efficiency and $CO_2$ Reduction:** The primary benefit of open rotor technology is its high propulsive efficiency, leading to reduced fuel consumption and $CO_2$ emissions.

**Challenges:**

- **Noise Reduction:** Open rotor engines are inherently noisier than turbofan engines. Significant advancements in noise reduction technologies are needed for their widespread adoption.
- **Integration Challenges:** The large size and different airflow characteristics of open rotor engines pose integration challenges for aircraft design, requiring modifications to the airframe and potentially impacting aircraft stability and control.

# 7. HYDROGEN PROPULSION

The symposium touched on the potential role of hydrogen as a fuel and its implications for non-$CO_2$ emissions. The discussions highlighted both potential benefits and areas requiring further research.

## 7.1. POTENTIAL BENEFITS

**No Soot Emissions:** As a carbon-free fuel, hydrogen combustion produces no soot, a major component of nvPM and the primary nuclei for ice crystals in contrails. This inherent advantage positions hydrogen as a potentially transformative solution for reducing contrail formation and its associated warming effects.

**Lower NOx Emissions:** Hydrogen combustion can potentially lead to lower NOx emissions compared to conventional jet fuel. However, the high combustion temperatures of hydrogen could counteract these reductions, requiring further investigation into ultra-lean combustion technologies to minimize NOx formation.

**Eliminating Sulfur and Aromatics:** Shifting to hydrogen completely eliminates concerns related to sulfur and aromatic content in fuel, simplifying the non-$CO_2$ emissions profile and removing a significant source of uncertainty associated with traditional and sustainable aviation fuels.

## 7.2. CHALLENGES

**Increased Water Vapour Emissions:** While hydrogen combustion eliminates carbon-based emissions, it significantly increases water vapor emissions. The climate impacts of this increase, particularly the potential for contrail formation in different atmospheric conditions, are not yet fully understood and require further research.

**Redesigning Aircraft and Engines:** Adapting aviation infrastructure for hydrogen propulsion necessitates a complete redesign of aircraft and engines. This includes developing new fuel storage and delivery systems, as well as optimizing combustion technologies for hydrogen's unique properties.

**Scaling Up Hydrogen Production and Supply:** Transitioning to a hydrogen-based aviation sector requires a substantial increase in the production of green hydrogen, derived from renewable energy sources, to ensure genuine environmental benefits. Establishing a reliable and cost-effective hydrogen supply chain for aviation poses a significant logistical and infrastructural challenge.

## 7.3. KNOWLEDGE GAPS

**Contrail Formation with Hydrogen Combustion:** While the absence of soot is promising, we need for further research to understand how the increased water vapor emissions from hydrogen combustion will influence contrail formation and persistence. This includes investigating the role of other emissions from hydrogen-powered aircraft, such as engine oil and potentially nitric acid, in providing condensation nuclei for ice crystal formation.

**Quantifying the Overall Climate Impact:** A comprehensive assessment of hydrogen's climate impact in aviation requires evaluating the trade-offs between its potential to reduce soot and NOx emissions with the increase in water vapor. This analysis necessitates sophisticated atmospheric modeling and data collection to accurately quantify the net effect of radiative forcing and climate change.

## 7.4. HYDROGEN RESEARCH NEEDS

The speakers called for a collaborative approach involving researchers, engine and aircraft manufacturers, fuel producers, and policymakers to address the knowledge gaps and accelerate the development of hydrogen-powered aviation. Key areas of focus include:

**Dedicated Research Programs:** Investing in focused research programs specifically investigating the non-$CO_2$ impacts of hydrogen combustion in aviation, including dedicated flight tests with instrumented aircraft to gather real-world data.

**Volatile Particle Characterization:** Research should prioritize the characterization of vPM formation from hydrogen combustion, focusing on the role of NOx in particle formation through the nitric acid pathway. This includes conducting laboratory experiments and developing sophisticated atmospheric models to accurately predict vPM formation rates and assess their contribution to contrail formation.

**Water Vapor Impact Assessment:** Comprehensive research is needed to assess the climate impacts of increased water vapor emissions from hydrogen-powered aircraft. This includes developing climate models that can accurately simulate the formation, persistence, and radiative properties of contrails formed from hydrogen combustion by-products.

**Life Cycle Analysis:** Conducting comprehensive life cycle analyses of hydrogen-based aviation, considering not only the emissions during flight but also those associated with hydrogen production, transportation, and storage, to ensure a holistic evaluation of its environmental impact.

**Operational Impact Analysis:** The operational aspects of hydrogen-powered aircraft, including ground handling procedures, refueling infrastructure, and potential safety implications, require thorough investigation. Developing comprehensive safety protocols and establishing robust infrastructure to support hydrogen-powered aviation are crucial for its successful integration.

# 8. MAJOR AREAS OF UNCERTAINTY AND RESEARCH NEEDS FOR NON-$CO_2$ EMISSIONS IN AVIATION

## 8.1. KEY UNCERTAINTIES

- **NOx:** While there is a consensus that NOx emissions from aviation currently contribute to warming, their future impact is unclear. This uncertainty stems from the complex chemical interactions of NOx in the atmosphere and their effects on ozone and methane, which have counteracting climate effects.

- **Contrail Formation:** The formation and persistence of contrails are heavily dependent on atmospheric conditions like water vapor and temperature, which are difficult to model and predict accurately. The composition of aircraft emissions, including soot, vPM and the size distribution of particles, also plays a significant role in contrail formation. Accurately quantifying the impact of these factors on contrail formation presents a considerable challenge.

- **Particulate Matter:** Significant uncertainties surround the climate impacts of both nvPM, primarily soot, and vPM. Although it is understood that nvPM contributes to contrail formation, its overall effect on climate, considering its interaction with clouds and ice formation, remains uncertain. Furthermore, the role of vPM, including its composition and contribution to contrail formation, is poorly understood.

- **Contrail Cirrus Effects:** A significant area of uncertainty lies in understanding the impact of contrails on cirrus cloud formation (contrail cirrus) and their subsequent effect on radiative forcing. Distinguishing between naturally occurring cirrus clouds and contrail cirrus poses a challenge in determining the actual impact of aviation on cirrus cloud cover.

## 8.2. MEASUREMENT AND MODELING UNCERTAINTIES

- **Atmospheric Variability:** Measuring and modeling non-CO2 emissions are challenging due to the highly variable nature of the atmosphere. Factors like altitude, temperature, humidity, and wind shear significantly influence the formation, persistence, and climate impact of contrails and other non-CO2 emissions. Replicating these conditions accurately in models is difficult, leading to uncertainties in predicting the climate impacts of aviation.

- **Volatile Particulate Matter:** Accurately measuring and characterizing vPM emissions from aircraft pose a significant challenge. The lack of standardized measurement techniques and the difficulty in distinguishing vPM from other atmospheric particles contribute to the uncertainty surrounding their impact on contrail formation and climate.

## 8.3. RESEARCH GAPS

- **Contrail Cirrus:** Research efforts need to focus on better understanding the formation and evolution of contrail cirrus and differentiating them from naturally occurring cirrus clouds. This includes improving the representation of ice crystal formation and radiative properties of contrail cirrus in climate models.
- **Aerosol-Cloud Interactions:** The complex interactions between aviation-induced aerosols (including soot and vPM) and natural clouds require further investigation. This includes improving the understanding of aerosol impacts on cloud formation, precipitation, and radiative properties, ultimately refining their representation in climate models.
- **Sustainable Aviation Fuels:** While SAFs are known to reduce nvPM emissions, their overall impact on contrail formation and other non-CO2 effects requires further research. This includes studying the impact of different SAF feedstocks and refining processes on vPM emissions and contrail properties.

## 8.4. FUTURE RESEARCH DIRECTIONS

- **Improved Measurement Techniques:** Develop and deploy more accurate and reliable sensors for measuring nvPM, vPM, water vapor, and other relevant atmospheric variables at different altitudes and under various atmospheric conditions. This includes exploring novel measurement techniques like using aircraft engines as humidity sensors.
- **Advanced Climate Modeling:** Improve the representation of contrail formation, contrail cirrus, and aerosol-cloud interactions in climate models. This involves incorporating more detailed microphysics, accounting for atmospheric variability, and developing methods to integrate data from various sources, including in situ measurements and remote sensing.
- **Integrated Research Approach:** Foster collaboration between atmospheric scientists, aerospace engineers, and policy-makers to ensure research addresses the most critical uncertainties and provides actionable insights for developing effective mitigation strategies. This includes facilitating data sharing and developing standardized methodologies for assessing non-CO2 impacts.
- **Hydrogen-Powered Aircraft:** As the aviation industry explores hydrogen as a potential fuel source, research should focus on understanding the climate implications of increased water vapor emissions from hydrogen combustion. This includes investigating the potential for contrail formation and the overall climate impact compared to conventional jet fuel.

# 9. MEASUREMENT, REPORTING, AND VERIFICATION OF NON-CO2 EFFECTS

The symposium discussed the Monitoring, Reporting, and Verification (MRV) scheme for non-$CO_2$ emissions in aviation. It focused on the EU's initiative but acknowledged the need for a global approach. The discussion highlighted the complexities, opportunities, and challenges of implementing such a scheme. It stressed the need for continued research, collaboration, and stakeholder engagement.

## 9.1. KEY FEATURES

The EU MRV scheme for non-CO2 emissions from aviation is designed to address the climate impacts of the industry beyond CO2 emissions. The scheme, set to commence in 2025, aims to increase transparency, incentivize research, and promote mitigation efforts.

- **Objective:** The EU MRV scheme acknowledges the significant climate impact of non-CO2 emissions from aviation, aiming to mainstream this understanding within the industry.
- **Scope:** The scheme will initially cover around 5 to 6 million flights per year, including those to and from the European Economic Area. This scope will expand in 2027 to include flights to and from outermost regions associated with EU member states, such as Martinique, Reunion Islands, French Guiana, Guadeloupe, Canary Islands, Azores, and Madeira, gathering data on long-haul flights.
- **Data Collection:** The EU MRV system will use a combination of reported data and modeling to determine non-CO2 effects.
- Airlines will be required to report specific information, including fuel properties (aromatic content, hydrogen to carbon ratio), aircraft properties (engine identifier, aircraft mass), and trajectory information.
- The scheme allows for the use of measured data, third-party provided data (like trajectory and weather information), or default values if an airline chooses not to report specific data points.
- **Modeling:** The scheme utilizes open-source models, ensuring transparency and facilitating ongoing refinement with input from experts.
- **NEATS:** The EU MRV will utilize a menu-like IT tool called NEATS (Non-CO2 Effects Aviation Tracking System) to calculate and assess non-CO2 effects. This tool, developed by the European Commission, will be available free of charge and promote transparency by using open-source models and publicly available parameters.
- The Boeing Fuel Flow Method 2 will be used to estimate emissions.
- The scheme will incorporate weather data, recognizing its significant impact on contrail formation, a major source of uncertainty in current models.

- **Flexibility and Iteration:** The EU MRV is designed to be flexible and iterative, acknowledging the evolving nature of scientific understanding and technological advancements in non-CO2 emission mitigation.
- Regular reassessments are built into the policy to accommodate new research and data.
- The scheme encourages partnerships and collaboration among stakeholders, including airlines, engine manufacturers, research institutions, and policymakers, to refine methodologies and improve the accuracy of non-CO2 impact assessments.

### 9.2. CHALLENGES AND OPPORTUNITIES

- **Uncertainty:** One of the main challenges in addressing non-CO2 emissions is the high level of uncertainty surrounding their climate impact. This is particularly true for contrail formation, which is heavily influenced by atmospheric conditions.
- **Data Gaps:** Accurate assessment of non-CO2 effects requires comprehensive data on various factors, including fuel properties, engine performance, and atmospheric conditions. Addressing these knowledge gaps through research and data collection is crucial.
- **Global Harmonization:** As non-CO2 effects are global, internationally harmonized standards and methodologies are crucial for effective mitigation. The EU MRV scheme can serve as a model for other regions to develop their own monitoring and reporting frameworks.
- **Balancing Costs and Benefits:** The costs of implementing and complying with MRV requirements, both for airlines and regulators, need to be carefully considered and balanced against the anticipated climate benefits and the potential for driving innovation.
- **Stakeholder Engagement and Collaboration:** Effective implementation requires ongoing dialogue and collaboration between policymakers, regulators, industry stakeholders (airlines, manufacturers, fuel producers), and the scientific community.

### 9.3. MOVING TOWARDS A GLOBAL FRAMEWORK

While acknowledging the EU MRV as a significant step, the symposium stressed the importance of developing a globally harmonized framework for addressing non-$CO_2$ emissions. This involves:

**International Cooperation and Data Sharing:** Facilitating data sharing and collaborative research initiatives between countries and regions will be essential for developing a comprehensive understanding of global non-$CO_2$ emissions and their impacts.

**Harmonized Metrics and Methodologies:** Establishing internationally agreed-upon standards for measuring, reporting, and verifying non-$CO_2$ emissions is crucial to ensure consistency, comparability, and a level playing field for all stakeholders.

**Equitable and Effective Policy Solutions:** Developing policy solutions that consider regional variations in emissions profiles, operational constraints, and economic circumstances is vital to ensuring a fair and effective global approach.

### 9.4. UNCERTAINTIES AND THE NEED FOR FURTHER RESEARCH

**Quantifying Economic Impacts:** One of the biggest challenges in assessing the economic aspects of non-$CO_2$ emissions lies in the significant uncertainties surrounding their climate impacts. Further research is needed to develop more accurate models and metrics for quantifying these impacts, which will then allow for more robust economic analysis and cost-benefit assessments of different mitigation strategies.

**Valuation of Non-$CO_2$ Effects:** The $CO_2$ equivalents are a potential metric for comparing the climate impacts of different emissions. However, there is ongoing debate about the appropriate time horizon to use for these calculations and how to value the non-$CO_2$ effects, such as changes in cloud formation or atmospheric chemistry. Developing a scientifically sound and widely accepted methodology for valuing these effects is essential for making informed economic decisions.

## 10.OVERARCHING TOPICS

### 10.1. IMPORTANCE OF DATA AND DATA SHARING

The symposium repeatedly stressed the critical need for robust data and effective data-sharing mechanisms to effectively address the complex challenge of non-CO2 emissions from aviation. This recurring theme underscores the recognition that a data-driven approach is essential for advancing scientific understanding, developing targeted mitigation strategies, and ensuring transparency and accountability within the aviation industry.

Data is fundamental to advancing the understanding and mitigation of non-CO2 emissions from aviation. This emphasis stems from the significant uncertainties surrounding the climate impacts of these emissions, particularly contrail formation and the long-term effects of various atmospheric constituents.

Key reasons why robust data is crucial:

- **Quantifying Climate Impacts:** Accurate data on emissions, atmospheric conditions, and the radiative properties of contrails is essential for developing reliable models to quantify the climate impacts of non-CO2 emissions. This data-driven understanding is crucial for informing policy decisions and prioritizing mitigation efforts.

- **Validating Mitigation Measures:** Data plays a vital role in evaluating the effectiveness of various mitigation strategies. For instance, real-world data on contrail formation under different atmospheric conditions is needed to assess the feasibility and effectiveness of contrail avoidance technologies.
- **Tracking Progress and Ensuring Accountability:** Robust data collection and analysis are essential for monitoring the aviation industry's progress in reducing non-CO2 emissions and holding stakeholders accountable for their commitments. This data-driven approach is crucial for building trust and ensuring the transparency of mitigation efforts.

### 10.1.1. BREAKING DOWN DATA SILOS: THE POWER OF COLLABORATION

The symposium strongly advocated for enhanced data sharing among stakeholders as a cornerstone of effective mitigation efforts. The experts highlight that data sharing is essential for:

- **Accelerating Scientific Research:** Sharing data on emissions, atmospheric conditions, and contrail properties enables researchers to develop more accurate models, test hypotheses more rigorously, and arrive at a shared understanding of non-CO2 impacts more rapidly.
- **Fostering Innovation:** Access to comprehensive data sets empowers technology developers and industry stakeholders to design, optimize, and validate new technologies and operational procedures aimed at minimizing non-CO2 emissions.
- **Informing Policy Decisions:** Transparent data sharing enables policymakers and regulators to base their decisions on the best available scientific evidence, promoting informed regulations and effective international cooperation.

### 10.1.2. EXAMPLES OF DATA SHARING INITIATIVES

The symposium showcased several promising data-sharing initiatives, including:

- **ICAO's Data Bank:** ICAO is developing a data bank to centralize information on non-CO2 emissions, aiming to facilitate data accessibility and promote global collaboration.
- **ContrailNet:** Eurocontrol's ContrailNet initiative promotes data sharing on contrail observations from satellites and ground-based systems, enabling researchers to validate models and improve understanding of contrail formation.
- **IAGOS Open Data Policy:** The European research infrastructure IAGOS follows an open data policy, making its vast dataset on atmospheric composition freely available to scientists worldwide.
- **Industry-Academia Collaborations:** Several speakers highlighted ongoing collaborations where airlines and manufacturers share operational data with research institutions to improve modeling and advance the development of mitigation technologies.

### 10.1.3. OVERCOMING BARRIERS TO DATA SHARING

While the benefits of data sharing are widely acknowledged, the sources also recognize the challenges in achieving seamless collaboration. Key obstacles include:

- **Commercial Sensitivities:** Airlines and manufacturers may be hesitant to share commercially sensitive operational data, such as detailed flight trajectories or fuel consumption figures.

- **Data Ownership and Intellectual Property Rights:** Clear agreements on data ownership, access rights, and intellectual property are needed to foster trust and encourage data sharing among stakeholders.

- **Data Standardization and Interoperability:** Differences in data formats, collection methods, and quality control procedures can hinder the effective integration and analysis of data from multiple sources.

### 10.1.4. CHARTING A COURSE FOR ENHANCED DATA SHARING

The symposium proposed several key steps to overcome these barriers and promote a more data-driven approach to mitigating non-CO2 emissions:

- **Developing Standardized Data Collection and Sharing Protocols:** Establishing common data formats and quality control standards can facilitate data interoperability and maximize its utility for research and policymaking.

- **Establishing Clear Data Governance Frameworks:** Transparent agreements on data ownership, access rights, and intellectual property protections are essential for building trust and encouraging data sharing among stakeholders.

- **Incentivizing Data Sharing:** Exploring incentives for data sharing, such as recognizing data contributions in regulatory frameworks or establishing data-sharing platforms that benefit all participants, could encourage wider participation.

- **Building Capacity for Data Management and Analysis:** Investing in data management infrastructure and providing training on data analysis techniques can empower stakeholders to effectively utilize shared data.

## 10.2. PARTNERSHIPS

The symposium emphasized the critical role of partnerships and collaboration in addressing the complex challenge of reducing non-CO2 emissions from aviation.

**Role of Partnerships in Advancing Solutions**

Effectively tackling non-CO2 emissions requires a multifaceted approach, encompassing research, technological innovation, policy development, and industry-wide adoption of sustainable practices. Partnerships are essential for driving progress across these areas by:

- **Facilitating Collaborative Research and Innovation:** Partnerships enable stakeholders to undertake joint research projects, share data, and leverage each other's expertise.

This collaborative approach is crucial for addressing knowledge gaps, validating findings, and accelerating the development of innovative solutions.

- **Aligning Goals and Strategies:** Partnerships foster dialogue and consensus-building among stakeholders, ensuring that research priorities, technological solutions, and policy initiatives are aligned with shared objectives. This coordinated approach is essential for maximizing the effectiveness of efforts to reduce non-CO2 emissions.
- **Overcoming Resource Constraints:** Partnerships allow stakeholders to pool financial resources, research infrastructure, and personnel, enabling more ambitious and impactful research projects. This collaborative approach is particularly crucial given the significant investment required to develop and deploy new technologies and operational practices.

**International Cooperation for Standardization and Harmonization**

Given the global nature of aviation, international cooperation is paramount for establishing consistent standards, sharing data, and coordinating policy responses to non-CO2 emissions. The experts highlighted the critical role of ICAO in this regard. ICAO provides a platform for:

- **Standardizing Data Collection and Modeling:** International agreement on data collection methodologies and modelling frameworks is essential for ensuring data comparability, validating research findings, and informing policy decisions. ICAO plays a key role in facilitating this harmonization process.
- **Developing Globally Harmonized Regulations:** ICAO is crucial in developing aviation environmental protection standards. This includes working towards globally consistent regulations for managing and mitigating non-CO2 emissions, ensuring a level playing field for the industry while effectively addressing the global climate impact.
- **Facilitating Global Partnerships:** ICAO's convening power and global reach are instrumental in bringing together stakeholders from around the world. Symposiums, workshops, and technical working groups facilitated by ICAO foster dialogue, knowledge sharing, and the formation of partnerships that drive progress on non-CO2 emission reduction.

**Public-Private Partnerships (PPPs) for Technology Development and Deployment**

Public-private partnerships (PPPs) play a crucial role in driving the development and scaling of technologies aimed at mitigating aviation's environmental impact. These partnerships leverage the strengths of both sectors:

- **Governments:** Provide funding, policy support, and regulatory frameworks to incentivize innovation and create market demand for sustainable aviation technologies.
- **Private Sector:** Brings industry expertise, technological innovation, and the capacity for large-scale production and deployment of new technologies.

Examples of successful PPPs in the context of non-CO2 emission reduction:

- **Sustainable Aviation Fuels (SAFs):** PPPs are instrumental in accelerating SAF production and uptake. Government incentives, such as tax credits and blending mandates, encourage investment in SAF production facilities. Concurrently, partnerships between airlines, fuel producers, and technology developers drive research and development of new SAF production pathways and ensure the compatibility of SAF with existing and future aircraft.

- **Engine Innovations:** PPPs support the development of next-generation aircraft engines with lower emissions. Government agencies, such as NASA and the European Commission, provide funding and collaborate with engine manufacturers to advance technologies that reduce NOx, soot, and other non-CO2 emissions.

### Cross-Sector Collaboration for Holistic Solutions

The experts emphasize that addressing non-CO2 emissions requires collaboration beyond traditional aviation stakeholders. Cross-sector partnerships involving environmental NGOs, academic institutions, and other relevant actors are crucial for:

- **Ensuring Environmental Integrity:** Environmental NGOs bring valuable expertise in climate science, ecological impacts, and sustainability assessment. Their involvement helps ensure that mitigation strategies effectively address environmental concerns and contribute to broader climate goals.

- **Integrating Scientific Knowledge:** Academic institutions play a key role in conducting fundamental research, developing modeling tools, and providing independent analysis. Partnerships with universities and research centers ensure that mitigation strategies are grounded in robust science.

- **Balancing Environmental Impact with Operational Viability:** Collaboration with airlines is crucial for ensuring that mitigation measures can be implemented effectively within existing operational constraints. Airlines provide real-world data, operational expertise, and feedback on the feasibility and practicality of proposed solutions.

### Examples of Networks and Partnerships

Here is a list of several existing networks and partnerships mentioned during the symposium:

- **Single European Sky ATM Research (SESAR):** This European initiative focuses on modernising air traffic management. The experts highlighted SESAR's role in funding and coordinating research projects, such as those aimed at mitigating the climate impact of aviation. They emphasize SESAR's commitment to sharing research results and collaborating with stakeholders.

- **Aviation Climate Change Experts Network (ANCEN):** Established by the European Commission and EASA, ANCEN aims to provide technical advice on non-CO2 emissions from aviation. This network fosters collaboration among policymakers, researchers, industry representatives, and civil society to achieve a common understanding of the issue and develop solutions.

- **ASCENT (Center of Excellence for Alternative Jet Fuels and the Environment):** ASCENT brings together researchers, manufacturers, operators, and the US FAA to research and advance sustainable aviation solutions. This collaborative approach ensures that research considers diverse perspectives and addresses real-world challenges faced by various stakeholders.

- **Reviate:** Driven by Breakthrough Energy, this community brings together stakeholders to develop common models, enhance understanding of uncertainties related to contrails, and build practical solutions.
- **European Aviation Stakeholder Fuel Network:** This forum, coordinated by EASA, focuses on aviation fuels. It brings together stakeholders from refineries, fuel suppliers, research institutions, and OEMs to address challenges related to SAF production, availability, and potential benefits.
- **International Forum for Aviation Research (IFAR):** This forum comprises 27 research organizations from different countries, aiming to scale up research capabilities and address global emission issues. IFAR highlights the importance of international collaboration, data sharing, and achieving consensus on research priorities.

## 10.3. UNCERTAINTY VS ACTION

The symposium mostly agreed on the balance between scientific uncertainty and the need for urgent action on aviation non-CO2 emissions. Experts, while aware of uncertainties, largely support a proactive approach. They say that uncertainty should not halt progress. It should instead drive focused research and strategic efforts to reduce risks.

**Key Positions and Arguments:**

- **Uncertainty is inherent but should not impede progress:** Many experts acknowledge the significant uncertainties surrounding non-CO2 emissions, particularly regarding their magnitude, atmospheric interactions, and long-term climate impacts. However, they argue that these uncertainties should not be a barrier to taking action. Uncertainty should be a catalyst to action on the research side rather than a blocker.
- **Focus on what is known, act where possible:** Experts suggest concentrating on areas where scientific understanding is more robust. For instance, there is a strong consensus that contrails, on balance, contribute to warming, even though the precise quantification of their impact remains uncertain. This knowledge supports the pursuit of contrail mitigation strategies, even as research continues to refine understanding.
- **Prioritize no-regret solutions and adaptive policies:** The experts advocate for implementing measures that deliver clear benefits even amidst uncertainty. SAFs, for example, offer a win-win scenario by reducing both CO2 and soot emissions, thus potentially mitigating both types of climate forcing. Additionally, experts highlight the need for flexible policies that can evolve alongside scientific understanding, avoiding premature lock-in to potentially ineffective or counterproductive measures.
- **Targeted research is crucial to reduce uncertainty:** Experts stress the vital role of continued research in refining understanding and reducing uncertainties surrounding non-CO2 emissions. This includes improving atmospheric models, developing more accurate measurement techniques, conducting large-scale trials of mitigation strategies, and fostering collaboration between scientists, industry stakeholders, and policymakers.

**Balancing Act: Research, Action, and Adaptive Governance**

The overarching message is that addressing aviation non-CO2 emissions necessitates a dynamic balance between research, action, and adaptive governance.

- **Research should guide and refine action:** Continuous investment in research is essential to reduce uncertainty and provide a robust scientific basis for decision-making.
- **Action should be taken where knowledge permits:** No-regret solutions like SAF and operational measures informed by current understanding can be implemented without waiting for absolute certainty.
- **Governance frameworks should be flexible and adaptive:** Policies and regulations must accommodate evolving scientific understanding, allowing for adjustments and refinements as new knowledge emerges.

## 11.CONCLUSIONS

Despite efforts to reduce aviation's climate impact, uncertainties remain. This is especially true in quantifying the effects of non-CO2 emissions. These uncertainties, stemming from limitations in atmospheric modeling, emission measurement techniques, and a lack of standardized reporting methods, pose challenges for accurately assessing the effectiveness of various mitigation strategies. Continuous research and development is critical, particularly in areas such as contrail formation, SAF impacts on non-CO2 emissions, and the development of robust economic models to evaluate mitigation costs and benefits. A balanced, multifaceted approach is vital for the aviation industry's sustainable future. It must align ambitious climate goals with economic competitiveness. International collaboration and strong policies are key to this.

# PART 2 – DETAILED SESSION SUMMARIES

## 12.DAY 1

### 12.1. SESSION 1: SCIENTIFIC KNOWLEDGE – HISTORICAL OVERVIEW & STATE OF THE ART

**Overview:**
This session, moderated by Neil Dickson (ICAO), reviewed the current scientific understanding of non-CO2 aviation emissions and their climate impacts. Speakers discussed research in the field, highlighting progress in understanding aviation's climate impacts and the remaining uncertainties.

**David Lee (Manchester Metropolitan University):** Non-CO2 aviation emissions have been studied for decades, but uncertainties persist, and new ones have emerged as scientific knowledge has grown.

- Non-CO2 emissions, including NOx, water vapor, sulfur oxides, hydrocarbons, and soot, have a complex impact on the climate.
- There is uncertainty in quantifying the effects of short-lived non-CO2 emissions relative to long-lived CO2 emissions.
- CO2 equivalence metrics can be helpful but require careful application due to inherent uncertainties and sensitivity to the choice of metric and time horizon.
- The net effect of soot on climate is a significant unknown, considering its complex interactions with contrails, cirrus clouds, and radiation.

**Christiane Voigt (German Aerospace Center - DLR):** Despite uncertainties, efforts to reduce non-CO2 emissions are crucial for achieving climate goals.

- Contrail cirrus, formed from persistent contrails, is a significant source of radiative forcing.
- Sustainable aviation fuels (SAFs) can contribute to reducing aviation's climate impact by lowering both CO2 and non-CO2 emissions.
- Targeted contrail avoidance strategies, such as flight rerouting, show potential for mitigating climate impact.
- Research into modern engine technologies, especially their impact on particle emissions, is essential for understanding future mitigation options.
- A 100-flight trial project promoted by the German government is set to demonstrate the feasibility of contrail avoidance.

**Nicolás Rivaben (World Meteorological Organization - WMO):** Comprehensive and accurate atmospheric measurements are crucial for advancing the understanding and prediction of non-CO2 emissions and their impacts.

- WMO has been measuring greenhouse gases and other atmospheric components through the Global Atmospheric Watch network of ground stations since 1989.
- Improved global water vapor measurements, particularly at cruise altitudes, are critical for refining contrail avoidance strategies.

- International collaboration, data sharing, and updated regulations are needed to support scientific research and effective policymaking in aviation climate science.
- The LuFo MEFKON project in Germany is an example of operational measurements for contrail avoidance.

**Alex Rap (University of Leeds):** Understanding aerosol-cloud interactions, particularly those involving soot and ice clouds, is crucial for improving the accuracy of climate models and predictions.

- Aerosols, small exhaust particles, impact the climate through aerosol radiation interactions (direct effect), aerosol-cloud interactions (indirect effect), and changes to contrail properties.
- Alternative fuels, while promising, require further research to assess their overall climate impact, considering potential trade-offs such as increased contrail cover with hydrogen propulsion.
- The uncertainties surrounding aerosol-cloud interactions are significant and require more research to quantify their impact accurately.

**Don Wuebbles (University of Illinois):** Major uncertainties remain in understanding the role of contrail cirrus, the impact of particles, and the overall effects of aviation on climate.

- While the radiative forcing from NOx is small due to counteracting effects, the effects from contrail cirrus dominate.
- Careful consideration of trade-offs associated with mitigation strategies is necessary, looking beyond simple global warming potential metrics to assess long-term climate impacts.
- More research is needed to understand the relationship between naturally forming cirrus clouds and contrail cirrus, which could lead to more accurate estimates of aviation's climate impact.
- Collaboration between scientists, industry stakeholders, and policymakers is crucial to translate scientific findings into effective policy and operational changes.

## 12.2. SESSION 2: ENHANCING SCIENTIFIC KNOWLEDGE - PART I: NOX AND PARTICULATE MATTER

**Overview:**
This session, moderated by Ray Speth (MIT), focused on enhancing scientific knowledge surrounding NOx and particulate matter emissions. Speakers presented their findings on the impact of these emissions on the climate, emphasizing the significant uncertainties associated with their study and the need for multiple research approaches. The session explored the complexities of NOx chemistry, the interaction of particulate matter with clouds, and the formation of contrails, highlighting the challenges in modeling and validating these phenomena. The speakers also discussed the importance of volatile particulate matter, a less-studied area, and its implications for contrail formation, particularly in the context of new engine technologies and sustainable aviation fuels.

**Philippe Novelli (ONERA - The French Aerospace Lab):** Reducing uncertainties associated with non-CO2 emissions is crucial, as these uncertainties pose a challenge to developing effective mitigation strategies and policy measures.

- Non-CO2 effects, particularly contrails, NOx, and particle-cloud interactions, could dominate the radiative impact of aviation, but there are significant uncertainties in their understanding.
- Studying non-CO2 effects heavily relies on modeling and simulation due to the difficulty of conducting controlled experiments.
- The Climaviation project in France aims to address these uncertainties by focusing on reducing uncertainties in non-CO2 effects, assessing the current climate impact of aviation, exploring future scenarios, and evaluating mitigation strategies.
- Discrepancies between different models used to study NOx effects highlight the complexity and uncertainty surrounding its impact, with a factor of three difference observed in the total impact estimated by five models.
- The interaction of particulate matter with clouds is particularly uncertain and challenging to model, with questions remaining about the concentration, size, nucleating properties, transport, and overall impact of particles on clouds.
- The emergence of lean-burn combustors, SAFs, and hydrogen propulsion raises questions about the role of secondary emissions and volatile particulate matter in contrail formation, particularly in scenarios with reduced soot production.

**Rick Miake-Lye (Aerodyne Research):** Volatile particulate matter (vPM), while often overlooked, requires more attention due to its potential impact on contrails, especially as aviation moves towards cleaner-burning engines.

- Volatile particulate matter, a less-discussed aspect of aviation emissions, plays a significant role in contrail formation and has implications for local air quality.
- Unlike non-volatile particulate matter, which is regulated with existing standards, volatile particulate matter is not currently part of emission regulations.
- The composition of volatile particulate matter is complex and influenced by factors like the combustion process, fuel composition, vented oil, and time after emission.
- Species contributing to volatile particulate matter include gaseous products of incomplete combustion, sulfuric acid formed from fuel sulfur, and engine oil.
- The presence of sulfuric acid, a strong nucleating agent, significantly influences the formation of volatile particulate matter and its interaction with other organic species.
- Airport studies measuring particle composition downwind often reveal a dominance of volatile species, including lubrication oil, highlighting their impact on local air quality.
- As engine technologies evolve towards cleaner burning with lower non-volatile particulate matter emissions, the role of volatile particulate matter in contrail formation becomes increasingly important, particularly in understanding the effects of sulfur and fuel composition.

**Marc Stettler (Imperial College London):** Understanding the impact of particle emissions on contrail formation is crucial, and while sustainable aviation fuels can contribute to emission reduction, they will not eliminate contrails.

- Not all contrails are created equal, as particle emissions, aircraft operations, and atmospheric conditions all influence the properties and lifetimes of contrails.
- While sustainable aviation fuels offer a potential solution for reducing aviation's climate impact, it's crucial to acknowledge that they will not eliminate contrails.
- As aviation technology progresses and non-volatile particulate matter emissions decrease, minimizing volatile particulate matter emissions becomes increasingly important, requiring further research and regulation.
- The impact of sulfur content in fuel on contrail formation is evident from studies showing visible differences in contrails formed from fuels with varying sulfur content, highlighting the role of sulfur in forming new particles and enhancing the water uptake of soot particles.
- Engine technology plays a significant role in determining particle emissions, with lean-burn combustors demonstrating a two-order-of-magnitude reduction in non-volatile particulate matter emissions compared to conventional combustors.
- While sustainable aviation fuels can contribute to reducing non-volatile particulate matter emissions, their impact is less significant than engine technology advancements, and research on their effects on contrails, especially with high SAF blends, is crucial.
- Observations of contrails from various aircraft types reveal that contrail lifetime decreases with lower non-volatile particulate matter emissions, highlighting the potential for reducing contrail impact by focusing on engine technology.

## 12.3. SESSION 2: ENHANCING SCIENTIFIC KNOWLEDGE - PART II: CONTRAILS

**Overview:**
This session, moderated by Steve Barrett (University of Cambridge), explored the crucial topic of contrails and their impact on climate. The session covered the science of contrail formation and persistence, discussed regional and global modeling efforts, examined uncertainties in current understanding, and explored potential mitigation strategies. The speakers emphasized the significance of contrail warming as a major contributor to aviation's climate impact, highlighting the need for continued research, technological advancements, and collaborative efforts to address this challenge effectively.

**Rich Moore (NASA Langley Research Center):** Understanding the basic science of contrail formation and persistence is crucial for developing effective mitigation strategies.

- Contrails form when hot, humid exhaust from aircraft engines mixes with cold, humid air at high altitudes, causing water vapor to condense and freeze into ice crystals.
- Contrail formation depends on atmospheric conditions (temperature, pressure, humidity), fuel composition (hydrogen content), and engine properties (propulsion efficiency).

- Contrail persistence, a key factor in their climate impact, is determined by the availability of water vapor in the surrounding atmosphere to sustain and grow ice crystals.
- Particle emissions, particularly soot, play a crucial role in providing nucleation sites for ice crystal formation, influencing the microphysical properties of contrails.
- Reducing soot emissions through cleaner-burning engines and sustainable aviation fuels is essential, but addressing second-order effects, like volatile aerosols and background aerosols, is crucial for further reducing contrail formation.
- Moore emphasized the need for more cruise data, particularly as new engine technologies and fuels are developed, to accurately assess their impact on contrail formation at relevant atmospheric conditions.
- The presentation included results from a recent flight experiment where NASA's DC-8 flying laboratory chased a new Boeing 737-10 burning 100% sustainable aviation fuel to study contrail formation and properties.

**Nicolas Bonne (ONERA - French Aerospace Lab):** Accurately modeling the initial conditions of contrails, including the complex fluid dynamics and aircraft-induced turbulence, is crucial for improving larger-scale climate models.

- Bonne's research focuses on simulating the first few seconds of contrail formation, a crucial phase that significantly influences the contrail's evolution and radiative properties.
- Analytical assumptions made in traditional contrail simulations, such as simplified jet dilution models and neglecting aircraft-induced turbulence, can lead to inaccuracies in predicting contrail properties and radiative forcing.
- Detailed simulations demonstrate that factors like aircraft geometry and the interaction of engine exhaust with the aircraft's wake vortices can significantly alter the shape, size, ice crystal concentration, and radiative properties of contrails.
- Improving the accuracy of contrail simulations by incorporating detailed aircraft geometry and fluid dynamic effects is crucial for providing better initial conditions for regional and global climate models.
- Research on optimizing aircraft design and engine placement to minimize the radiative impact of contrails by influencing their initial formation and evolution is an area of future exploration.

**Zane Dedekind (Environment and Climate Change Canada):** Regional-scale modeling of contrails, incorporating detailed microphysics and wake vortex dynamics, is essential for understanding their persistence and potential mitigation strategies.

- Dedekind's work focuses on developing a contrail avoidance tool using regional-scale models that incorporate both the Schmidt-Appleman criterion (predicting contrail formation conditions) and a wake vortex model.
- The Schmidt-Appleman criterion, based on atmospheric temperature, pressure, and humidity, helps determine the regions in the atmosphere where persistent contrails are likely to form.
- Incorporating wake vortex dynamics into regional models is crucial for understanding how the initial spread and evolution of contrails are influenced by aircraft-induced turbulence.

- By coupling the Schmidt-Appleman criterion with wake vortex modeling, Dedekind's research aims to predict contrail formation and persistence more accurately, allowing for the development of effective mitigation strategies like flight rerouting.

**Andrew Gettelman (Pacific Northwest National Laboratory):** Global climate models, incorporating contrail formation and persistence, are crucial for assessing the overall climate impact of aviation, despite existing uncertainties.

- Gettelman emphasized that while uncertainties exist in quantifying the climate impact of contrails, their overall warming effect is well-established, and these uncertainties should not hinder policy decisions aimed at mitigation.
- Global climate models, incorporating data from observations, flight inventories, and contrail microphysics, provide valuable insights into the large-scale impact of contrails on the climate system.
- Despite their coarse resolution, global climate models can be used to assess the radiative forcing of contrails, their interaction with atmospheric radiation, and their influence on regional and global temperature patterns.
- Research efforts are focused on improving the representation of contrails in global models by incorporating more detailed information on ice crystal properties, aerosol effects, and the impact of different engine technologies and fuels.
- Gettelman highlighted the importance of considering the full life cycle of aviation emissions, including the formation, persistence, and eventual fate of contrail ice crystals and aerosol particles, in climate models.

**Florian Allrogen (Laboratory for Aviation and the Environment, MIT):** Assessing the economic impacts and developing robust policy decisions require a nuanced understanding of the uncertainties surrounding contrail science and consideration of societal values.

- Allrogen explored the use of monetary metrics, alongside traditional metrics like radiative forcing, to assess the climate impact of contrails and inform policy decisions related to mitigation.
- The economic impact of contrails, expressed in monetary terms, can be estimated by modeling the chain from emissions to atmospheric impacts, temperature changes, and, finally, to socioeconomic consequences.
- Considering the short lifespan of contrails compared to long-lived CO2 emissions introduces complexities in evaluating their relative importance, further complicated by the choice of discount rates, which reflect societal preferences for valuing present versus future impacts.
- Allrogen argued that despite uncertainties in contrail science and variability in economic valuations, robust policy decisions can still be made, focusing on strategies that yield significant benefits even with a wide range of uncertainty.
- Flight path deviations, aimed at avoiding ice-supersaturated regions in the atmosphere, present a promising mitigation strategy with the potential to significantly reduce contrail formation at a relatively low cost.

## 12.4. HIGH-LEVEL PANEL: WHEN POLICY DEVELOPMENT MEETS SCIENCE

This discussion centred around three crucial areas:

- **Urgency of the Climate Crisis and the Need for Immediate Action**: Panellists emphasize the urgent need to address non-CO2 emissions alongside CO2 reduction efforts due to the climate emergency. They highlighted the limited carbon budget and the potential for non-CO2 emissions to outweigh CO2's impact. The call to action is to accelerate research and development of mitigation strategies, particularly focusing on solutions that can be implemented in the short term.
- **Balancing Non-CO2 Mitigation with Existing Decarbonization Efforts**: While acknowledging the significance of non-CO2 emissions, speakers caution against undermining ongoing CO2 reduction initiatives, particularly the scaling up of Sustainable Aviation Fuel production. They stressed the importance of an integrated approach, considering both CO2 and non-CO2 impacts when developing policies and technologies. A key message is the need to evaluate the non-CO2 effects of SAF and the potential economic benefits of monetizing non-CO2 reductions to bridge the cost gap with conventional fuels.
- **The Importance of Collaboration and a Global Approach**: The panel emphasizes the need for international cooperation and collaboration between policymakers, industry stakeholders, researchers, and scientists. They highlight the global nature of aviation and non-CO2 emissions, stressing the need for globally agreed-upon standards, measurement frameworks, and policy initiatives. Speakers pointed to the success of the Montreal Protocol in addressing the ozone layer as a potential model for international cooperation on non-CO2 emissions.

### 12.4.1. KEY MESSAGES FROM THE MODERATOR AND EACH SPEAKER

**Moderator Michel Arslanian (Permanent Representative of Brazil to ICAO Council)**

- When addressing non-CO2 emissions, it's crucial to avoid negatively impacting existing efforts to reduce CO2 emissions.
- Aviation faces a significant challenge in scaling up SAF production, which is considered the most promising short- and medium-term decarbonization solution.
- A truly global effort involving current and new players from around the world is necessary to meet the SAF challenge.
- While economic competition can influence priorities and create trade-offs, it's vital to think broadly and prevent narrow perspectives from hindering collective efforts to address the climate emergency.
- A nuanced view that incorporates urgency, the need to act correctly, and effective communication is crucial in developing science-based policies for non-CO2 emissions.

**Matteo Mirolo (Breakthrough Energy)**

- Non-CO2 effects, specifically contrails, should be treated as a separate policy and industry priority, similar to SAF.
- Successfully addressing non-CO2 emissions presents an opportunity to enhance the aviation industry's image and position it as a leader in climate action.
- Large-scale trials are crucial for understanding the complexities of contrail mitigation and require significant financial investment, making de-risking these trials through policy support essential.
- Policymakers play a vital role in fostering cooperation between different stakeholders involved in non-CO2 research and mitigation efforts.

**Valérie Guénon (Safran Aircraft Engines)**

- The aviation industry is developing new knowledge and skills in atmospheric science to address non-CO2 effects.
- Safran has created a dedicated team and hired its first atmospheric scientist, reflecting a commitment to understanding and mitigating non-CO2 emissions.
- Engine manufacturers possess the knowledge and expertise to reduce NOx and non-volatile particulate matter emissions, but require certainty in policy expectations to make informed technological choices for future aircraft engines.

**Philippe Mattei (Airbus)**

- The aviation industry needs increased public support for research on non-CO2 emissions due to the specialized nature of the topic and the high costs associated with data collection.
- Developing humidity sensors specifically for high-altitude measurements is challenging due to limited applications and funding constraints.
- Addressing short-lived climate forcers, including non-CO2 emissions from aviation, is a global policy issue best tackled at the ICAO level.
- Blanket multipliers on top of CO2 emissions would be unfair, particularly for tropical countries, and a global set of rules with regionally specific assessments of non-CO2 effects is necessary.

**Ben Foulser (KPMG)**

- Policymakers need confidence in the problem, the magnitude of the impact, potential interventions, and the implementability of those interventions before enacting policies related to non-CO2 emissions.
- A key challenge in setting policy is establishing consistent measurement and metrics for non-CO2 emissions, including determining appropriate indicators like Radiative Forcing (RF) or Effective Radiative Forcing (ERF).
- Stakeholders across the aviation ecosystem emphasize the need for a clearly defined question, existing metrics, a defined time frame, a counterfactual, comparability between metrics, transparency in calculations, and consideration of other industry drivers when addressing non-CO2 emissions.

- Aircraft leasing and financing practices, particularly the greening of loan books by financial institutions, can play a significant role in driving the adoption of technologies and practices that reduce non-CO2 emissions.

**Adam Morton (Aerospace Technology Institute - ATI)**

- The contribution of non-CO2 emissions to climate change may be as significant as, or even greater than, that of CO2.
- The level of uncertainty regarding non-CO2 emissions is high, particularly concerning specific emission sources and the impact of transitioning to new fuels and technologies.
- Waiting for a complete understanding of the fundamental science before developing mitigation technologies could result in delays, highlighting the need for parallel efforts in both areas.
- Effectively communicating the complexities of non-CO2 emissions to stakeholders without a technical background is crucial for policy development.

**Maxime Meijers (Estuaire)**

- The problem of non-CO2 emissions, particularly contrails, can be addressed more rapidly through software and operational changes compared to the longer timescales associated with developing new aircraft or SAF plants.
- Improving humidity prediction on a finer grid, enhancing engine modeling to understand emissions based on various factors, and furthering research on atmospheric and aerosol-cloud interactions are crucial areas for scientific progress.
- 92% of aviation kilometers flown occur in the northern hemisphere, with 60% of contrail impact coming from domestic North American flights, domestic European flights, or North Atlantic routes.

# 13. DAY 2

## 13.1. SETTING THE SCENE BY THE INDUSTRY

**Overview:**

The session, moderated by Capt. Claude Hurley (IBAC), explored ways to mitigate non-CO2 emissions from the aviation industry. Speakers discussed various mitigation strategies, including advances in technology, operational changes, and the use of sustainable aviation fuels. A key theme was the need for a balanced approach that considers both CO2 and non-CO2 emissions. The importance of continued research and collaboration to reduce uncertainties and develop effective mitigation measures was also emphasized.

**Moderator Claude Hurley (IBAC):** A collaborative, evidence-based approach is crucial for effectively addressing the challenge of non-CO2 emissions.

- Business aviation is committed to sustainability, with only a small portion of its flight time spent in contrail-forming regions.

- Effective mitigation requires a systemic approach, supported by comprehensive data analysis and an understanding of potential consequences.
- Currently, there are no real-time tools available to pilots for monitoring contrail formation.

**Charles Renard (ICCAIA):** Aircraft manufacturers have made significant strides in reducing non-CO2 emissions, but the complex nature of these emissions requires a holistic, life-cycle approach.

- ICAO has been setting standards for non-CO2 aircraft engine emissions since the 1970s.
- Non-CO2 emissions are difficult to model, quantify, and mitigate, requiring a comprehensive strategy that considers the entire life cycle of aircraft and engines.
- ICCAIA is actively involved in numerous research projects, including the SESAR CICONIA project, exploring areas like aircraft and engine design, sustainable aviation fuels, and the optimization of flight paths for reduced climate impact.
- The ECLIF 3 and VOLCAN flight test campaigns have demonstrated that sustainable aviation fuels can significantly reduce ice crystal formation.
- Further research is needed, especially the development of accurate emission measurement tools and a deeper understanding of ice crystal formation mechanisms, particularly in low soot emission scenarios.

**Michelle Bishop (CANSO):** Mitigating contrail formation poses practical challenges for air traffic management, demanding a system-wide approach and consideration of potential consequences.

- Most warming contrails are produced by a small but consistent percentage of flights, frequently occurring in congested airspaces.
- Addressing contrail formation effectively requires a system-wide approach to air traffic management.
- The fragmented structure of air traffic control, divided into Flight Information Regions and sectors, adds complexity to the implementation of contrail avoidance measures.
- The North Atlantic airspace, with its unique features and high contrail formation, presents distinct challenges for air traffic management.
- Continued research and testing are essential to determine the most effective operational methods for minimizing contrail formation on a system level.

**Alejandro Block (IATA):** IATA emphasizes the importance of collaborative efforts and accurate atmospheric data collection using commercial aircraft to improve prediction and mitigation strategies.

- Airlines are engaged in research projects focused on understanding and mitigating non-CO2 emissions, including those related to sustainable aviation fuels, contrail observation, and contrail avoidance trials.
- Accurate temperature and humidity data are crucial for predicting ice-supersaturated regions, but current data is insufficient for precise predictions.
- IATA advocates for the expanded use of humidity sensors on commercial aircraft and leveraging existing data collection platforms like IAGOS to gather more comprehensive atmospheric data.

**Michael Rossell (ACI World):** ACI World underscores the potential impact of contrail avoidance on airport operations, highlighting the need to maintain predictability and consider unintended consequences.

- ACI represents nearly 2,000 airports globally and anticipates significant air traffic growth, particularly in the Middle East and Far East, which could exacerbate the impact of contrails.
- Unforeseen consequences, such as ground delays and increased emissions at airports, are major concerns related to contrail avoidance measures.
- Predictability is paramount for efficient airport operations, and contrail mitigation efforts should not compromise this.
- Airport Operation Centers play a crucial role in enhancing predictability by gathering and analysing data from various sources, helping to minimize congestion and reduce emissions both in the air and on the ground.

## 13.2. SESSION 3: MITIGATING NON-CO$_2$ AVIATION EMISSIONS – WHAT IS POSSIBLE – PART I: INNOVATIVE TECHNOLOGIES

**Overview:**

This session, moderated by Bethan Owen (MMU), focused on technological innovations for mitigating non-CO2 emissions from aviation. The session highlighted the importance of collaboration between regulators, industry, and academia in addressing this complex issue. Speakers discussed the need to improve understanding of non-CO2 effects, develop new technologies and methodologies, and establish a common understanding of the trade-offs involved in reducing both CO2 and non-CO2 emissions.

**Moderator Bethan Owen (Manchester Metropolitan University):** Collaborative efforts to innovate technologies are crucial for mitigating the impacts of non-CO2 emissions from aviation, with a particular focus on reducing emissions at the engine and airplane level and improving contrail prediction and measurement.

- Non-CO2 impacts and emissions should be considered separately as there are complex pathways between the emission and the impact.
- Technological innovations aim to reduce non-CO2 emissions, which can then help reduce their impact.
- The aviation industry needs to work towards a consensus on how to address the uncertainties associated with non-CO2 emissions, particularly considering the long development time frames for new technologies and the need for more data.

**Theo Rindlisbacher (Federal Office of Civil Aviation, Switzerland):** Engine-level innovations, guided by the precautionary principle, show promise in reducing non-CO2 emissions. Applying existing technologies and focusing on continuous improvement can lead to significant reductions in NOx and nvPM emissions.

- Engine emissions can have both warming and cooling effects, making it crucial to consider uncertainties when optimizing engines to avoid unintended consequences.

- The long development timeframe of aircraft engines necessitates careful consideration of potential impacts before implementing new technologies.
- Non-CO2 emissions, aside from water vapor, are essentially pollutants with climate impacts. Reducing these emissions at the source benefits both the climate and local air quality.
- Technological advancements, such as improved fuel injectors and catalytic converters for engine oil vapors, can contribute to substantial reductions in nvPM and vPM emissions, respectively.
- Introducing new reporting points for nvPM emissions, including a midpoint measurement (57.5% static takeoff thrust) and the thrust percentage at maximum emission, will improve the accuracy of data used in climate models.
- A proposed cruise NOx metric, utilizing existing certification points, could complement the current LTO NOx regulation for better control of NOx emissions during cruise.

**David Ostdiek (GE):** Building on the success of current-generation engines like the GEnx, LEAP, and GE9X, GE Aerospace and CFM International's RISE technology program aims to further reduce both CO2 and non-CO2 emissions.

- The RISE program, focused on open fan technology, an advanced compact core, a scalable hybrid-electric system, and alternative fuels, aims for a 20% reduction in fuel burn.
- Continuous learning and data collection are crucial to address challenges like scaling down combustion technology for smaller cores and understanding volatile particulate emissions in lean-burn combustion.
- GE Aerospace actively participates in fundamental testing (e.g., NASA's particular aerosol lab), flight campaigns like VOLCAN and EcoDemonstrator, and fleet operations programs like PRE-TRAILS and EPIC-Trails to gather data and advance the science around non-CO2 emissions.

**Feijia Lin (TU Delft):** A multidisciplinary approach that integrates design, operations, and atmospheric science is crucial for developing climate-optimized aircraft. Addressing trade-offs between CO2, NOx, and local versus global impacts requires innovative solutions, including multi-fuel combustion technologies.

- Aircraft design methodologies should move beyond efficiency-driven approaches and incorporate climate impact considerations, accounting for the complexities and uncertainties associated with non-CO2 emissions.
- The long development cycles of aircraft engines, the slow uptake of new technologies, and the mix of older and newer fleets all contribute to the challenges in mitigating aviation's climate impact.
- A key focus area is decoupling CO2 and NOx emissions and balancing local and global impacts, which requires considering the altitude-dependent nature of NOx emissions and weather-sensitive regions.
- The HOPE project aims to develop multi-fuel combustion technologies that enable aircraft to utilize a mix of kerosene, SAF, and hydrogen, providing flexibility and potentially reducing reliance on a single fuel source.

**Raphael Felipe Gama Ribeiro (Embraer):** Embraer's Energia family of concept aircraft aims to achieve significant CO2 reductions through hybrid-electric, hydrogen, and fuel cell technologies, while also addressing non-CO2 emissions through innovative design and operational features.

- Embraer is committed to achieving net-zero carbon emissions by 2050, with a focus on SAF compatibility, fleet replacement, and the development of new technologies like the fully electric eVTOL EVE concept and the Energia family.
- The Energia family includes three concepts: the Energia Hybrid Electric, designed for a 25% CO2 reduction; the Energia Hydrogen or Dual Fuel Gas Turbine Engine, targeting a 100% CO2 reduction; and the Energia Fuel Cell, aiming for 100% CO2 reduction.
- Non-CO2 emission reduction strategies for the Energia concepts include electric taxi systems for improved local air quality, ultra-lean combustion for reduced NOx emissions in hydrogen-powered aircraft, and high-aspect-ratio wings for overall fuel burn and emissions reduction.

**Peter De Bock (US Department of Energy):** The US Department of Energy's ARPA-E agency launched the PRE-TRAILS program to develop predictive technologies for accurately forecasting persistent contrail formation, aiming to understand and mitigate the climate impact of aviation.

- PRE-TRAILS aims to develop a system that provides pilots with real-time information on the likelihood of their aircraft producing persistent contrails, enabling informed decisions regarding altitude and trajectory.
- The program emphasizes collaboration between different sectors, including atmospheric science, aerospace engineering, and data science, to leverage expertise and data from various sources.
- A key element of PRE-TRAILS is the development of new, highly accurate water vapor sensors for improved atmospheric modeling and contrail prediction.

## 13.3. SESSION 3: MITIGATING NON-$CO_2$ AVIATION EMISSIONS – WHAT IS POSSIBLE – PART II: INNOVATIVE OPERATIONS

**Overview:**
This session, moderated by Captain Robert Brons (IFALPA), explored the challenges and opportunities in mitigating non-CO2 aviation emissions, particularly the formation of contrails. discussed the importance of collaborative research and development, while highlighting existing and emerging technologies to enable effective contrail avoidance. A central theme was the need for balancing climate goals with operational realities, underscoring the complex trade-offs involved.

**Moderator Robert Brons (IFALPA):** Addressing non-CO2 emissions, specifically contrails, necessitates operational strategies.

- The majority of research so far has concentrated on avoiding contrails by adjusting flight trajectories.
- For research to be successfully implemented, it requires close collaboration between scientists and operational stakeholders, including airlines, software developers, and meteorological offices.
- Pilots, ultimately responsible for flight safety, possess operational expertise that is critical to developing and implementing effective mitigation strategies.

**Stella Saldana (SESAR JU):** SESAR JU coordinates a portfolio of projects, grouping related initiatives into "flagships" and facilitating the transition of concepts from research to operation through an "innovation pipeline".

- One such flagship, Green Deal, is dedicated to researching and developing solutions for mitigating non-CO2 emissions from aviation.
- The Green Deal flagship encompasses a range of projects—including AEROPLANE, E-CONTRAIL, CICONIA, ECHOES, and CONCERTO—each addressing non-CO2 emissions from different perspectives.

**Philippe Masson (Airbus):** The CICONIA project, led by Airbus, is developing a user-friendly weather forecasting service that not only predicts conditions conducive to contrail formation but also provides confidence levels for these forecasts.

- This service will leverage improved numerical weather prediction models to enhance the prediction of ice-supersaturated regions (ISSRs).
- Beyond predicting ISSRs, CICONIA also aims to provide users with climate impact models that consider aircraft emissions data and offer a comprehensive evaluation of a flight's climate impact.
- CICONIA is assessing three primary concepts of operation: pre-tactical trajectory optimization for short-haul flights, pre-tactical optimization with potential for in-flight adjustments for long-haul flights, and possible optimization by ATC during flight.

**David Antonello (Thales):** The CONCERTO project concentrates on optimizing air traffic flow to effectively reduce the overall climate impact of aviation, taking into account both CO2 and non-CO2 effects.

- CONCERTO emphasizes that achieving meaningful reductions in non-CO2 emissions hinges on successful collaboration between airlines and ANSPs.
- The project focuses on developing strategies that act locally, targeting a limited number of flights identified as having a disproportionately high climate impact, aiming to minimize disruption to air traffic flow.
- CONCERTO is developing an optimizer tool designed to pinpoint climate-sensitive areas, suggest mitigation options, and provide ANSPs with key performance indicators (KPIs) relevant to contrail formation.

**Raimund Zopp (FlightKeys):** FlightKeys has created a cost-effective system for reducing the climate impact of contrails. This system integrates contrail forecasts into its flight planning software and automates the identification and optimization of flight trajectories for contrail avoidance.

- This automated approach minimizes the workload for dispatchers, allowing for scalable implementation.
- Simulations conducted by FlightKeys using American Airlines flight data demonstrated that the system had the potential to reduce the energy forcing from contrails by 73%, with only a 0.11% increase in fuel consumption.
- The company's Loretta tool is designed for use in the cockpit, allowing pilots to visualize contrail-prone areas and make informed decisions about potential adjustments to their flight path.

**Irène Boyer-Souchet (Air France):** Airlines must take ownership of their non-CO2 emissions. This includes establishing appropriate governance structures, acknowledging the impact of their operations, and communicating transparently with stakeholders.

- Airlines need the industry to define a single, standardized metric for quantifying non-CO2 emissions to ensure consistency in measurement, reporting, and communication with customers.
- Analysis of Air France's data revealed that a small percentage of flights are responsible for a majority of the airline's non-CO2 impact. Additionally, these high-impact flights cannot always be predicted in advance.
- Live trials are essential for accurately evaluating the feasibility of proposed mitigation strategies, understanding potential collateral impacts on the broader air traffic system, and determining if the projected climate benefits are achievable in real-world operational contexts.

**Asuka Boehm (NAV Canada):** ANSPs have a crucial role in facilitating airline efforts to mitigate non-CO2 emissions by ensuring flexibility and predictability within the airspace they manage. Implementing trajectory-based operations (TBO) is essential to enabling this flexibility.

- NAV Canada is pursuing three key initiatives to modernize its airspace management and enhance flexibility: airspace modernization, digital facilities, and trajectory-based operations.
- Collaborative efforts between ANSPs and airlines, including data sharing, are crucial for comprehensively understanding and mitigating the environmental impacts of aviation.
- ANSPs are uniquely positioned to support airlines in modifying their operations to achieve climate goals, particularly by providing the necessary airspace flexibility for trajectory adjustments.

## 13.4. KEYNOTE SPEECH BY KLM

**Lisanne van Wijngaarden (KLM):** Effectively addressing non-CO2 emissions requires a collaborative approach involving all stakeholders in the aviation ecosystem.

- KLM, demonstrating its commitment to sustainability, has actively participated in research initiatives and trials to investigate the effectiveness of contrail avoidance strategies.
- The development and adoption of a single, standardized metric for measuring non-CO2 emissions is crucial for ensuring industry transparency, facilitating effective decision-making, and communicating clearly with customers.
- More accurate weather forecasting methods, coupled with a clear understanding of the inherent uncertainties in these forecasts, are necessary to give airlines the confidence to implement mitigation measures. Additionally, reliable validation methods are needed to assess the effectiveness of these measures.

## 13.5. SESSION 3: MITIGATING NON-$CO_2$ AVIATION EMISSIONS – WHAT IS POSSIBLE – PART II: SAF, LCAF AND CLEANER ENERGY

**Overview:**

This session, moderated by Ross Adams (representative of Australia to ICAO Council), focused on the potential of Sustainable Aviation Fuels (SAF), Lower Carbon Aviation Fuels (LCAF), and cleaner energy to mitigate non-CO2 emissions from aviation. Panellists discussed the importance of fuel composition, particularly the role of aromatics in soot formation and contrail generation. They highlighted ongoing research, industry initiatives, and policy considerations related to increasing the use of cleaner fuels and optimizing fuel properties for reduced climate impact.

**Moderator Ross Adams (Representative of Australia to ICAO Council):** SAF, LCAF, and cleaner energies are critical for decarbonizing aviation and mitigating non-CO2 emissions, with fuels expected to contribute to 80% of emissions reductions for the long-term aspirational goal.

- The global framework on SAF, LCAF, and cleaner energies includes an aspiration for a 5% CO2 reduction through fuel use by 2030.
- It is important to understand the impact of fuel choices on non-CO2 emissions, such as the effects of low aromatic and sulphur content in SAF on nvPM and contrail formation.

**Astrid Sonneveld (Neste):** SAF, particularly paraffinic types like Neste's HEFA-SPK, can significantly reduce both CO2 and non-CO2 emissions due to their low aromatic content.

- Extensive research, including the ECLIF campaigns, has consistently demonstrated that SAF with lower aromatic and naphthalene content leads to reduced nvPM emissions and ice crystal formation.
- A key indicator of a fuel's non-CO2 benefits is the H:C ratio, with higher ratios indicating cleaner combustion and reduced soot formation.

**Joshua Steven Heyne (Washington State University):** Not all SAF is created equal; fuel composition, particularly the presence of aromatics, significantly impacts soot formation.

- It's crucial to maintain existing safety and operability standards for aviation fuels while minimizing soot production, a balance achievable through strategic SAF composition.
- The WSU Bioproducts lab is developing drop-in SAF compositions that minimize soot and meet existing fuel standards.
- Research using the Threshold Sooting Index (TSI) has shown that significant reductions in nvPM are achievable with drop-in SAF solutions.

**Mukund Karanjikar (CleanJoule):** Cycloparaffins offer a promising avenue to create 100% SAF blends that are both drop-in compatible and address the density limitations of purely paraffinic fuels.

- Achieving IATA's goal of net-zero aviation by 2050, with a 65% contribution from SAF, necessitates moving beyond the current 50% blend wall.
- Research by DLR and NASA has shown a direct correlation between reducing aromatic content in fuel and decreasing carbon particle and contrail formation.

**Mohamed Pourkashanian (University of Sheffield):** While transitioning to SAF is crucial, decarbonizing existing fossil-based jet fuel through methods like reducing aromatic content is vital, especially considering the long-term use of jet fuel, particularly for long-haul flights.

- Simply focusing on a single fuel property, like aromatic content, can negatively impact other critical properties, potentially necessitating changes in engine design or fuel handling.
- A University of Sheffield project, funded by the UK Department for Transport, is investigating the impact of reducing aromatic content in fossil jet fuel.
- The project's findings indicate a strong correlation between reduced aromatic content in jet fuel and lower soot emissions, aligning with previous research.

**Valérie Guénon (Safran Aircraft Engines):** Reducing aromatic and sulphur content in aviation fuels offers numerous benefits, including reduced climate impact, improved local air quality, reduced engine corrosion, and potentially lower CO2 emissions.

- While the industry transitions to 100% SAF, ensuring the safety and feasibility of different fuel compositions, especially concerning their impact on existing and future aircraft and engine systems, is paramount.
- There is a need for further research to fully understand the impact of low aromatic fuels, particularly in lean-burn combustors where reduced soot may not directly translate to less contrail formation.

**Māra Dāme (EASA):** EASA is actively working on a two-year project to assess and potentially revise aviation fuel standards, aiming to reduce aromatic, naphthalene, and sulphur content while ensuring safety and global harmonization.

- The project involves evaluating the European and global landscape of fuel production and use, collaborating with stakeholders, and conducting modelling exercises with DLR to assess the feasibility and climate impact of reducing specific fuel components.
- A key aspect of the project is the creation of a European aviation stakeholder fuel network to facilitate collaboration, information exchange, and identification of future research needs.

## 13.6. HIGH-LEVEL PANEL: MITIGATING NON-CO2 AVIATION EMISSIONS – WHAT IS POSSIBLE: POLICY DEVELOPMENT

This discussion centred around three crucial areas:

- **Collaboration to Address Uncertainty in Non-CO2 Emission Mitigation:** The panel discussion emphasized the significant uncertainty surrounding non-CO2 emissions and their impact while advocating for collaborative efforts between policymakers, industry stakeholders, and researchers to address these knowledge gaps and develop effective mitigation strategies.
- **Policy and Regulation Development for Non-CO2 Emission Reduction:** Panellists discussed the importance of developing policies and regulations to drive progress in reducing non-CO2 emissions, emphasizing the need for science-based approaches to avoid unintended consequences, such as competitive imbalances or compromising aviation safety.
- **Operational and Technological Challenges in Mitigating Non-CO2 Emissions:** The discussion highlighted various operational and technological challenges associated with non-CO2 emission mitigation, including the need for accurate weather forecasting for contrail avoidance, airspace integration issues, the potential for increased fuel burn, and the training required for pilots and air traffic controllers to implement new procedures.

### 13.6.1. KEY MESSAGES FROM THE MODERATOR AND EACH SPEAKER

**Moderator: Ambassador Anita Adjei-Nmashie (Permanent Representative of Ghana on the ICAO Council)**

- ICAO prioritizes predictability and aims to avoid unintended consequences when developing policies and regulations.
- Stakeholders need to work together to establish a consolidated approach for mitigating non-CO2 emissions to ensure the aviation industry can progress safely and sustainably.
- Airspace integration presents a challenge when implementing contrail avoidance measures, as changing flight trajectories require coordination between airlines, pilots, and air traffic controllers.
- It is crucial to have confidence in the necessity of actions taken to mitigate non-CO2 emissions, especially given the uncertainties surrounding their impact.
- The symposium highlighted the various initiatives and actions underway to understand and address non-CO2 aviation emissions, demonstrating a strong momentum for action in the field.
- While taking action is crucial, implementing mitigation measures without addressing scientific uncertainties is not advisable. Policy decisions should prioritize a "no regret" approach and avoid unintended trade-offs.
- A harmonized approach to policymaking that encourages collaboration between stakeholders is vital, along with a clear scientific agenda to focus research efforts effectively.

**Jim Hileman (Boeing) - recorded message**

- Boeing is actively engaged in research and development efforts focused on non-CO2 climate effects, particularly contrails, through initiatives involving emissions testing, contrail forecasting and observation, and tool development.
- Addressing non-CO2 emissions requires a collaborative approach involving scientists, engineers, government agencies, academia, and industry partners to tackle this complex challenge effectively.
- Boeing's research on fuel composition and product design aims to mitigate the climate impact of persistent contrails and inform their strategy on using 100% SAF.
- Collaboration is needed to develop accurate weather models for contrail forecasting by combining data from aircraft-based sensors and satellites, enabling airlines to avoid contrail formation safely and effectively.
- Boeing is developing tools to support contrail avoidance, including flight brief software with contrail forming area visualization and collaboration with Breakthrough Energy to develop services for business aviation.
- A collaborative environment is essential, with positive incentives for data sharing and coordinated efforts to improve weather and contrail models, enabling effective mitigation strategies.

**Cesar Augusto Souto Pereira (Embraer)**

- While the environmental impacts of non-CO2 emissions are acknowledged, the extent of their effects and interactions requires further understanding.
- Addressing non-CO2 emissions requires careful consideration and a science-based approach to policy and regulation development to avoid unintended consequences, particularly concerning aviation safety.
- Rushing into policies and regulations with high uncertainty levels could lead to competitive imbalances, additional costs for the industry, and potentially ineffective mitigation strategies.
- Collaboration is crucial when addressing non-CO2 emissions, emphasizing the need for data sharing, joint research efforts, and a united approach to understanding and mitigating these emissions.
- Premature implementation of policies or regulations based on incomplete data and uncertain metrics could negatively impact specific airlines or aircraft types, leading to unfair disadvantages and market distortions.

**Brandon Graver (American Airlines)**

- Airlines recognize their responsibility in addressing the environmental impact of aviation, including non-CO2 emissions, and are actively involved in research, trials, and partnerships to mitigate these effects.
- Data and scientific evidence should drive decision-making processes regarding non-CO2 emission reduction to ensure effective and well-informed actions are taken.
- One of the most significant concerns for airlines is the potential trade-off between CO2 and non-CO2 emissions, particularly regarding fuel burn increases associated with contrail avoidance.

- Improved weather models are crucial for accurate contrail forecasting and avoidance, requiring significant investment in research and development.
- Implementing contrail avoidance strategies will necessitate educating and training a large workforce, including pilots, dispatchers, and meteorologists, demanding substantial resources and commitment from airlines.

**Denis Bonnet (Thales)**

- Tackling contrail formation presents a significant opportunity to reduce the aviation industry's environmental footprint, potentially mitigating up to 0.5% of global warming in the coming decade.
- Contrail avoidance, while challenging, is achievable, primarily involving managing aircraft trajectories to avoid ISSRs in the airspace.
- While airline-initiated contrail avoidance schemes are beneficial, they may face challenges in achieving widespread adoption and effectively integrating with existing air traffic management systems.
- ANSP-initiated contrail avoidance could be more efficient due to their familiarity with airspace management, ability to coordinate traffic flow, and understanding of the broader airspace context.
- Successfully addressing non-CO2 emissions, particularly contrail formation, requires collaboration and a willingness to embrace technological and operational transformations within the aviation industry.
- Focusing on additional benefits of contrail avoidance technologies, such as improved flight efficiency, access to favourable winds, or turbulence avoidance, could incentivize their adoption and offset potential costs.

**Michelle Bishop (CANSO)**

- The aviation industry's commitment to addressing climate change extends beyond CO2 emissions to include non-CO2 effects like contrails, acknowledging the need to plan for their mitigation.
- While uncertainty regarding non-CO2 effects remains, efforts should focus on narrowing it down to guide effective decision-making and prevent unintended consequences.
- Accurate weather forecasting is crucial for successful contrail mitigation, as uncertainties in weather prediction could impact the effectiveness of avoidance manoeuvres and lead to unnecessary fuel burn.
- CANSO recognizes that mitigating non-CO2 emissions, particularly through contrail avoidance, may require significant changes to airspace management and flight procedures, potentially surpassing the impact of CO2 reduction efforts.
- The aviation industry has a history of collaborating to manage airspace safely and efficiently, and these existing collaborative mechanisms can be leveraged to address the challenges of contrail avoidance.

**Andrei Mungiu (European Commission)**

- The aviation industry has a proven track record of successfully addressing complex challenges, and this problem-solving capability should be applied to understanding and mitigating non-CO2 emissions.

- Solving the challenges posed by non-CO2 emissions requires a collaborative, cross-disciplinary approach, involving experts from various fields, including aviation, energy, and environmental science.
- Policymakers' focus on non-CO2 emissions reflects their commitment to science-based policymaking, using scientific understanding to guide effective policy decisions and regulations.
- Discussions and initiatives related to non-CO2 emissions are crucial for setting a course of action with potentially generational impacts on the sustainability of the aviation industry.
- Addressing non-CO2 emissions should be viewed as an extension of existing efforts to reduce pollutants like NOx and nvPM, recognizing that actions taken to mitigate these emissions often have co-benefits for the environment.

**Lukas Söffing (NLR)**

- Addressing non-CO2 emissions requires a proactive approach, with research and development of mitigation measures running parallel to efforts to improve scientific understanding.
- Efforts should focus on developing solutions across multiple areas, including technology, operations, and fuels, as a multi-faceted approach is necessary to effectively mitigate non-CO2 emissions.
- While contrail avoidance is a significant area of focus, it is crucial to consider all non-CO2 effects to comprehensively assess and mitigate the industry's climate impact.
- Short-term solutions, such as deploying SAF and implementing operational improvements like free route airspace, can contribute to reducing both CO2 and non-CO2 emissions.
- Targeted mitigation strategies, such as night contrail avoidance and prioritizing contrail avoidance during winter months when the climate impact is higher, can optimize mitigation efforts.
- While global efforts through ICAO are crucial, regional and national initiatives, such as the non-CO2 MRV in Europe and the policy approach on non-CO2 adopted by the Netherlands, demonstrate proactive steps towards addressing non-CO2 emissions.
- International collaboration is essential for addressing non-CO2 emissions from long-haul flights, as these flights often contribute significantly to non-CO2 effects due to their high altitudes and extended flight durations.

**Jane Hupe (ICAO)**

- Data collection for assessing and mitigating non-CO2 emissions should be comprehensive and consider potential biases, ensuring that data represents various regions, aircraft types, and operational contexts.
- The focus on "nowcasting" contrail formation using real-time data and AI-powered models will be crucial for enabling pilots to make informed decisions to avoid contrail formation during flight.
- Developing effective nowcasting capabilities for contrail avoidance requires significant investment in research and development to improve atmospheric models, data collection, and AI algorithms.

- Addressing non-CO2 emissions requires a balance between acknowledging uncertainty and taking action, fostering a culture of collaboration and adaptability within the aviation industry.

## 14.DAY 3

### 14.1. SESSION 4: PARTNERSHIPS TO ACT ON – PART I: RESEARCH AND MONITORING

**Overview:**
This session, moderated by Urs Ziegler (FOCA), explored the importance of partnerships in advancing research and monitoring efforts to understand and mitigate the climate impacts of non-CO2 aviation emissions. Speakers discussed various research initiatives underway, including the development of technologies for monitoring and modelling these emissions. The need for collaborative data sharing platforms to enhance global cooperation was a central theme. The session acknowledged the challenges posed by uncertainties in existing models and highlighted the importance of ongoing research to improve accuracy and develop effective mitigation strategies for a more sustainable aviation industry.

**Moderator Urs Ziegler (FOCA Switzerland):** There is a need for urgent action to address the impact of non-CO2 aviation emissions, but more research and a better understanding of these impacts is needed before effective regulatory action can be taken.

- There is a lack of knowledge on the magnitude of the climate impacts from non-CO2 emissions, how to predict these impacts, and the appropriate metrics to use to quantify them.
- The aviation industry's current understanding of the non-CO2 impacts of aviation is similar to where understanding of CO2 emissions was 20 years ago.
- The session will examine multiple initiatives that aim to increase research and monitoring efforts to better understand non-CO2 aviation emissions.

**Nicole Didik Wells (FAA):** Collaboration between stakeholders, including government agencies, research institutions, and industry, is crucial to improve understanding of and develop solutions to mitigate the non-CO2 impacts of aviation.

- The FAA is supporting a range of research on non-CO2 impacts, including research on new engine and airframe technologies, the use of sustainable aviation fuels, and potential changes to aircraft operations.
- Sharing research findings through publications, conferences and meetings with policymakers is crucial to ensuring that research findings translate into policy action.
- Data from emission measurement campaigns can be used to improve the accuracy of models for predicting non-CO2 impacts.

**Pervez Canteennwalla (NRC Canada):** Long-term partnerships are vital for improving understanding of the non-CO2 impacts of aviation, translating scientific knowledge into practical solutions, and developing policy interventions to reduce emissions.

- NRC Canada has participated in several collaborative research campaigns over the past decade, focusing on the measurement of emissions from aircraft using sustainable aviation fuels (SAF).
- The NRC is developing and renewing several research capabilities, including a chase aircraft to measure emissions and contrails, novel sensors for measuring volatile emissions, and ground-based facilities for simulating contrail formation.
- International coordination is needed to avoid duplication of research efforts, share data, and ensure that resources for non-CO2 research are used effectively.

**Dr. Jayant Mukhopadhaya (ICCT):** Policy interventions to address the non-CO2 impacts of aviation need to be flexible, informed by scientific evidence, and carefully designed to avoid unintended consequences.

- Regulations should incorporate periodic reassessments to account for the rapid pace of progress in understanding and monitoring non-CO2 impacts, emissions estimations, and impact estimations.
- The focus on increasing the percentage blend of SAF in conventional jet fuel should be broadened to consider fuel quality, which also has a bearing on non-CO2 emissions.
- Given that 50% of contrail-related warming is estimated to occur over the US, North Atlantic and the EU, bilateral cooperation between these regions is important.

**Dimitar Nikov (European Commission, DG Climate Action):** The EU is committed to addressing the climate impacts of aviation and the new EU MRV system for monitoring, reporting, and verifying these impacts will enter into force in 2025

- The EU MRV system will use state-of-the-art, open-source models to calculate the non-CO2 effects of aviation.
- From 1 January 2027, the system will apply to all flights departing from the European Economic Area, which equates to 5-6 million flights annually.
- The MRV system will initially have a reduced scope to facilitate implementation, with the full scope being phased in over time.

**Dr. Adam Durant (Satavia):** Accurately forecasting humidity levels is vital for predicting contrail formation, which is essential for developing effective mitigation strategies.

- Satavia has developed atmospheric modelling capabilities that integrate numerical weather prediction, earth observation data, and aircraft location data to predict the formation and persistence of contrail clouds.
- These capabilities allow airlines to optimise their flight plans to minimise contrail formation.
- Satavia is partnering with Gold Standard to develop a system for estimating and generating carbon credits for airlines that successfully avoid contrail formation.

**Philippe Very (Eurocontrol):** Data sharing initiatives like Eurocontrol's ContrailNet project are essential for facilitating research and improving understanding of contrail formation, which will support the development of effective mitigation strategies.

- A key goal of the ContrailNet project is to create a database of images where experts have identified and labelled the contours of contrails to train AI models.

- The project will also establish a common language for comparing different contrail models.
- The database will be open to researchers and other stakeholders to improve collaboration and knowledge sharing.

**Pierre Quintard (Ellona):** Real-time multi-sensor monitoring systems at airports can generate valuable data on emissions for integration with other systems to support efforts to avoid the non-CO2 impacts of aviation.

- Ellona has developed multi-sensor technology that provides real-time data on several environmental parameters, including sound, odours, and particles.
- One of the advantages of this technology is its ability to triangulate the source of emissions, which has applications for monitoring emissions from aircraft at airports.
- Ellona is seeking to collaborate with other stakeholders in the sector to explore how its technology and data can contribute to the development of solutions to reduce the climate impacts of aviation.

## 14.2. SESSION 4: PARTNERSHIPS TO ACT ON – PART II: IMPLEMENTING MITIGATION MEASURES

**Overview:**
Moderated by Vincent de Haes (To70), this session focused on the importance of partnerships in implementing mitigation measures to reduce the non-CO2 climate impacts of aviation. Speakers discussed the need for collaboration to reduce uncertainties in scientific understanding of non-CO2 effects and to share data from research initiatives, including large-scale trials of contrail avoidance technologies. Several speakers highlighted the challenge of translating research findings into practical solutions that can be implemented by airlines and ANSPs.

**Moderator Vincent de Haes (To70):** This session aims to examine how partnerships between stakeholders can achieve greater certainty regarding the climate impacts of non-CO2 emissions and support initiatives, including trials, to test the efficacy of technologies and operational procedures for mitigating these impacts.

- There are two main themes relating to non-CO2 impacts: achieving certainty and taking action.
- Achieving certainty entails improving scientific understanding of non-CO2 impacts and developing technologies and procedures for mitigating them.
- Taking action entails conducting trials to test the efficacy of technologies and operational procedures for mitigating these impacts.

**Stephen Arrowsmith (EASA):** The Aviation Non-CO2 Experts Network (ANCEN), comprising policymakers, researchers, industry, and civil society representatives, has been established to facilitate cooperation and knowledge sharing on non-CO2 effects of aviation within Europe.

- There is a need to move beyond discussions of uncertainty regarding non-CO2 effects and to cooperate to find solutions.

- ANCEN will provide a forum to discuss non-CO2 effects and deliver objective technical advice.
- Key objectives of ANCEN are to develop a common terminology for discussing non-CO2 effects, establish a framework for communicating uncertainties, and identify research gaps and priorities.
- ANCEN will also facilitate data sharing, disseminate best practices, and communicate findings to the wider world.
- The network will also explore opportunities to engage with international partners to share knowledge and facilitate global cooperation on non-CO2 effects.

**Nicolas Meijers (Estuaire):** Estuaire is collaborating with stakeholders across the aviation value chain, including engine manufacturers, the aviation finance community, airports, airlines, and academia, to develop data-driven solutions to mitigate the climate impacts of aviation, with a particular focus on contrails.

- Estuaire is a startup that focuses on the climate impacts of aviation, with a particular focus on contrails.
- The company is collaborating with a range of stakeholders, including OEMs like Safran, aviation finance organisations, airports, airlines like Boeing, and universities, including Imperial College London.
- Estuaire is involved in the REVIATE community, led by Breakthrough Energy, which aims to develop common models and a shared understanding of uncertainties relating to contrails.
- The company is also involved in large-scale contrail avoidance trials, including the CoLab project.

**Simone Lini (Google):** Google has developed an AI-based contrail forecasting model that is available to stakeholders through a free API to support efforts to avoid contrail formation.

- Google is committed to achieving net zero emissions by 2030 and to helping the world reduce CO2 emissions by 1 gigaton annually.
- The company has identified contrail avoidance as a key opportunity to reduce aviation's climate impact.
- Google has developed an AI-based contrail forecasting model that is available through a free API.
- Google's goal is to support efforts to avoid contrails rather than to generate profit.

**Ilona Sitova (Eurocontrol):** Eurocontrol’s Maastricht Upper Area Control Centre (MUAC) has conducted several successful large-scale real-world trials to assess the feasibility of reducing contrail formation by strategically rerouting aircraft to avoid areas where contrails are likely to form.

- MUAC conducted the world’s first real-world contrail avoidance trial in partnership with DLR, the German Aerospace Agency, in 2021.
- In 2023 MUAC conducted a real-time simulation to investigate the impact of contrail avoidance on airspace capacity.
- The simulation found that contrail avoidance is possible even in very busy airspace and could potentially reduce contrail coverage by 20%.

- MUAC conducted a trial in partnership with Google in 2023, using Google's AI-based contrail prediction tool to avoid contrail formation.
- Future trials will involve collaboration with airlines to develop procedures for coordinating contrail avoidance.

**Mark Shapiro (Breakthrough Energy):** Greater investment and a stronger commitment from stakeholders are needed to accelerate the development and implementation of solutions to mitigate the climate impacts of contrails.

- Breakthrough Energy's non-profit applied science group is working on fundamental research into contrails, developing accessible tools, and communicating findings.
- The organisation estimates that contrails have a radiative forcing of 50 milliwatts per square metre, equivalent to a trillion dollars in social cost.
- The main barriers to mitigating contrail impacts are insufficient funding, focus, and commitment from industry stakeholders.
- Breakthrough Energy is calling on stakeholders to invest in demonstrations and trials of technologies for mitigating contrail impacts to generate data to inform decision making.

## 14.3. KEYNOTE SPEECH BY AIRBUS

**Sabine Klauke (Airbus):** Airbus is engaging in research, technology development, and collaborative partnerships to reduce the climate impacts of non-CO2 aviation emissions through initiatives focusing on engine technology, sustainable aviation fuels, operational measures such as contrail avoidance, and improved weather forecasting.

- Airbus is working to reduce non-CO2 emissions through technological development, cleaner fuels, predictive modelling, and changes to flight operations.
- Non-CO2 effects could account for as much as 50% of aviation's total climate impact.
- The company is exploring several mitigation strategies, including improving engine combustor design, using sustainable aviation fuels and hydrogen, developing more accurate contrail prediction models, and optimising flight routes.
- Airbus is collaborating with other stakeholders on several research projects, including CICONIA, which is investigating contrail avoidance, and ECLIF3, which focuses on the impact of different fuel compositions on contrail formation.

## 14.4. SESSION 5: PANEL DISCUSSION ON THE WAY FORWARD ON NON-$CO_2$ AVIATION EMISSIONS

**Overview:**

Moderated by Annick Goulet (permanent representative of Canada on the ICAO Council), this session explored the way forward for research and policy on non-CO2 emissions from aviation. Speakers discussed the importance of collaboration between stakeholders, including international organisations, research institutions, industry, and civil society, to improve scientific understanding of non-CO2 effects, share data from research and trials, and develop effective mitigation measures. A key theme was the need to translate scientific knowledge into practical solutions that can be implemented by airlines and ANSPs.

**Moderator Annick Goulet (Permanent Representative of Canada on the ICAO Council):** The symposium highlighted the need for greater research into non-CO2 emissions from aviation and for cooperation between stakeholders to develop and implement effective mitigation measures.

- Non-CO2 emissions represent a significant, but poorly understood, aspect of aviation's environmental impact.
- The symposium helped to reduce uncertainty about non-CO2 effects but also highlighted the need for more research.
- Mitigation of non-CO2 effects will require cooperation between stakeholders from international organisations, industry, research institutions, and civil society.

**Haldane Dodd (ATAG):** While the industry has made progress in understanding and mitigating CO2 emissions from aviation, more research and large-scale trials are needed to find effective solutions for reducing non-CO2 effects, such as contrails.

- The aviation industry has made significant progress in understanding and mitigating CO2 emissions, but non-CO2 effects are a newer and less well-understood area.
- Scientific research indicates that contrails have a warming effect, but there are still uncertainties regarding the best ways to mitigate them.
- Large-scale trials are needed to test the efficacy of different contrail mitigation options and to understand their operational impacts.
- Regulation of non-CO2 emissions should be avoided until the impacts are better understood.
- Some proposed solutions for mitigating non-CO2 effects may appear simple, but they could have complex operational implications.

**Andreas Petzold (IAGOS):** IAGOS is contributing to research into non-CO2 emissions from aviation by collecting atmospheric data from commercial aircraft, which can be used to improve the accuracy of contrail forecasting models and inform the development of effective mitigation measures.

- IAGOS is a European research infrastructure that uses commercial aircraft to collect atmospheric data, including measurements of water vapor, NOx, and ozone.
- IAGOS data is open access and has been used to identify the regions where contrails are most likely to form.
- IAGOS data is being used to evaluate the accuracy of weather forecasts to support the development of more effective contrail avoidance strategies.
- More accurate atmospheric sensors are needed on commercial aircraft to improve the accuracy of contrail forecasts and to support data assimilation for weather forecasting.

**Tim Johnson (ICSA):** Civil society organizations can play an important role in supporting research into the non-CO2 effects of aviation, communicating findings to the public, and advocating for policies to mitigate these effects. While uncertainty remains, stakeholders should focus on what is known about non-CO2 effects and take action to reduce the climate impacts of aviation.

- Public awareness of non-CO2 effects is increasing, and civil society organizations can play an important role in communicating information about these effects and advocating for policy solutions.
- It is important to consider the non-CO2 effects of new aviation technologies, such as hydrogen-powered aircraft, at an early stage.
- While uncertainty regarding non-CO2 effects is high, it is important to focus on what is known and to take action to mitigate these effects.
- Focusing on contrail avoidance in certain geographical corridors could be a promising approach.

**Ibrahim Yimer (National Research Council of Canada):** International collaboration and government funding are essential to support the large-scale research and trials needed to address non-CO2 effects of aviation. It is important to ensure that research findings are translated into effective policies and that the aging research infrastructure is renewed.

- Addressing the global challenge of non-CO2 emissions from aviation will require international collaboration between research institutions.
- Collaboration with industry provides valuable opportunities to leverage resources and ensure that research findings are translated into practical solutions.
- Regulators, such as Transport Canada, should be involved in the design and planning of large-scale research projects.
- There is a need for sustained government funding to support research into non-CO2 effects and to ensure that research infrastructure is renewed.

**Neil Dickson (ICAO):** ICAO can play a key role in facilitating international cooperation on research into non-CO2 effects of aviation, developing standards and recommended practices (SARPs) for mitigating these effects, and sharing best practices between states.

- ICAO has a long history of working with Member States to develop standards and recommended practices (SARPs) for mitigating environmental impacts of aviation, including noise, local air quality, and CO2 emissions.
- The organization is well-placed to facilitate international cooperation and data sharing on non-CO2 effects.
- Any action to mitigate non-CO2 effects should be global in nature and should not disadvantage any states.
- ICAO's existing processes for developing SARPs can be adapted to address non-CO2 effects, but innovation will be required to ensure that these processes are effective.
- Reducing scientific uncertainty around non-CO2 effects is crucial to avoid unintended consequences from new policies.

## 14.5. HIGH-LEVEL PANEL: WAY FORWARD ON NON-$CO_2$ AVIATION EMISSIONS

The discussion centered around these three areas:

- **Importance of Collaboration**: Speakers emphasized the need for robust collaboration between states, industry stakeholders, and the scientific community. This collaborative approach is deemed essential to address the challenges posed by non-CO2 emissions effectively. Sharing research findings and data is crucial to ensure that all stakeholders have access to the latest information and can work together to develop solutions.
- **Bridging Knowledge Gaps and Reducing Uncertainties**: Panellists underscored the existence of knowledge gaps and uncertainties related to non-CO2 emissions. A key area of focus is the need for further research to better understand the impact of these emissions and to develop accurate models and metrics. Addressing these knowledge gaps will provide a solid foundation for informed decision-making and the development of effective mitigation strategies.
- **Transitioning from Research to Actionable Solutions**: While research remains crucial, the panel also stressed the importance of translating scientific findings into concrete actions. The call to action centers around establishing a clear roadmap with well-defined next steps. This roadmap should encompass a multi-pronged strategy that includes technological advancements, operational improvements, and the development of supportive policies and regulations to achieve tangible reductions in non-CO2 emissions.

### 14.5.1.KEY MESSAGES FROM THE MODERATOR AND EACH SPEAKER

**Moderator Jane Hupe (ICAO):**

- ICAO has a rich history of taking action on non-CO2 emissions, with standards like Annex 16, Volume 2 already in place for 40 years.
- ICAO will develop a website to consolidate all available information on non-CO2 emissions, results, ongoing research, and initiatives.
- It is crucial to not only share existing information but also to encourage research in various parts of the world to leverage diverse perspectives and expertise.
- ICAO's independent science group within CAEP plays a vital role in collecting, compiling, and presenting scientific data to inform the committee's technical work on non-CO2 emissions.

**Holly Greig (UK Department for Transport):**

- The UK government is committed to making the UK a green energy superpower and accelerating its journey to net-zero, including the aviation sector.
- The UK has initiated a multi-million pound, multi-year research and development programme, partnering with various stakeholders to address non-CO2 emissions in aviation.
- Sharing research results and making them accessible to all is crucial to ensure a global understanding of the issue and promote collaborative mitigation efforts.

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**Julie Marks (US FAA):**

- Collaboration is crucial to achieving true sustainability in the aviation industry, and research in the US is often carried out in partnership with various stakeholders, including government, industry, and international organisations.
- The US is dedicated to compiling and publicly sharing its research findings on non-CO2 emissions, aiming for transparency, identifying knowledge gaps, and fostering collaboration.
- The primary goal of research is to inform decision-making, ensuring that actions taken are effective and contribute to sustainability within the aviation industry.

**Charity Muthoni Musila (Representative of Kenya to ICAO):**

- Kenya currently focuses on traditional monitoring and implementing existing NOx standards; however, there's a recognition of the need to address a broader range of non-CO2 effects from aviation.
- A science-based approach to regulation is essential, with policies based on a clear understanding of the science and a reduction of uncertainties in non-CO2 research.
- International collaboration is key, recognizing that the impact of non-CO2 emissions is global and requires a coordinated effort to monitor, understand, and mitigate these emissions.

**Richard Ossendorp (Netherlands Representative to ICAO):**

- The Netherlands actively participates in non-CO2 research and initiatives through national research institutions, including NLR and Delft University of Technology, and the engagement of KLM.
- Public awareness regarding non-CO2 emissions is paramount, driven by increasing public concern over aviation's environmental footprint, urging for leadership from states and ICAO in addressing this issue.
- Sharing research findings is essential, especially considering that expertise and research capabilities are often concentrated in specific regions, advocating for a globally informed approach to mitigation.

**Rachid Rahim (Qatar Civil Aviation Authority):**

- Qatar has been addressing non-CO2 emissions for a decade by using GTL jet fuel, which is sulfur-free and aromatic-free.
- A global solution is needed to address non-CO2 emissions, ensuring no country or stakeholder is left behind. ICAO plays a crucial role in facilitating this global collaboration.
- Monitoring progress is crucial for informing future decisions and actions related to mitigating non-CO2 emissions in aviation.

**Closing Remarks**

**Jan Fuglestvedt (CICERO)**

- The IPCC will hold a scoping meeting in Kuala Lumpur in December 2024, with over 240 experts to outline research priorities, including those related to aviation and climate change.

**Juan Carlos Salazar (ICAO Secretary General)**

- Addressing key knowledge gaps in non-CO2 aviation emissions is crucial, requiring a collaborative approach between scientists, engineers, policymakers, and industry leaders.
- ICAO is committed to a globally harmonized approach to non-CO2 emissions, leveraging its role to promote consistent standards, policies, and strategies based on the best available science.
- Continuous assessment of scientific findings is essential for refining and adapting policies and strategies, ensuring they remain effective and relevant in light of emerging knowledge.

**Key Announcement**

**Neil Dickson (ICAO)**

- ICAO will develop a dedicated tracker tool (similar to the successful tools for sustainable aviation fuels, technology, and CO2 emissions) to centralize information on all non-CO2 initiatives.
- This one-stop repository will compile information shared during the symposium, including details and links to relevant web pages and resources.
- The tracker tool is expected to be a valuable resource for promoting transparency, facilitating collaboration, and tracking progress in addressing non-CO2 emissions from aviation.