Better Contrails Mitigation - BeCoM

European Union Horizon Europe Research and innovation program
Under grant agreement
No 101056885

D6.4

Distillation of policy-relevant outcomes

Table of acronyms

aCCF	algorithmic Climate Change Function
ADS-B	Automatic Dependent Surveillance–Broadcast
AI	Artificial Intelligence
AMDAR	Aircraft Meteorological Data Relay
ANSP	Air Navigation Service Provider
ATM	Air Traffic Management
p-ATR100	Persistent Average Temperature Response over 100 years
BeCoM	Better Contrail Mitigation
CAEP	Committee on Aviation Environmental Protection
CAEP WG2	CAEP Working Group 2 (Airports and Operations)
CAEP WG3	CAEP Working Group 3 (Emissions)
CHIPS	Clouds with enHanced Ice Prognostics Submodel
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Contrail	Condensation trail
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CNRS	Centre National de la Recherche Scientifique
DIPS	Direct In-cloud humidity Prediction Scheme
DWD	Deutscher Wetterdienst
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EASA	European Union Aviation Safety Agency
ECATS	Environmentally Compatible Air Transport System
EMAC	ECHAM/MESSy Atmospheric Chemistry
ECHAM	ECMWF Hamburg Atmospheric Model
ECMWF	European Centre for Medium Range Weather Forecasts
ECMWF IFS	ECMWF Integrated Forecasting System
ERA5	Fifth generation ECMWF ReAnalysis of the global climate
ETS	Emissions Trading System
EU	European Union
EUA	European Union Allowances
EUMETNET	European Meteorological Network
FLASH-B	Fluorescent Lyman-Alpha Stratospheric Hygrometer
GWP	Global Warming Potential
IAGOS	In-service Aircraft for a Global Observing System
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICON	Icosahedral non-hydrostatic general circulation model

IPCC	Intergovernmental Panel on Climate Change
ISG	Impacts and Science Group (ICAO)
ISSR	Ice-Supersaturated Regions
LIDAR	Light detection and ranging
MESSy	Modular Earth Submodel System
ML	Machine Learning
MOZAIC	Measurement of Ozone and Water Vapour on Airbus In-service Aircraft
MRV	Monitoring, Reporting, and Verification
NAO	North Atlantic Oscillation
NATSPG	North Atlantic Systems Planning Group
NEATS	Non-CO_2 Aviation Effects Tracking System
NOx	Nitrogen oxides
NWP	Numerical Weather Prediction
O	Objective
ODD	Operational Design Domain
OTS	Organised Track System
R	Recommendation
RHi	Relative Humidity with respect to ice
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SIRTA	Site Instrumental de Recherche par Télédétection Atmosphérique
SME	Small and Medium Enterprise
TUD / TU Delft	Technische Universität Delft
UK NATS	United Kingdom National Air Traffic Services
WP	Work Package

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About this report

The document that follows has been put together by a consortium of research institutions, SMEs and industry partners involved in the BeCoM (Better Contrail Mitigation) Horizon Europe research project. It summarises the policy-relevant outcomes of the research activities throughout the project lifetime (2022-2026) and is enhanced by stakeholder input received. Its intent is to inform both the interested reader and policy discussions on mitigating aviation's non-CO_2 *climate effects.*

Context

Aviation accounts for around 2% of total anthropogenic carbon dioxide (CO_2) emissions but its overall contribution to global warming could be as high as 5% when less conservative estimates[1] of the remaining, non-CO_2 effects, are included. Specifically, the atmospheric radiative forcing from cirrus clouds resulting from condensation trails (contrails) is estimated to represent roughly two thirds of this additional climate impact. At the beginning of the decade, these effects remained largely unaccounted for in global climate policy frameworks, despite a scientific consensus having been established on their potential magnitude a few years prior.

The Better Contrail Mitigation (BeCoM) project under the Horizon Europe framework was conceived in late 2021 in response to the HORIZON-CL5-2021-D5-01-05 research call, to close several knowledge gaps in the emergent field of contrail science:

- Insufficient observations of relative humidity in the upper troposphere to map contrail-prone regions;
- Inadequate representation of ice-phase microphysics relevant for contrail formation in numerical weather prediction (NWP) models;
- Lack of machine learning (ML) or ML-enhanced contrail detection capacity for the European airspace and context;
- A largely unmapped or under-explored policy instrument design space at the project inception.

The policy-relevant findings from the project's five work packages[2] are distilled below, with the underlying work summarised under five sections covering the main research topics of upper troposphere humidity observations, numerical weather prediction, contrail detection, climate-optimised trajectory planning and non-CO_2 policy instrument design.

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[1] Lee et al. (2021), Atmospheric Environment 244:117834. The 5% estimate reflects aviation's share of total anthropogenic effective radiative forcing when non-CO_2 effects — including contrail-induced cirrus, nitrogen oxides (NO_x)-induced ozone and methane, water vapour, and aerosols— are included at higher-range uncertainty estimates. The 2% CO_2-only figure and the two-thirds contrail share are from the same assessment.

[2] A detailed description of the work package scope and structure is provided in Annex B.

Executive Summary

BeCoM research shows that selective, weather-conditional contrail avoidance is an operationally meaningful mitigation lever. Trajectory simulations over the North Atlantic indicate that the climate benefit and cost of avoidance vary with identifiable weather patterns, allowing instances in which large contrail reductions are achievable at low fuel penalty to be anticipated. In parallel, hybrid AI methods developed in the project detect contrails in geostationary satellite imagery using substantially less training data than conventional approaches, supporting the post-flight assessment of avoidance measures.

These capabilities rest on improved forecasting foundations. As part of BeCoM research, ERA5 reanalysis was found to underestimate ice-supersaturated region (ISSR) occurrence frequency, with a 10–20% bias towards lower humidity values at cruise altitudes over Europe (a "dry bias") that likely leads to under-attribution of contrail formation potential in systems depending on it. Model adjustments alone would be insufficient to correct said bias; it is best addressed through expanded observational input and enhanced data assimilation.

Analysis on a potential CO_2-equivalent (CO_2e) impact integration into the EU Emissions Trading System (EU ETS) shows that weather dependent climate-response surfaces (e.g., algorithmic climate change functions, aCCF; contrail cirrus prediction model, CoCiP/pycontrails) can capture flight-specific effects and support trajectory-based impact mitigation. While the operational mitigation potential is largely determined by weather conditions, BeCoM finds that pricing non-CO_2 aviation climate effects into the EU ETS — as an indirect economic incentive for climate-optimised routing — is technically feasible, could deliver meaningful contrail reduction, and would have modest impacts on ticket prices. Sensitivities of six design parameters were analysed within the project: the share of impact accounted for; the integration of perceived uncertainties in impact accounting; the CO_2e price level; the climate impact metric applied; the geographic scope of the scheme; and the set of non-CO_2 impacts included. Together, these define a design space within which policy choices must be made — each involving value judgments that science can inform but not resolve on its own.

BeCoM explores phased implementation as a means to smoothen the transition towards non-CO_2 accounting in the EU ETS by limiting economic impacts, facilitating operational adaptation and allowing underlying methodologies to be refined. Such an approach could also help mitigate instances of flight rerouting where costs outweigh benefits and help further advances in scientific knowledge, while still introducing incentives for contrail climate impact mitigation. Support for continued research is essential to incorporating these advances into adaptive policy design approaches that enable effective action on non-CO_2 aviation impacts.

An important conclusion from the BeCoM project is that many of the remaining questions around the operationalisation of contrail avoidance can be addressed by the deployment of enhanced measurement and prediction capabilities and, in parallel, further research on operational trials. Importantly, the current level of scientific understanding does not preclude the implementation of policy instruments to mitigate contrail impacts, as long as their design both fosters and is informed by scientific research.

Key Terms

Ice-supersaturated regions

Ice-supersaturated regions (ISSRs) are the layers of atmosphere where persistent contrails form and spread. Ambient air there has a high degree of humidity, such that water vapour readily deposits on any surface, allowing ice crystals in contrails formed in ISSRs to persist and grow. Forecasting where ISSRs are present - and when - is a 4D problem of determining latitude, longitude, altitude and timing. It is the basic requirement for the successful operationalisation of contrail avoidance schemes.

Numerical weather prediction models

Numerical Weather Prediction (NWP) involves the use of computer-based mathematical models of the atmosphere, initialized with current observational data, to forecast future weather conditions. In the context of contrail mitigation, NWP provides the essential estimates of temperature, pressure, and upper-tropospheric humidity required to identify ice-supersaturated regions.

On uncertainty

The topic of *scientific uncertainty* is often present in discussions on contrail climate impacts. For explanatory purposes only, we have chosen to distinguish several categories of uncertainty, based on their implications for contrail mitigation:

Measurement uncertainty affects data reliability like, for example, humidity levels measured at cruise altitudes. It has consequences for contrail-mitigation measures such as navigational avoidance and their integration in flight planning. An expanded observational infrastructure (for example, ground-based observations, satellite, LIDAR) combined with improved detection algorithms can both improve numerical weather prediction (NWP) models - through better model data assimilation - and support overall contrail impact monitoring in MRV schemes; work performed in Topics 1 and 3 addresses some aspects of measurement uncertainty.

Model performance can vary, as was found to be the case for ISSR representation in NWP models. It affects the transposition of meteorological data into concrete contrail formation probabilities. Some uncertainty is also present in the models describing the overall climate response to non-CO_2 emissions such as contrails. Modelling uncertainty is typically reduced through improved model parameterisation and data assimilation, as shown in Topic 2. Additionally, modelling uncertainty can be incorporated in trajectory optimisation or possible pricing schemes (Topic 4 and 5).

Operational impact uncertainty is the difficulty in determining the real-world effects of contrail avoidance on flight operations, including its impacts on fuel consumption, flight time, costs, and its operational feasibility. It can be reduced by carefully designed avoidance trials to collect real operational data and improve cost estimates. Topics 4 and 5 include work on costs.

Meteorological variability is inherent to atmospheric conditions, particularly on timescales shorter than common forecast horizons. Residual uncertainty in ISSR location and extent will always remain, regardless of how good models and measurements become. This should not preclude action on contrail impacts: policy and operational protocols can be designed with it in mind - uncertainty will be a feature of any contrail management regime, in the same way that it is present in the existing broader climate impact mitigation policies and frameworks.

Why aviation non-CO_2 climate impact can no longer be ignored

Accounting for aviation's full climate impact

For decades, aviation climate policy has focused predominantly on carbon dioxide. This is understandable, since the warming effect of CO_2 is well characterised, emissions from aircraft are proportional to fuel burn and therefore predictably reduced through operational efficiency gains, improved aircraft design and engine performance.

A growing body of evidence, anchored in the seminal assessment by Lee et al. (2021) has, however, established that CO_2 emissions account for only part of aviation's contribution to atmospheric warming and that, when non-CO_2 effects are included, aviation's total radiative forcing is substantially larger than that of CO_2 alone.

The dominant non-CO_2 warming impact is attributed to contrail-induced cirrus: the ice-crystal clouds that form when aircraft exhaust mixes with cold, ice-supersaturated air at cruise altitude. Unlike CO_2, which accumulates in the atmosphere over centuries, individual contrails mostly dissipate within hours; their collective warming effect can nonetheless be substantial as contrail cirrus clouds can extend across significant areas on high-traffic routes when atmospheric conditions favour their persistence. Reducing CO_2 emissions and reducing the warming effect of contrail cirrus can therefore require distinct interventions.

The state of the science before BeCoM

The potential for climate effects from contrails has been identified since at least the late 1990s. However, contrail formation and persistence depend on atmospheric conditions that are considerably harder to forecast at aircraft cruise altitudes than the lower-troposphere for which conventional Numerical Weather Prediction (NWP) models are optimised. Upper-tropospheric humidity observations have historically been sparse and only a small number of commercial aircraft carry dedicated humidity sensors capable of providing in-situ measurements at cruise altitudes.

Moreover, the ice cloud microphysics schemes in operational NWP models have employed simplifications that prevent sufficiently accurate representations of ice-supersaturated states and, as a result, the spatial and temporal precision needed to plan contrail avoidance manoeuvres lay outside of these models' capabilities when BeCoM was conceived. Without reliable forecasts to support operational contrail avoidance, and to verify whether the manoeuvres involved are effective in preventing contrail formation, the case for implementing a contrail avoidance regime has remained difficult to translate into policy, despite substantial prior scientific advances.

Starting in the mid-2000s, simplified representations of ice supersaturation were incorporated into global NWP models and the MOZAIC and IAGOS networks began delivering the first humidity measurements in the upper troposphere from commercial aircraft. Coverage, however, remained too sparse for ISSR forecasting. Later, trajectory optimisation to avoid contrail formation was demonstrated in simulations and early flight trials. Ensemble studies quantified the concentration of contrail climate impacts - pointing to a small proportion of flights accounting for approximately 80% of radiative forcing[3] - and established the case for selective contrail avoidance. Importantly, NWP performance in this period was mostly ineffective in contrail persistence prediction — the consequence of models lacking sufficient data on relative humidity at cruise altitudes.

BeCoM's five technical work packages (WPs) and their core research objectives were devised in response to several knowledge gaps identified at the project inception. Implicitly, each Topic section in the Findings chapter of this document corresponds to a research work package[4]:

Table 1. BeCoM's technical Work Packages.

Technical Work Package	Title	Core objective
WP1	Operational & New Measurements & Characterisation	Expand and improve upper-tropospheric relative humidity measurements from commercial aircraft and ground-based LIDAR for assimilation into NWP models.
WP2	Cloud Physics & Weather Models & Assimilation	Improve NWP model representation of ice cloud microphysics and ice-supersaturated regions; assimilate new humidity data to enhance persistent contrail prediction skill.
WP3	Evaluation of Data and Model Predictions	Develop and validate hybrid machine-learning algorithms for data assimilation, contrail detection, and contrail classification; design an experimental methodology for AI algorithmic-uncertainty evaluation, applied to trajectory optimisation.
WP4	Climate-Optimised Trajectories	Implement improved contrail prediction into trajectory optimisation tools; quantify the climate and cost impact of avoidance strategies under realistic operational constraints.
WP5	Policy-Driven Flight Planning	Develop regulatory concepts for integrating non-CO_2 climate effects into existing policy frameworks; assess feasibility of climate-charged airspace and related instruments.

[3] *Gierens et al. (2020), Lee et al. (2021), Teoh et al. (2022).*

[4] *A full account of the project's formal objectives (O1–O6), deliverables, and Horizon Europe context is provided in Annex B.*

1. Findings

Topic 1: Measuring relative humidity in the upper troposphere

One of BeCoM's first major findings is that ERA5 reanalysis — one of the standard meteorological references used for contrail climate impact modelling — captures ice-supersaturated conditions at significantly lower frequency than actually observed, exhibiting a 10–20% "dry bias" i.e. it consistently underestimates humidity levels at cruise altitudes over Europe. The likely cause is the sparse observational network: some commercial aircraft can deliver routine temperature and wind profiles via AMDAR (Aircraft Meteorological Data Relay), but obtaining sufficiently accurate data on relative humidity in the upper troposphere in European airspace currently mostly depends on a small number of commercial aircraft equipped with research-grade hygrometers as part of the IAGOS[5] programme.

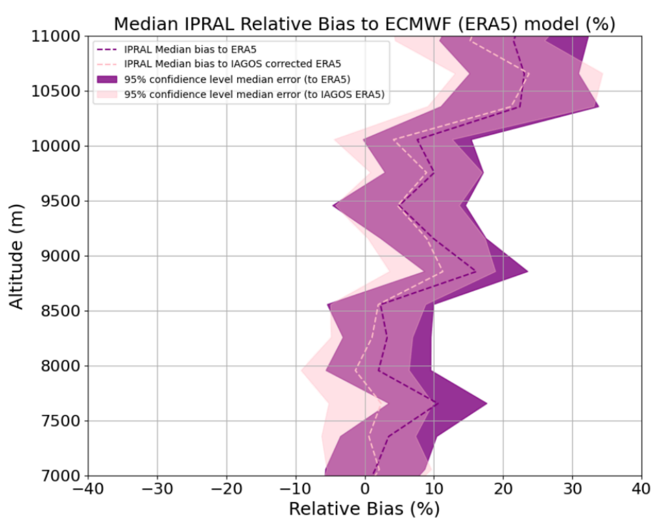

Figure 1. Median IPRAL LIDAR water-vapour relative bias versus ERA5 (purple) and IAGOS-corrected ERA5 (pink) over the Paris region, 7–11 km; shaded zones show the 95% confidence interval. Source: CNRS (Alraddawi et al., 2025).

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[5] *IAGOS — In-service Aircraft for a Global Observing System — is a research infrastructure that equips commercial aircraft with scientific instruments to measure atmospheric conditions and composition at cruise altitudes, including temperature, ozone, humidity, and carbon monoxide. IAGOS instruments fly aboard regular commercial services, making them uniquely suited to systematic upper-tropospheric observations across operational routes.*

Models supplied with such "biased" data may systematically under-attribute contrail climate impact. They could also potentially carry this structural bias into policy considerations — underestimating both the scale of the contrail problem and the mitigation potential available.

With the dry-bias identified, further research under BeCoM has sought to address this deficit by deploying Raman LIDAR in both metropolitan France and Réunion Island, producing a multi-year dataset of upper-tropospheric relative humidity measurements from ground stations. A case study combining LIDAR, all-sky camera imagery, and ADS-B flight tracking documented individual contrail events under characterised atmospheric conditions with persistent contrails forming at relative humidity over ice (RHi) exceeding 105%, temperatures of 217–223K, measured horizontal widths of 350–1.900m and vertical extents of 340–440m. This was reinforced by an in-situ measurement campaign: deploying aerostatic instruments in the atmosphere at the SIRTA observatory near Paris in 2025. The result is a high-resolution reference dataset, as well as a universal calibration methodology for water vapour Raman LIDAR. This approach removes the cross-site offsets that had previously prevented network-level comparison. The empirically characterised formation and persistence conditions provide benchmarks against which the contrail models that underpin per-flight impact calculations can be assessed.

> **What this means for policy**
>
> Deficiencies identified in ERA5 reanalysis ("dry bias" and resulting underestimation of ISSR occurrence) may propagate into downstream elements as systems relying on unadjusted data may inherit under-attribution of contrail climate impacts that cannot be corrected through parametrisation alone. Potential solutions include leveraging existing AMDAR architecture and expanding the IAGOS programme to target routes providing adequate spatial coverage, supported by public funding mechanisms such as the EU ETS Innovation Fund. Ground-based contrail observations show promise in providing a complementary, independent verification pathway for per-flight impact calculations in non-CO_2 monitoring frameworks.

Topic 2: Teaching forecast models to represent ice supersaturation

Improving inputs from atmospheric observations and measurements is a necessary condition to improve ISSR and contrail formation forecasting, but not a sufficient one. The weather models that ingest the data must also then be able to represent ice supersaturation with the needed level of accuracy. One-moment cloud ice schemes[6] prevalent in operational NWP models assume all available moisture converts immediately to ice upon cloud formation, suppressing the modelled frequency of supersaturated conditions. Research in BeCoM addressed this by improving how humidity observations are ingested into the ICON[7] model framework in two important ways: by using measurement from commercial flights (AMDAR and IAGOS) and adding satellite-based cloud observations. To convert observation data into improved humidity forecasts, BeCoM tested three methods: physics-based model equations, machine learning (ML) emulation, and ensemble correlations. All three reduced humidity biases and improved cloud representation, with the ML and ensemble methods performing the strongest. This allows the model to sustain ice-supersaturated states. A comparison of the two ICON configurations illustrates how the improved model resolves ISSRs more accurately than the standard operational model, providing a more reliable basis for identifying airspace relevant for contrail avoidance:

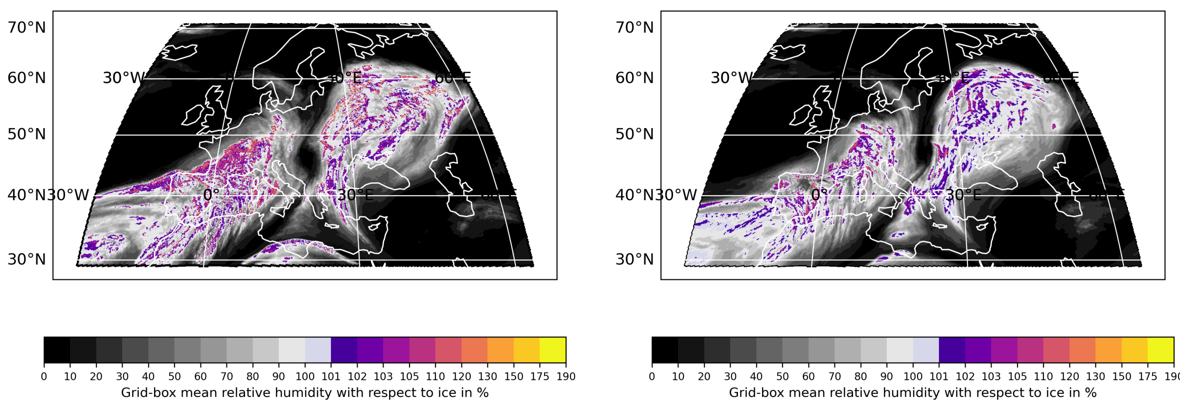

Figure 2. Grid-box mean relative humidity with respect to ice (RHi) at approximately FL 350, 27/01/2025 ICON with CHIPS with DIPS humidity assimilation (left) vs. standard ICON NWP (right). Coloured pixels indicate ice-supersaturated conditions

Uncertainty in the characterisation of initial atmospheric conditions remains, primarily due to the low availability of high-quality in-situ observations described earlier, as well as the still-limited use of satellite-based cloud information in current data assimilation systems.

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[6] A conventional one-moment scheme tracks only total ice mass, assuming all water vapor above ice saturation converts instantly and completely into ice crystals. This works well for large-scale cloud systems but not contrails. A two-moment scheme independently tracks total ice mass and ice crystal number, allowing the model to represent nucleation, growth, fall speed, and the residence time of ice crystals separately — and critically, to sustain the ice-supersaturated states that most one-moment schemes cannot maintain.

[7] ICON (Icosahedral Nonhydrostatic Model) is the operational weather forecast model used by Germany's national meteorological service (DWD) to predict atmospheric conditions every three hours globally. It ingests observations from aircraft, satellites, weather balloons, and ground stations to create an updated picture of current atmospheric humidity, temperature and wind to then forecast how these conditions will evolve.

What this means for policy

BeCoM's primary cloud physics contribution — an improved one-moment scheme that sustains ice-supersaturated states — has been successfully tested within DWD's ICON model, reducing the modelled upper-tropospheric humidity bias owing to enhanced data assimilation combining physics-based, machine-learning and ensemble methods. A two-moment ice microphysics scheme is being integrated into ICON in parallel, with outputs expected to eventually benefit the EU ETS non-CO_2 MRV. Coordinating performance comparison with other models (e.g. ECMWF) is an important next step. Critically, these improvements will enable probabilistic ISSR forecasts for uncertainty-adjusted impact accounting.

Topic 3: Detecting contrails in satellite images with hybrid AI approaches

Accurately forecasting where contrails are likely to form is one part of the challenge; confirming whether and where they did, is equally important for the operational deployment of avoidance schemes. Specifically, it allows independent post-flight assessment of avoidance measure effectiveness against observations. Geostationary satellites are particularly well-suited for contrail detection and machine-learning algorithms applied to satellite images achieve good detection performance. However, they typically require large quantities of human-labelled training data. BeCoM first set out to address this by creating a dataset of geostationary satellite images containing contrail instances for algorithm training. It then developed data-frugal machine learning (ML) and hybrid approaches for contrail detection from satellite imagery[8] using knowledge of contrail symmetries (localisation, orientation) as geometric structural constraints within the learning architecture. These rely much less on large human-labelled satellite image sets, showing stable detection performance with very little training data, while displaying improved detection compared to standard ML methods. Work performed by BeCoM partners shows that models with approximately 36 times fewer parameters maintain or exceed detection performance while requiring substantially less labelled training data — supporting integration into potential satellite-based verification workflows.

What this means for policy

Machine-learning and related detection tools show promise in supporting post-flight automated identification of contrail occurrence and extent — a capability on which the

[8] *Preliminary cross-sensor validation demonstrated detection on Meteosat SEVIRI from a model trained on GOES-16 data, establishing European transfer learning proof-of-concept. The hybrid model performance was demonstrated on Meteosat SEVIRI geostationary imagery across multiple seasons*

assessment of any operational avoidance measure would ultimately rely. The hybrid AI methods developed in BeCoM require significantly less training data and computational resources than conventional approaches. The main remaining limitation — reliably identifying *aged* contrails — reinforces the case for phased implementation, in step with advancing observational capabilities.

Topic 4: Trajectory optimisation — when and where contrail avoidance pays off

The benefit-to-cost ratio of operationalising contrail avoidance can vary substantially, and understanding better how both costs and benefits are distributed is a prerequisite for designing effective avoidance schemes. BeCoM has conducted research[9] to simulate and assess contrail avoidance on North Atlantic routes across multiple seasons, establish whether the climate benefit of rerouting around persistent contrail formation areas outweighs the associated costs, and how this relationship varies across days, seasons, and atmospheric conditions.

Simulations covering 100 representative North Atlantic flights conclude that both the climate benefit and the operational cost of avoidance can vary substantially depending on flight date, owing to variability in the configuration of the jet stream and the location and extent of ISSR layers. Variability here is, however, organised by weather patterns that can be classified in advance. The highest benefit-to-cost ratio consistently occurs under the negative phase of the East Atlantic teleconnection pattern: a weakened, southward-displaced jet stream[10] that creates extensive ISSR layers at mid-latitudes while leaving accessible avoidance corridors at modest lateral deviations from direct routes, also known as great-circle trajectories. Under strong positive North Atlantic Oscillation (NAO)[11] phases, the jet stream intensifies and contracts, ISSRs concentrate at higher latitudes, and fuel/timing penalties from avoidance increase. Because these patterns are identifiable from forecasts, advance assessment of avoidance effectiveness is feasible.

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[9] *Castino et al., 2026, under review.*

[10] *More broadly, the East Atlantic pattern is the second leading mode of low-frequency atmospheric variability over the North Atlantic, after the North Atlantic Oscillation. It modulates the strength and, in particular, the latitude of the North Atlantic jet stream and storm track, and its phases interact with those of the Oscillation to shape European winter weather.*

[11] *The North Atlantic Oscillation is the dominant mode of winter atmospheric variability over the North Atlantic, expressed as the surface-pressure difference between the Icelandic Low and the Azores High. In its positive phase the pressure gradient and the North Atlantic jet stream are strong, bringing milder, stormier conditions to north-west Europe; in its negative phase the gradient and jet are weak.*

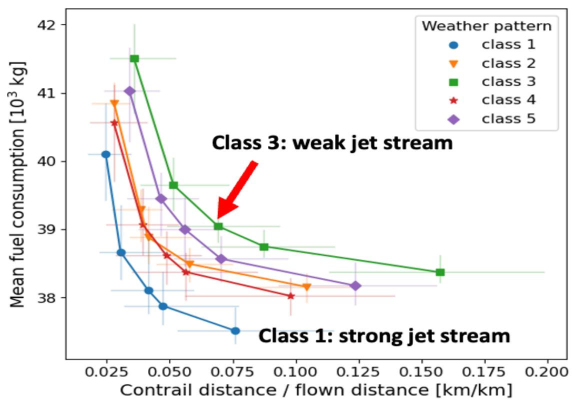

Figure 3. Mean fuel consumption versus contrail distance per unit flown distance under five North Atlantic winter weather-pattern classes, averaged over 100 representative routes. Class 1 corresponds to a strong, zonal jet stream and Class 3 to a weak, tilted jet stream, which yields the greatest contrail reduction at the lowest fuel penalty.

An evaluation of the AI-based trajectory optimiser's sensitivity to its hyper-parameters gives three additional findings: First, allowing larger vertical deviations improves both climate and internalised cost outcomes, suggesting that operational frameworks for contrail avoidance should aim not to impose tight constraints on flight level changes. Second, the optimiser's performance is strongly sensitive to the accuracy of the aCCF field used, underscoring the value of improved NWP input for avoidance decisions. Third, the analysis supports a multi-configuration approach to trajectory optimisation in which solutions from different parameter settings are pooled into a combined Pareto front[12], expanding the set of climate-cost tradeoff options available to decisionmakers and reducing the risk of suboptimal operational parameters.

This input takes the form of a four-dimensional aCCF field in which warming (positive) and cooling (negative) regions coexist along a route; Figure 4 illustrates such a field for a single cruise segment:

[12] *A Pareto front is the set of solutions for which no other solution is simultaneously better on all objectives. A meta-Pareto front pools solutions from multiple configurations, offering a broader trade-off surface. In this context one should be conscious of the risk of "overfitting", i.e. the optimiser exploiting noise or artefacts in the aCCF field rather than genuine atmospheric gradients — a risk that increases as input data uncertainty grows.*

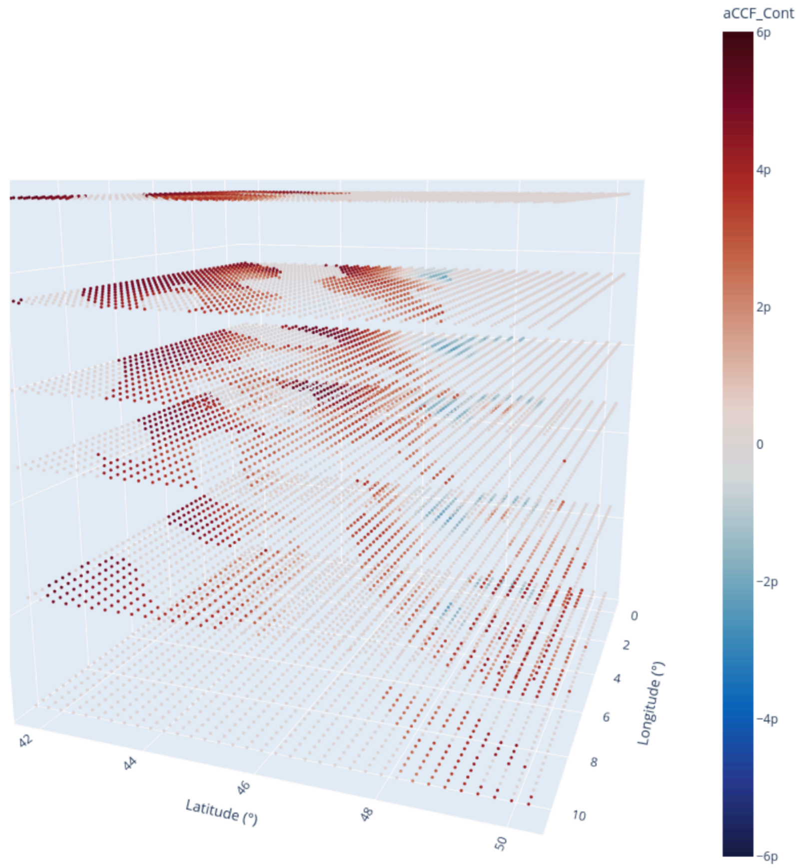

Figure 4. Illustrative aCCF field for a single cruise segment, showing warming (red, positive) and cooling (blue, negative) regions through which the trajectory optimiser routes; values in arbitrary units. Source: D3.4, Thales.

Separately, preliminary trajectory simulations using two versions of the ICON model — with and without the improved cloud physics described in Topic 2 — indicate that different ISSR forecasts may reduce the estimated avoidance potential, because the new models tend to produce more horizontally homogeneous supersaturation layers that are harder to circumnavigate through trajectory deviations. This does not diminish the case for avoidance but it does reinforce the importance of aligning expectations from policy with the available forecast capabilities, and that of adjustments in policy design as said capabilities improve.

What this means for policy

While there is variability in contrail avoidance potential in simulations performed for flights over the North Atlantic, this in itself is not an obstacle for policy action but rather a consideration for policy design: a well-designed pricing or incentive instrument that efficiently assigns the estimated CO_2-equivalent will encourage avoidance where the climate benefit-to-cost ratio is highest. The magnitude of estimated mitigation potential is sensitive to limitations in the climate response functions used, raising the case for uncertainty-adjusted approaches (see Topic 5). A weather-conditional approach is therefore superior to blanket avoidance requirements. All trajectory optimisation simulations were conducted in unconstrained airspace; real-world airspace structure and traffic density will constrain the achievable mitigation potential — a constraint that operational trials can quantify. Weather pattern classes also provide a practical basis for selecting days and routes for avoidance trials. This also points to the North Atlantic Organised Track System as an operationally less complex context for large-scale avoidance trials.

Topic 5: Non-CO_2 pricing instruments — Integrating climate costs into flight planning

Non-CO_2 mitigation measures can increase operational costs through higher fuel consumption, longer flight times, etc. However, well designed policy interventions can also shift these trade-offs by creating economic incentives or regulatory obligations that make climate-optimised trajectories more attractive and cost-effective for operators.

Effective policies must be simple, transparent, economically viable, and compatible with existing operational procedures. One potential approach is to extend the EU Emissions Trading System (EU ETS) to account for non-CO_2 effects. This could be done by introducing a CO_2-equivalent (CO_2e) charge or, conversely, an incentive. Climate impacts could be calculated on a flight-by-flight basis, translated to monetary terms and integrated into the operational considerations of flight planning. By assigning a price to CO_2e emissions, aircraft operators would be accounting for both operating costs and the broader climate costs of flights. This would encourage climate-optimised flight planning — the charge thus acting, indirectly, as an incentive for avoidance — with the acknowledgment that other means of incentivising avoidance not studied under BeCoM do exist. It would then be up to policymakers to determine the climate metrics, pricing or incentive levels, geographic scope to apply and regulatory mechanisms to enforce them.

Prior to the NEATS tool becoming available, a calculation chain was developed within BeCoM Work Package 5 and designed to be broadly compatible with the EU non-CO_2 MRV regulation and to serve as the theoretical basis for a weather-dependent CO_2e pricing scheme for individual flights by applying algorithmic Climate Change Functions[13] (aCCFs). Following the principle of addressing externalities through pricing mechanisms[14], the resulting climate effects were expressed in CO_2e and applied to EUA[15] prices to incorporate a climate-effect component in the modelled operating cost function. The resulting weather-dependent pricing represents climate cost as a function of emission location and time, and as such, is implementable in existing flight planning tools.

Illustrative mission results

The evaluation of the effectiveness of non-CO_2 accounting in mitigating climate impacts was performed based on trajectory simulations. For example, on a Barcelona–Frankfurt flight on 16 June 2018 the cost optimisation of trajectories including full CO_2e accounting achieves 55% CO_2e mitigation at a 1.3% increase in operating costs. Crucially, once climate costs are internalised, the re-routed cost-optimal trajectory also provides a climate benefit. Across the simulated missions, CO_2e abatement costs range from 3 to 74 Euro per ton CO_2e, with a median of 14 Euro and lower costs on days with effective contrail avoidance. These cost estimates are below expected abatement cost in other sectors such as direct air capture. The effectiveness of CO_2e accounting is confirmed across seasons in simulations but with clear seasonal variations in mitigation potentials and cost impacts.

Six design parameters that determine outcomes

The research demonstrates that an accounting approach based on CO_2-equivalent can lead to significant climate impact reduction when applied to optimised flight planning. Six design parameters were investigated, along with their influence on mitigation potential, associated costs, demand impact and ticket price. Two of these — the accounted share and the treatment of uncertainty — largely determine how robustly the proposed accounting scheme can be introduced; the remaining four — the price level, climate metric, geographic scope and agent selection — relating to its ambition and reach:

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[13] *aCCFs are parametric functions that estimate the climate impact of aviation emissions — including contrail formation, NO_x effects on ozone, methane and primary mode ozone, and water vapour — per unit of fuel burned, expressed as a CO_2-equivalent warming coefficient, varying continuously across latitude, longitude, altitude, and time. The result is a four-dimensional map of climate sensitivity that can be evaluated for any flight trajectory, at operational resolution, using forecast data already available in airline dispatch systems.*

[14] *Also known as the "polluter pays" principle*

[15] *EU ETS Allowances*

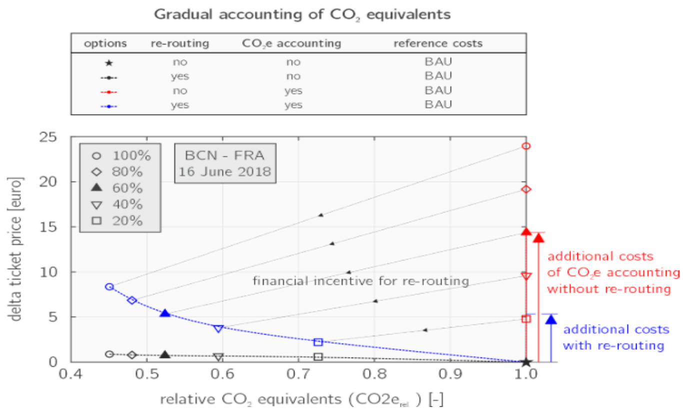

Figure 5. Changes in ticket price and relative climate effect (CO_2e) for a mission from BCN to FRA on June 16, 2018 at 12:00 UTC. A stepwise implementation of non-CO_2 pricing (e.g., 60% CO_2e coverage in year x after implementation) reduces cost impacts while maintaining incentives for climate-optimised rerouting

Accounting share — Operators could be required to surrender allowances for the full CO_2-equivalent of their non-CO_2 impacts, or only for a defined fraction of these, which could be gradually increased over time. Our simulation indicates that a phased approach can support a smooth transition by limiting economic impacts while still providing meaningful incentives for mitigation. This can facilitate operational adaptation and enable further methodological development ahead of full-impact accounting.

Uncertainty treatment — An uncertainty-based impact accounting can reduce the risk of CO_2e pricing incentivising rerouting in flights where low confidence in the resulting impact could negate the overall CO_2e reduction through higher flight CO_2 emissions. The treatment can involve central-estimate CO_2e values or values based on confidence intervals. It may therefore provide a robust starting point for policy implementation, with the potential to achieve higher mitigation at moderate ticket price increases, complementing the phased-accounting approach[16].

Carbon price level — This was found to be the primary driver of CO_2e accounting impacts on ticket price. At a level of approximately €80 per tonne of CO_2e, the additional ticket price increase for the intra-European routes studied remains well within previously observed annual price variations, meaning the impact is likely modest for those flights.

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[16] *Niklaß, Zengerling et al., Meteorologische Zeitschrift (2025, preprint). Uncertainty-based accounting of 10th percentiles of contrail effects has a higher impact than a 20% accounting of median CO_2e.; assuming that all cost increases are directly transferred to passengers*

Climate metric — This concerns the questions around measuring climate impacts, for example using the Global Warming Potential (GWP) or Average Temperature Response (ATR), and over what time horizon. The choice of metric involves value judgements — for example on prioritising short-lived versus long-lived climate effects — and is ultimately one for policymakers to make. The BeCoM analysis uses p-ATR100 as its primary metric, with conversion factors validated against multiple independent assessments. The accounting incentive mechanism appears robust towards different climate metrics[17].

Geographic scope — A key question is whether pricing should cover all flights under the EU ETS non-CO_2 MRV ("full scope") or intra-European flights only. Cost impacts vary strongly by route and fleet, leading to different ticket price and demand effects, as well as changes in network structure. A full-scope scenario maximises mitigation potential but may create leakage if demand displacement is observed - and not addressed. A reduced scope might better balance environmental effectiveness with economic competitiveness and market impact[18].

Selection of non-CO_2 agents – An important consideration is whether all agents and associated impacts, or only selected ones are accounted for in non-CO_2 pricing. The choice of climate-forcing agents strongly affects the CO_2-equivalent calculated, as well as the data and models applicable. While a phased integration of different non-CO_2 effects is possible, this may influence the selection of mitigation measures and may lead to unintended trade-offs. Thus, the decision to include a particular agent depends on its contribution to total climate impact (relevance) and on how well the underlying processes are understood, to avoid misinterpretation of effects (e.g., mistaking warming effects as cooling or vice versa).

Incentives for other mitigation approaches

Ideally, non-CO_2 mitigation policies also create incentives for implementing climate-friendly technologies, alternative fuels, and operational measures.[19] Results show that selected operational measures offer substantial climate mitigation potential, but often at higher operating costs. Extending existing accounting schemes to include non-CO_2 effects can reduce these and other implementation barriers: CO_2e pricing lowers the relative cost of mitigating versus not mitigating, even though operators' absolute operating costs still rise as a new cost component is added. The use of SAF could offer even greater mitigation potential, although the higher cost associated cannot currently be offset through extended accounting alone. Additional mitigation can be achieved through technical efficiency improvements, while policy

[17] *Dietmüller et al., Geoscientific Model Development (2023); Bruder et al., Geoscientific Model Development (2026).*
[18] *Kölker et al., Transportation Research Procedia (2026).*
[19] *Zengerling et al., Transportation Research Procedia (2026)*

design options such as phased introduction for non-CO_2 effects accounting can help limit cost and ticket price increases.

Non-CO_2 cost integration in tickets

Since non-CO_2 impacts are weather- and location-dependent, there is an inverse relationship between CO_2e accuracy and remaining time to flight departure. While ticket prices are set well in advance and respond to demand fluctuations, operators could incorporate estimated CO_2e costs into fares at booking, using historical CO_2e data as a reference, and hedge against CO_2e price volatility by pre-purchasing emission allowances. Since estimates show that a small fraction of flights contribute to the majority of contrail radiative forcing (Teoh et al., 2022), these flights would carry the largest per-passenger CO_2e cost — or, equivalently, stand to gain the most where avoidance is rewarded. Operators spreading these costs across their flight network would make ticket price increases smaller and more predictable, while the routing optimisation incentive is preserved — the operator still faces the actual CO_2e cost at flight planning, whether applied as a charge or returned as an incentive for verified avoidance, and impact avoidance can yield a competitive advantage.

EU ETS Integration and Cross-Sectoral Implications

While including CO_2e in emissions trading may enable cost-efficient climate mitigation and appears to provide lower abatement cost than approaches in other sectors, it also creates a risk that in some cases, less certain non-CO_2 reductions could substitute for more robust CO_2 abatement elsewhere. A dedicated non-CO_2 cap could safeguard the integrity of the existing ETS while maintaining incentives to reduce both CO_2 and non-CO_2 climate impacts, but would limit cross-sectoral cost efficiency by restricting mitigation to sectors with the lowest marginal abatement costs. Further research is needed to better assess these trade-offs and their implications.

What this means for policy

When non-CO_2 climate costs are internalised in model operator cost functions, cost-optimal routing and climate-optimal routing appear to converge: analysis suggests that meaningful CO_2e mitigation could be achievable at a modest operating cost increase, with indicative abatement costs comparing favourably with other sectors. A phased introduction combined with uncertainty-adjusted accounting could help limit the risk of counter-productive rerouting while still preserving a mitigation incentive signal as forecast skill keeps improving; at

> carbon-price levels observed under the EU ETS, the estimated ticket-price effect of internalising non-CO_2 costs in intra-European routes lies within observed fare variations..

2. Cross-cutting conclusions and policy considerations

The science now supports action

The research assembled across BeCoM's five work packages converges on a consistent finding: the knowledge gaps that previously precluded bringing the full scope of non-CO_2 aviation effects into environmental policy have been substantially reduced over the project. Several of these uncertainties can now be managed within policy design itself — through phased and uncertainty-adjusted approaches — rather than treated as reasons for inaction. With the non-CO_2 MRV scheme operational and data collection underway since January 2025, the practical foundations for the next stage of policy development are materially stronger than at the project's inception. The envisaged return to full MRV's scope from 2027 would further strengthen this evidence base, particularly for the long-haul routes where contrail impacts concentrate.

Policy instrument design considerations

BeCoM's parameter analysis rests on a limited set of routes and weather scenarios, so its values are indicative and a broader, network-scale assessment is still required. What the analysis provides is the quantitative mapping between design parameters and outcomes — mitigation potential, cost change, and ticket-price impact — that allows instrument design choices to be made transparently and with understood consequences. A network-scale assessment would benefit directly from operational data generated in structured avoidance trials.

The North Atlantic as one potential starting environment

A first application is best suited where climate impact is high but operational complexity is low. North Atlantic routes meet both conditions: they contribute a disproportionate share of contrail radiative forcing, their trajectories run almost parallel within the Organised Track System (OTS), and sector congestion is far lower than in continental European airspace — which lowers the difficulty of weather-conditional routing changes and makes the region the most practical setting for a first structured avoidance trial. Such a trial would require the active participation of at least one commercial operator alongside meteorological and research partners.

International dimensions

The current EU-led regulatory action is necessary but likely insufficient: the North Atlantic and other long-haul international routes that generate a disproportionate share of contrail warming involve aircraft operators from multiple jurisdictions. The International Civil Aviation Organisation (ICAO) is fostering advances in non-CO_2 emissions science through the Impacts and Science Group (ISG). Within the broader CAEP/13–14 work programme (2025–2028), Working Group 2 (WG2), which addresses operational measures, has included contrail avoidance in its work programme. Working Group 3 (WG3), responsible for engine emissions certification under Annex 16 Volume II, is reviewing the NOx standard. ICAO is however not actively working on a global MRV or market-based measure to address non-CO_2 emissions. European leadership in advancing a credible non-CO_2 monitoring and reporting framework — building on the MRV data collection already operative under EU ETS since January 2025 — is the appropriate position while global frameworks develop.

3. Research priorities and next steps

BeCoM has substantially advanced the observational, modelling, detection, and policy foundations for non-CO_2 aviation climate mitigation. The project has also identified, with greater precision than previously possible, where knowledge gaps remain.

On upper-tropospheric observations

The ERA5 dry bias is now characterised and its downstream consequences understood. The next priority is a systematic expansion of the observational network for relative humidity in the upper troposphere. This requires targeted data assimilation development building directly on the methodology established here.

On NWP and cloud physics

The immediate priority is validation of the improved one-moment scheme and the emerging two-moment microphysics against real-flight contrail observations, coupled with a systematic NWP intercomparison of ISSR prediction skill across European meteorological centres. The hybrid ensemble-ML assimilation approach validated in Topic 2 requires further development before operational deployment beyond DWD.

On detection and validation

The remaining detection gap — discrimination between aged contrail cirrus and natural cirrus — requires multi-spectral or multi-angle observational data beyond current geostationary capabilities. The Meteosat Third Generation (MTG) Flexible Combined Imager offers improved spectral coverage that partially addresses this; systematic exploitation of MTG data should begin once sensor calibration is complete. Combining multiple geostationary sources — GOES, Himawari, and Meteosat — offers a practical near-term path to improved coverage and cross-validation.

On trajectory optimisation and policy

The research tools developed in BeCoM are ready for operational testing, with validation drawn from the non-CO_2 MRV data now being collected and from ongoing contrail avoidance flight trials. Given remaining modelling uncertainties, the risk assessments and safeguards that should precede any pricing instrument can be developed in parallel with this testing rather than after it. Incentive-based approaches can precede full pricing, allowing operational experience and MRV evidence to accumulate while the underlying methodologies mature. Dedicated avoidance trials conducted with commercial operators would supply the operational evidence that simulation alone cannot.

The research agenda assembled across these four areas constitutes a coherent programme with a defined endpoint: the scientific, operational, and regulatory conditions for a first generation of non-CO_2 mitigation measures that are technically credible, economically proportionate, and internationally coordinated. BeCoM has advanced this agenda substantially. The gaps that remain — observational network expansion, NWP intercomparison and satellite data integration, real-flight validation, and network-scale policy simulation — are not open-ended questions. They are bounded and addressable within a defined research horizon, and are well placed to be carried forward on the foundations this programme has established.

4. Policy recommendations

The following recommendations draw on the cross-cutting findings from Topics 1–5 and the research priorities identified above. They are organised by decision horizon, reflecting the increasing importance of timescale considerations in contrail mitigation policy:

Near-term — ahead of 2027 non-CO_2 legislative proposal assessment

R1. Launch a coordinated North Atlantic contrail avoidance pilot through the North Atlantic Systems Planning Group (NATSPG) and ICAO CAEP, using the Organised Track System as the operational framework. Design it explicitly as an evidence-generation exercise with agreed metrics, independent scientific evaluation, and pre-specified success criteria. This is the missing empirical link between modelling and operational deployment.

R2. Enable structured data sharing between airlines, meteorological services, and researchers using the non-CO_2 MRV data collected since January 2025. This requires a data governance framework — not new collection — and would immediately improve validation study quality and policy impact assessments.

R3. Commission risk assessments for the non-CO_2 climate agents proposed for inclusion in any pricing instrument. Assessments would quantify the probability that CO_2e-priced rerouting delivers net climate benefit on average, and confirm that, while individual flights may generate adverse effects, the scheme does not systematically incentivise counter-productive behaviour.

R4. Promote routine atmospheric humidity reporting from commercial aircraft operating in European airspace by, for example, leveraging existing AMDAR architecture and potentially expanding the IAGOS programme, and targeting routes identified as providing adequate spatial coverage for improved ISSR prediction.

Medium-term — 2027–2030 legislative window

R5. A phased approach to non-CO_2 pricing — combining gradual increases in the accounted CO_2e share with uncertainty-adjusted accounting keyed to forecast confidence levels — would reduce the risk of unintended rerouting while maintaining a meaningful mitigation signal as scientific precision improves. The remaining four design parameters identified in Topic 5 (carbon price level, climate metric, geographic scope, and agent selection) involve policy value judgements that cannot be determined by science alone.

Enabling research conditions

R6. Conduct an intercomparison of NWP models for ISSR prediction, building on the DWD methodological framework developed within BeCoM. The intercomparison should assess forecast skill against a common observational benchmark and identify which NWP configurations deliver the best performance for contrail formation prediction specifically.

R7. Extend the non-CO_2 policy simulation framework from representative route studies to full European network scale — including uncertainties, discrete-choice demand modelling, and multi-airline competitive dynamics— to underpin the future impact assessment with robust cost-distribution and network-restructuring analysis.

R8. Initiate coordinated flight trial campaigns under operational conditions to validate contrail avoidance modelling against real-flight observations. Trial design should specify detection of both avoided contrails and predicted contrails that actually formed — a distinction that current post-flight analysis frameworks have not addressed systematically.

BeCoM D6.4 — Annexes

Annex A. Stakeholder engagement — thematic synthesis

Structured engagement with airlines, air navigation service providers, meteorological agencies, and regulatory authorities was conducted across four dedicated workshops between February 2025 and January 2026, all conducted under the Chatham House Rule (participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed). The programme comprised: a virtual workshop with airlines (February 2025); a virtual workshop with ANSPs and meteorological services (May 2025); a virtual workshop with regulatory authorities (July 2025); and a final in-person joint workshop at TU Delft, Delft, Netherlands (January 2026) attended by over 60 participants spanning all stakeholder groups. The expanded stakeholder synthesis document is available upon request and represents views collected from stakeholders who may hold divergent perspectives; the BeCoM team has however sought to consolidate and, where possible, incorporate these, with the recognition that they are not necessarily representative of the findings of the project itself.

Annex B. BeCoM project description

B1. Horizon Europe context

BeCoM (Better Contrail Mitigation) was funded under the European Union's Horizon Europe research and innovation programme, grant agreement No. 101056885. It responded to call topic HORIZON-CL5-2021-D5-01-05: 'Greenhouse gas aviation emissions reduction technologies towards climate neutrality by 2050', under Cluster 5 (Climate, Energy and Mobility).

The specific scope of this call topic addressed the gap between scientific knowledge of aviation's non-CO_2 climate effects and the operational and regulatory tools needed to act on that knowledge. The call explicitly identified: the need to fill gaps in the understanding of non-CO_2 effects including contrails; the need to develop measurement and monitoring capabilities; and the need to develop climate-optimised trajectory planning approaches aligned with existing and potential EU and international market-based measures including the EU ETS and ICAO CORSIA. BeCoM was designed to address all three simultaneously.The project ran from June 2022 to May 2026 (48 months). Total budget: approximately €5.6 million.

B2. Consortium and advisory board

The BeCoM consortium comprised seven partners across five European countries:

- Technische Universiteit Delft (TUD, coordinator) — Netherlands
- Deutscher Wetterdienst (DWD) — Germany
- Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) — Germany
- Thales Research and Technology — France
- Centre National de la Recherche Scientifique (CNRS) — France
- ENV-ISA SAS — France
- ECATS International Association — Belgium

The advisory board comprised several organisations providing independent oversight and industry perspective: EUROCONTROL, KLM, and the German Environmental Agency (Umweltbundesamt).

B3. Project objectives O1–O6

Six formal objectives structured the BeCoM work programme:

Objective	Description	Key deliverables
O1	Enhance the routine measurement of atmospheric humidity at cruise altitude — through Raman LIDAR network deployment, AMDAR extension, and combined multi-platform observation campaigns.	D1.1 Upgraded instrumentation D1.2 Humidity analysis D1.3 Routine operations
O2	Improve the treatment of ice supersaturation in numerical weather prediction (NWP) models — through satellite data assimilation, new ice cloud microphysics, and ensemble-based uncertainty quantification of ISSR forecasts.	D2.1 Cloud measurement assimilation D2.2 Humidity observation concept D2.3 Ice cloud microphysics module

O3	Develop appropriate machine-learning algorithms for data assimilation, contrail detection, contrail classification, and quantification of uncertainties in contrail prediction — validated against empirical observations from measurements.	D3.1 Training datasets D3.2 AI algorithm specifications D3.3 Trained and validated AI algorithm D3.4 AI-based evaluation method for contrail prediction models
O4	Minimise cost impact when implementing climate-optimised trajectories — by incorporating improved contrail prediction into trajectory optimisation tools and quantifying climate and cost trade-offs under realistic operational constraints.	D4.1 ISSR prediction through flight trajectories D4.2 Mitigation potential of avoiding warming contrails
O5	Develop and evaluate non-CO_2-based measures applicable to ATM strategies for climate impact mitigation — including integration of non-CO_2 effects into the EU ETS and ICAO CORSIA, and assessment of climate-charged airspace instruments.	D5.1 Algorithmic cost functions D5.2 Effectiveness assessment of non-CO_2 policy-driven flight planning
O6	Disseminate and exploit BeCoM results to scientific, industrial, and regulatory communities — through publications, stakeholder engagement, a project website, and this document series.	D6.1 Project website D6.2 Plan for dissemination D6.3 Mid-term assessment D6.4 Distillation of outcomes D6.5 Final assessment