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Department of Aerospace Engineering

PhD Aerospace Engineering UC3M
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Current contrail modeling limitations & viable solutions

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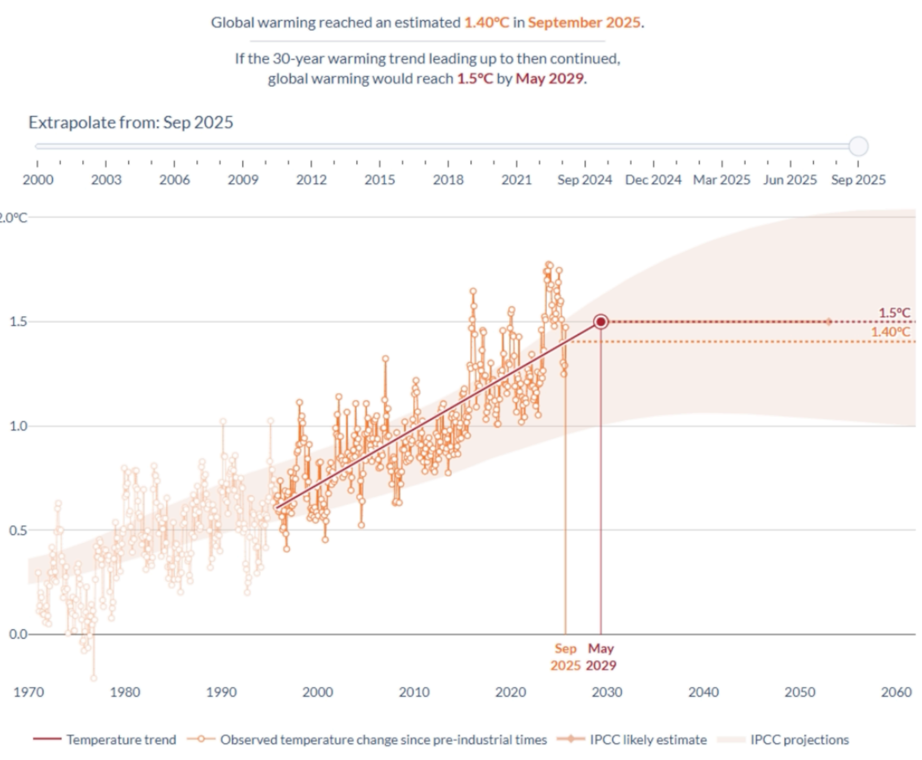
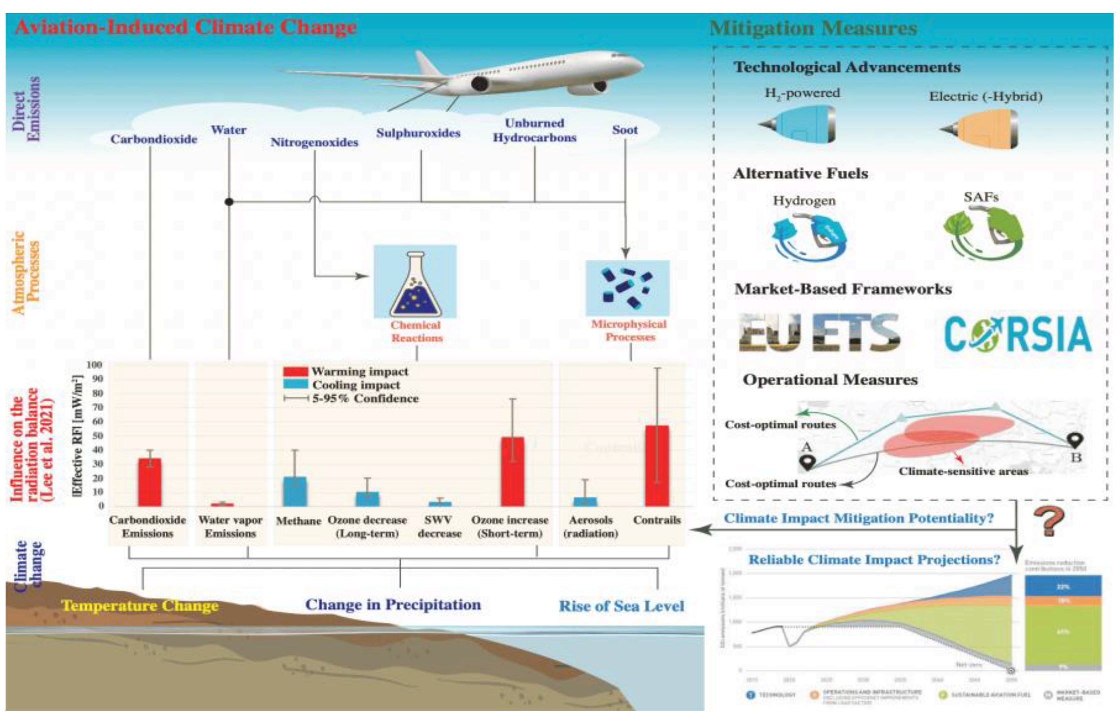
Motivation

Since the conception of the first Schmidt thermodynamic mixing problem, the contrail research has come a long way, moving from a curiosity into a serious open issue contributing **57%** of total RF. Although, challenged by the **1.5°C** heat threshold breach , to achieve EU's ambitions climate neutrality by 2050 in support of the **Paris agreement** goal, improvements across aircraft technology, operational efficiency, SAF's, and CORSIA are taking place.





State of the Art

Observational tools

⚠ Introduces fisheye distortion, horizon effects, parallax, and altitude-assumption errors when the image is reprojected onto a fixed cloud height. Variable detection based on sun angle, background brightness, aerosol haze, and cloud contamination.

⚠ Spatial footprint is limited and strongly dependent on camera location, cloud obstruction, solar illumination, viewing geometry, and local weather.
Calibration necessary

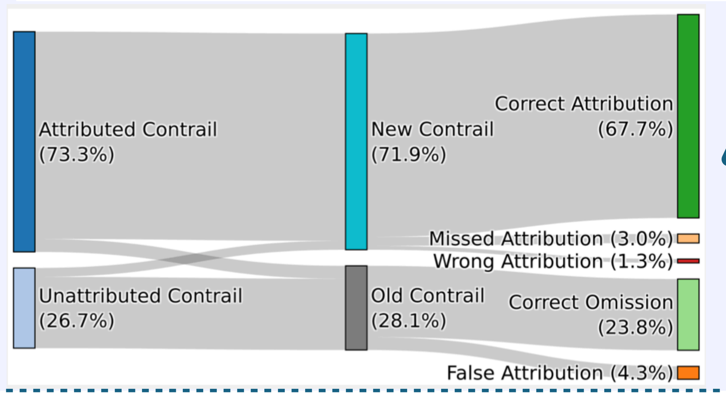
⚠ Signal is strongly affected by atmospheric water vapour and viewing angle.
Requires theoretical clear-sky correction based on local temperature, density, and humidity due to larger air mass in the horizon.

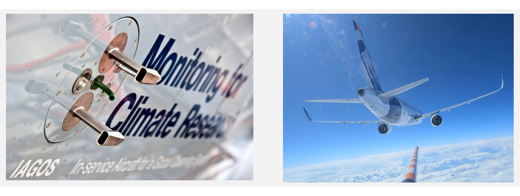
⚠ Typically provide only one observation point per geographic area per day.
- Narrow swath and sparse overpass frequency limit their ability to capture the complete formation-to-dissipation lifecycle

⚠ Coarse ~2km spacial resolution for narrow contrails.
- Cannot directly retrieve altitude, optical depth, or vertical structure without complementary sensors.

⚠ No single observation tool provides all required information at once

Sensor Type	Wide Angle Visible/SWIR	All-sky Visible	All-sky LWIR	Polar Orbit	Geostationary Satellite
Remote Sensor	Reuniwatt/Miratlas Cameras	Reuniwatt/Miratlas Cameras	Reuniwatt/Miratlas Cameras	EarthCARE (LEO), Landsat	MTG, GOES, HIMAWARI





In-Situ Measurements

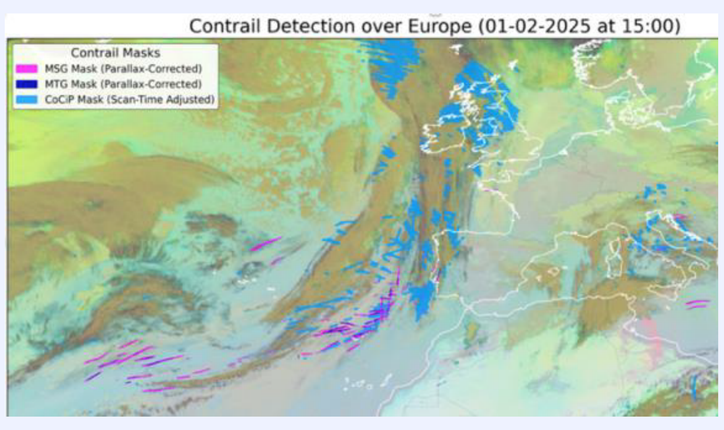
IAGOS, MOZAIC, DLR Falcon 20E
⚠ Limited in space and time, expensive to operate, and rarely coincide perfectly with the full lifecycle of individual contrail objects.

Modeling

CoCiP
Zero-dimensional Lagrangian bulk contrail-cirrus model using ODE-based plume evolution with simplified mono-disperse microphysics.

APCEMM
Two-dimensional Lagrangian plume-scale model with binned, polydisperse aerosol–ice microphysics and cross-sectional plume evolution.

MultiCon
Higher-dimensional Eulerian multi-physics contrail model using PDE-based advection–diffusion, particle growth, settling, and plume-interaction dynamics.



CoCiP enables computationally efficient trajectory-scale contrail prediction, but its 0D bulk formulation limits the representation of cross-plume structure, polydisperse microphysics, plume interaction, and spatially variable atmospheric transport.

APCEMM partially addresses these limitations through a 2D binned microphysical plume framework, but remains computationally demanding and still constrained in large-scale multi-plume interaction, along-track diffusion, turbulent settling, and long-term contrail-cirrus evolution.

MultiCon extends the modelling capability through a higher-dimensional Eulerian advection–diffusion framework with particle growth, settling, habit evolution, and plume-interaction dynamics, but remains an emerging model requiring extensive validation against multi-sensor observations and established model benchmarks.

Objectives

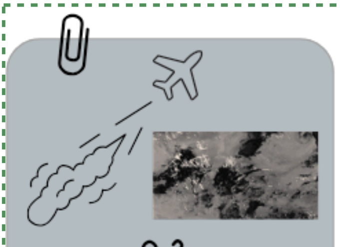
The main objective:

To address high degree of uncertainty in contrail detection and RF estimation, aligned with the O-2 and O-3 of E-CONTRAIL 2 project, and with consideration of previous/on-going work (projects E-CONTRAIL, ContrailNet, CICONIA), identify and address open gaps between different scale models, and bridge intermodel data exchange (e.g. metrics) with respect to limitations and specific properties of observations and models.

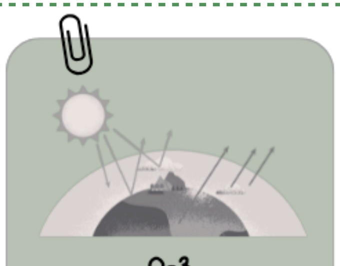
Secondly, establish level-based ground truth by building fused validation reference object from MTG/FCI (MSG), EarthCARE MSI imagery, Hi-res imagery from Reuniwatt visible all-sky cameras in combination with SkyInSight LWIR, GMN, and IAGOS / MOZAIC in-situ measurements for direct validation.

Organized into levels ground truth would cover confirmed contrail, vertically validated contrail, physically characterized contrail, and high-confidence validated contrail.

O-1
Create multi-sensor observational dataset of aircraft contrails in Europe (through the ContrailNet portal public repository), including MTG, EartCARE spectral images, LIDAR, RADAR, Visible and IR ground cameras.



O-2
Develop a physics-informed data-driven contrail detection and tracking framework that simulates contrail evolution through advection–diffusion processes and embeds the governing physics in a neural network to detect contrails in multispectral satellite imagery (namely, MTG).



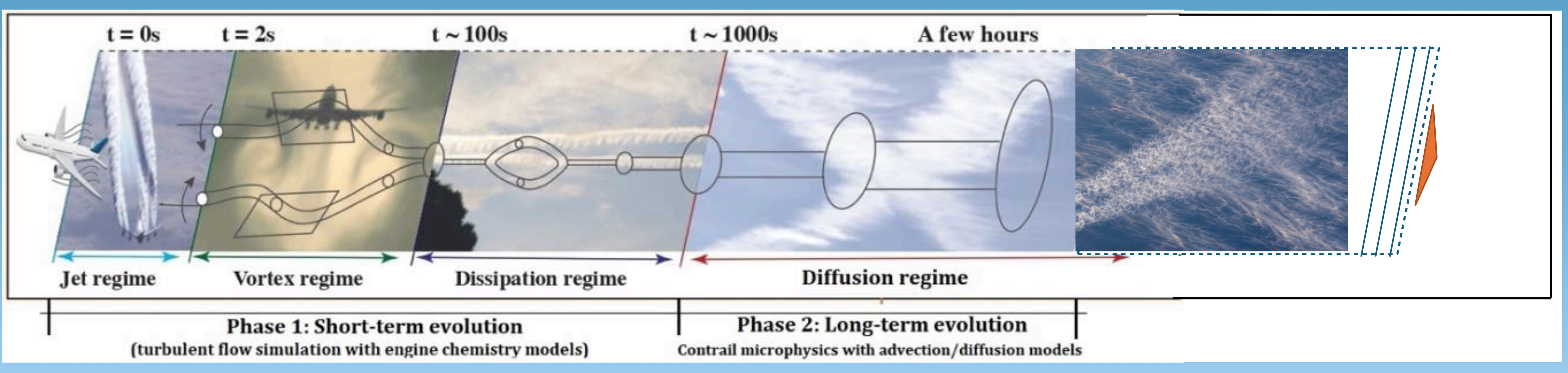
O-3
Quantify the radiative forcing of cirrus clouds using observations from geostationary satellite, low Earth orbit satellites, and ground-based imagers combined with radiative transfer modelling, and a closure scheme between measured and simulated radiances.

O-4
O-4 is to develop a dashboard for the visualization of geo-referenced detected contrails, their associated climate impacts; yet to leverage existing deep learning models for the prediction of contrail outbreaks (including their expected associated radiative forcing).

Methodology

Problem Definition

Long-term contrail tracking



- If the aircraft is not entering into SAC/ISSR region, the resulting plume may later advect into a neighboring SAC/ISSR saturated region, in which case, any emitted particles/plume remnants later contribute to an aviation-induced ice cloud after advection into a favourable ISSR?
- How can detection of mutated contrails be improved, in order to infer relational plime interaction for MultiCon model?
- Can zonal mapping algorithms compare or improve pixel-by-pixel contrail tracing?

Challenges

The central challenge is to move from pixel-level contrail detection to uncertainty-aware lifecycle attribution, where each detected AIC object is represented as a deformable, multi-source, flight-linked plume candidate with spatial, temporal, vertical, and radiative uncertainty attached.

In dense traffic, multiple flight influence zones may overlap; the algorithm must assign probabilistic, not absolute, ownership.

A **2D** zone may overlap a cloud in satellite imagery, but the plume and cloud may be at different altitudes. Lidar/radar or flight-level constraints may be insufficient.

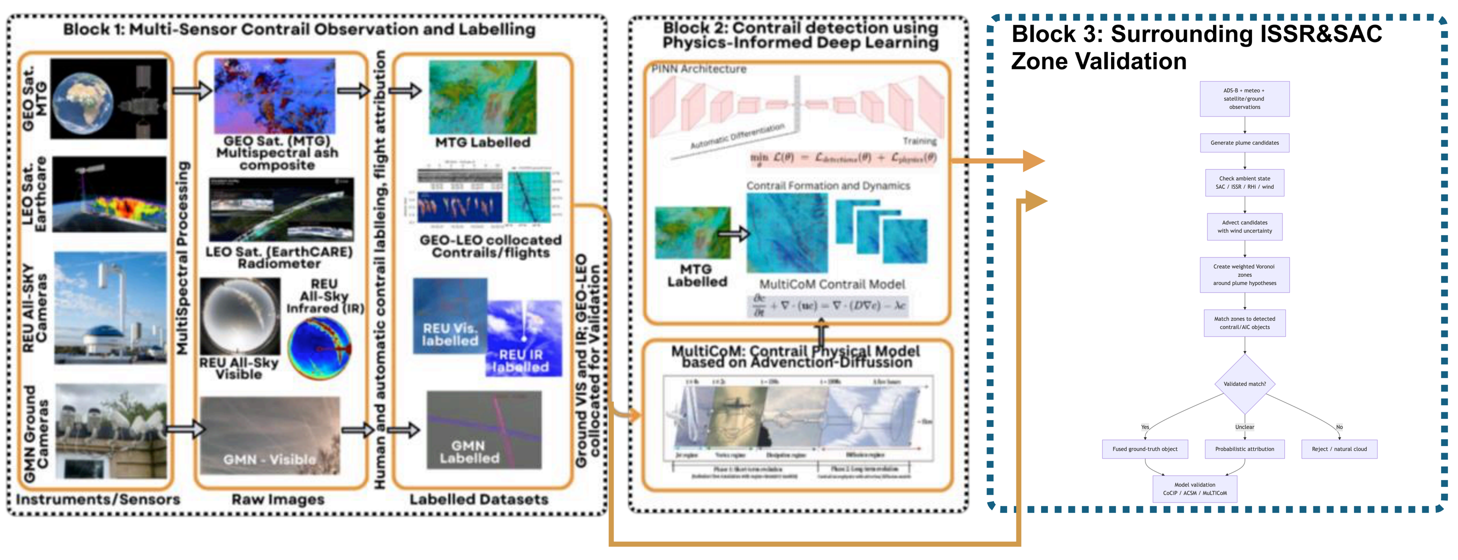
Conditions favourable for **long-lived contrails** occur mostly **inside pre-existing cirrus**, not in clear sky: about **87–90%**of long-lived-contrail conditions in Northern midlatitudes occur in **subvisible or visible clouds**, and almost **100%** in the Southeast Asian subtropics.

Note: However, for **clear sky (also subvisible cirrus)** persistent contrail, a stronger RF is foreseeable because of the radiative contrast between a "no contrail" and "contrail" sky.

Preliminary Research/Results

Multi-Stage Zone Augumented Ambient Conditions Validation

Proposed contrail validation framework. Multi-sensor observations are transformed into labelled contrail datasets, used to train physics-informed detection and MuLTICoM evolution models, and then finally, the validation block compares detected contrail/AIC objects with dynamically advected plume hypotheses and surrounding SAC/ISSR conditions using Voronoi zones, allowing ambiguous, delayed, or mutated contrails to be assessed probabilistically rather than only through pixel-by-pixel tracing.



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