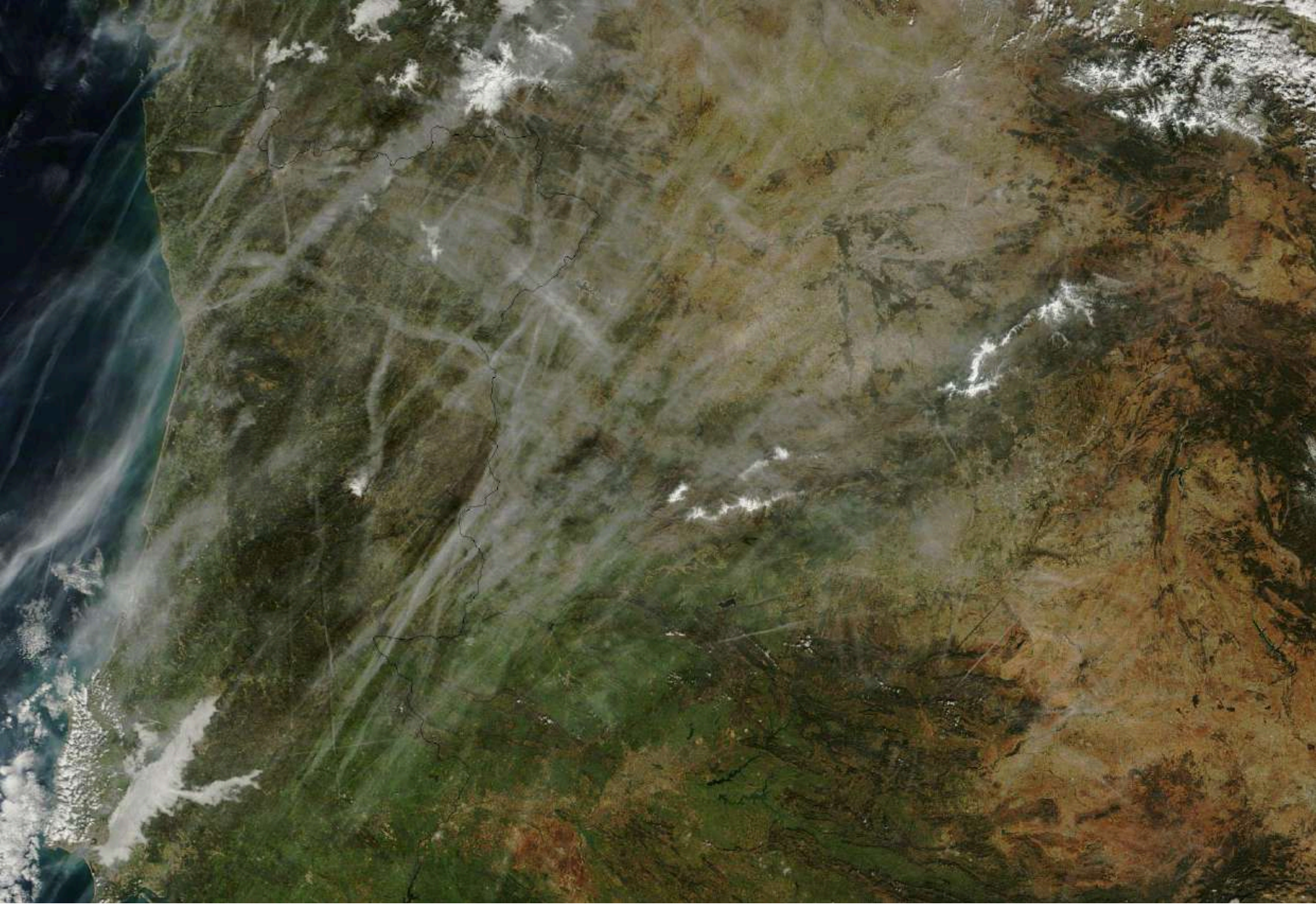

REPORT - JANUARY 2026

Managing complexity: How to scale up contrail avoidance in Europe?

Opportunities for scaling up contrail avoidance in harmony with air traffic management

Managing complexity: How to scale up contrail avoidance in Europe?

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Their inclusion here does not imply review, endorsement, or agreement with the full report. Any remaining errors and interpretations remain the authors' responsibility.

The contrail image on the title page was taken from the NASA Earth Observatory.

Executive summary

Contrail avoidance is air traffic management's biggest climate opportunity

Contrail avoidance is a key opportunity for reducing aviation's climate impact. According to some estimates, contrails represent 1-2% of global warming and will only increase as air traffic grows. Contrail avoidance involves both airlines and air traffic management, with the latter playing a key role in enabling airlines to reroute flights to avoid the warming impact of contrails. This report seeks to understand how contrail avoidance can be performed at scale **without compromising safety.** Targeting the flights with the highest contrail warming impact - usually night flights in autumn and winter - when air traffic is low would minimise disruption to the air traffic network while operating fully within existing safety constraints. **25% of European contrail warming could be addressed in autumn and winter nights, which accounted for only 10% of traffic in 2019**.

In this light, T&E recommends the following:

- Scale up contrail avoidance through **large-scale trials** that are embedded in a dedicated SESAR workstream and funded through the EU Innovation Fund and Horizon Europe. In the UK, building on the JetZero strategy, continue allocating and increasing funds for a large-scale trial in the UK airspace and for non-CO_2 research.
- Include a **dedicated climate KPI in the Single European Sky II+ and national performance schemes** that explicitly covers non-CO_2 effects, including contrails.
- Maintain the **automatic extension of the EU non-CO_2 MRV to extra-EEA flights and set up a non-CO_2 MRV for UK departure flights.**
- **Support airlines financially** when performing contrail avoidance through an incentivisation mechanism within the ETS.

Autumn and winter flights have a disproportionate contrail climate impact

Total flown distance and contrail warming by month in European airspace

Source: T&E (2025), based on Teoh et al. (2024) for the year 2019, re-run by ICL with an updated version of pycontrails (v0.54.8)

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Section 1

1. Why does contrail avoidance matter?

1.1 What is contrail avoidance?

When an aircraft burns jet fuel, it emits water vapour, soot and other particles. Sometimes, the water vapour condenses around the particles, creating ice crystals that make up contrails - the white lines we see behind planes. Most contrails are short-lived and disappear within a few minutes. However, if a plane flies through regions with very cold and humid air, contrails can stay in the atmosphere for hours and form clouds that act like a giant blanket. They trap heat that would normally escape from Earth into space, and their warming impact on the climate is estimated to be roughly as bad as that of aviation's CO_2 emissions.

Contrails are a **very concentrated problem** - less than 3% of flights generated 80% of global contrail warming in 2019. Fortunately, promising mitigation measures are currently being developed. Amongst them, one solution stands out: navigational contrail avoidance, or contrail avoidance for short. This mitigation measure consists of small adjustments to flight paths, notably minor climbs or descents, to avoid those cold and humid atmospheric areas where contrails form. Simulations and real-life tests have proven that this solution can reduce contrail formation and warming, with very limited extra fuel burn.

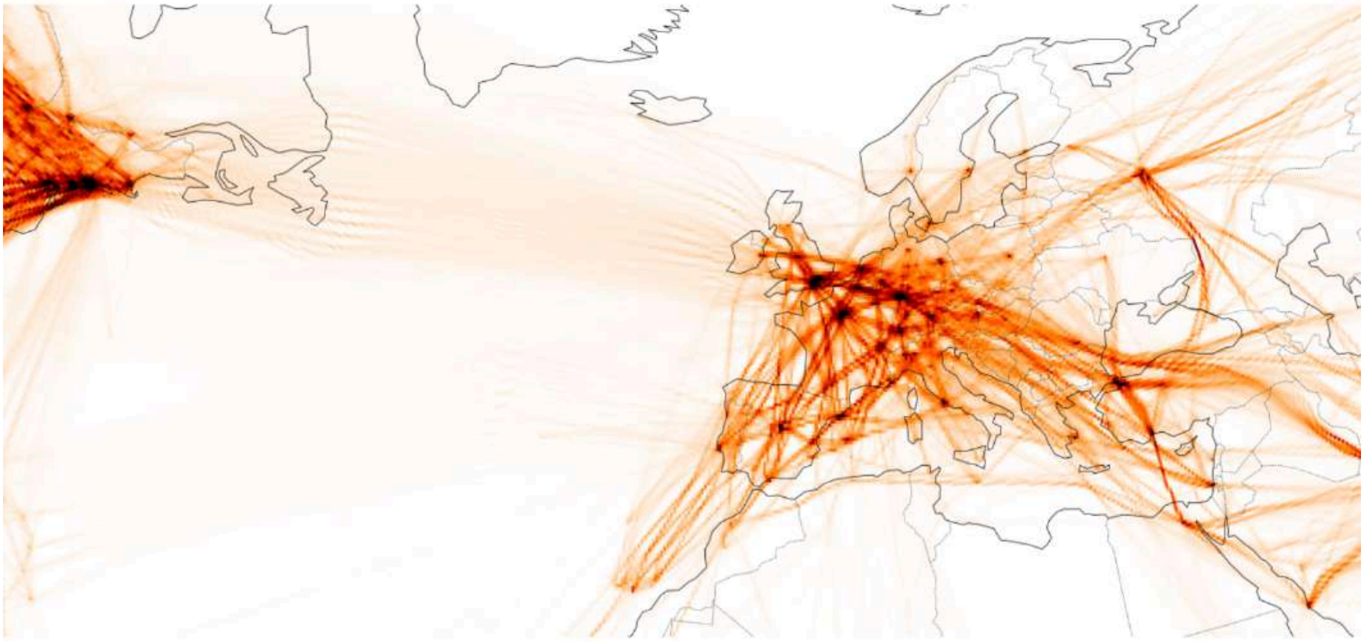
We already know enough to act. While there is uncertainty around the magnitude of the warming effect of contrails, the evidence we have today is already strong enough to justify action based on the precautionary principle: the potential harm from inaction is large, while the risk of acting prematurely is small. Addressing contrails would only require rerouting a small number of flights. This means that even in the unlikely event that contrail models were systematically wrong, the consequence would be modest: at worst a small increase in CO_2 from occasional, unnecessary flight deviations. In contrast, ignoring the problem or waiting for perfect data could lock in years of avoidable climate warming.

Contrail avoidance is one of aviation's biggest climate opportunities. In fact, contrail management could be the most effective lever to reduce aviation's climate impact until 2050. And air traffic management is at the heart of it: contrail avoidance cannot happen without air traffic management enabling airlines to reroute their flights to avoid the warming impact of contrails. Therefore, **contrails are arguably also air traffic management's biggest climate opportunity**. This report seeks to understand how contrail avoidance can be integrated into efficient air traffic management **by targeting the highest contrail warming flights when air traffic is low.**

1.2 Where to do contrail avoidance?

North Atlantic and Northern Europe have lower air traffic density than Central Europe

Traffic density over Europe and Atlantic in 2019, shown as a heatmap where darker cells correspond to more flown distance.

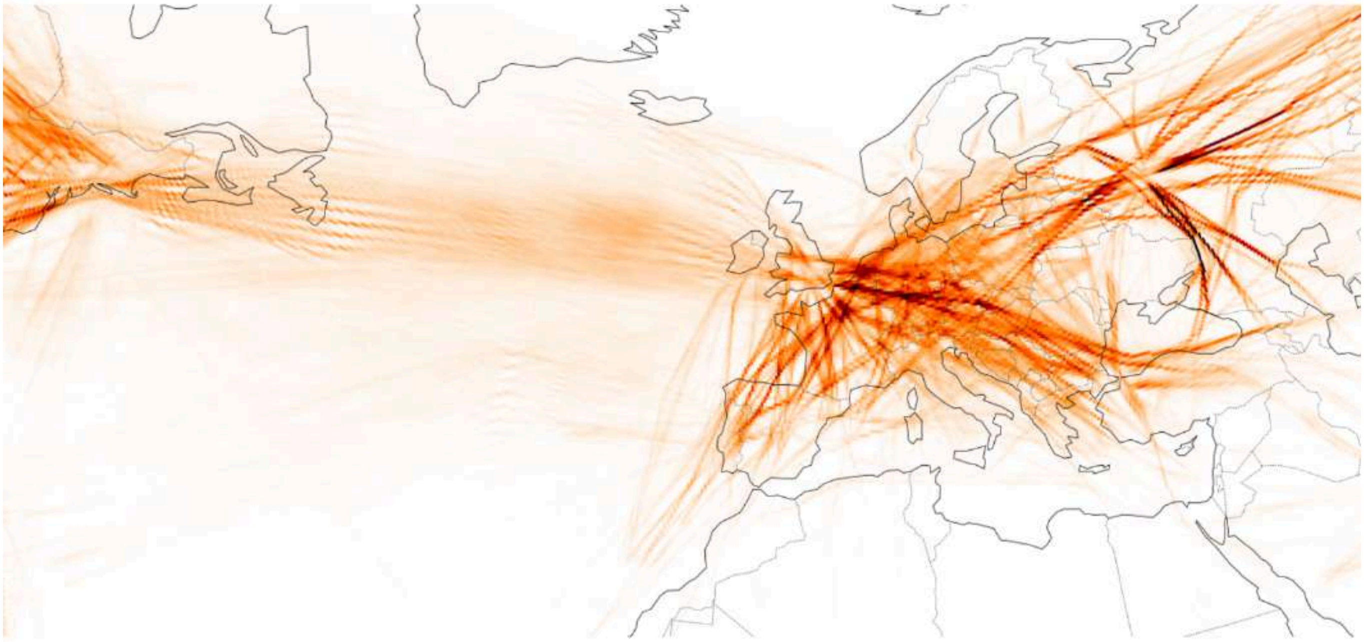


Source: T&E (2025), based on Teoh et al. (2024), re-run by ICL with an updated version of pycontrails (v0.54.8) • Using Albers equal-area projection.

The above map shows the air traffic density over Europe and the North Atlantic in 2019, covering roughly 25% of global traffic. It highlights that **air traffic densities over Central Europe are higher than over the Atlantic and Northern Europe**. The concentration over Central Europe reflects the intensity of both intra-EU traffic and long-haul connections via major European hubs. The North Atlantic corridor also shows traffic organised in structured paths, the so-called North Atlantic Tracks. These flights are long-haul connections, which are fewer in number than short-haul European flights. Accordingly, traffic densities here are lower than over continental Europe.

A large share of European contrail warming is caused over continental Europe

Contrail warming in 2019. Darker cells indicate regions where aircraft activity produced contrails that caused the most warming.



Source: T&E (2025), based on Teoh et al. (2024), re-run by ICL with an updated version of pycontrails (v0.54.8) • Using Albers equal-area projection.

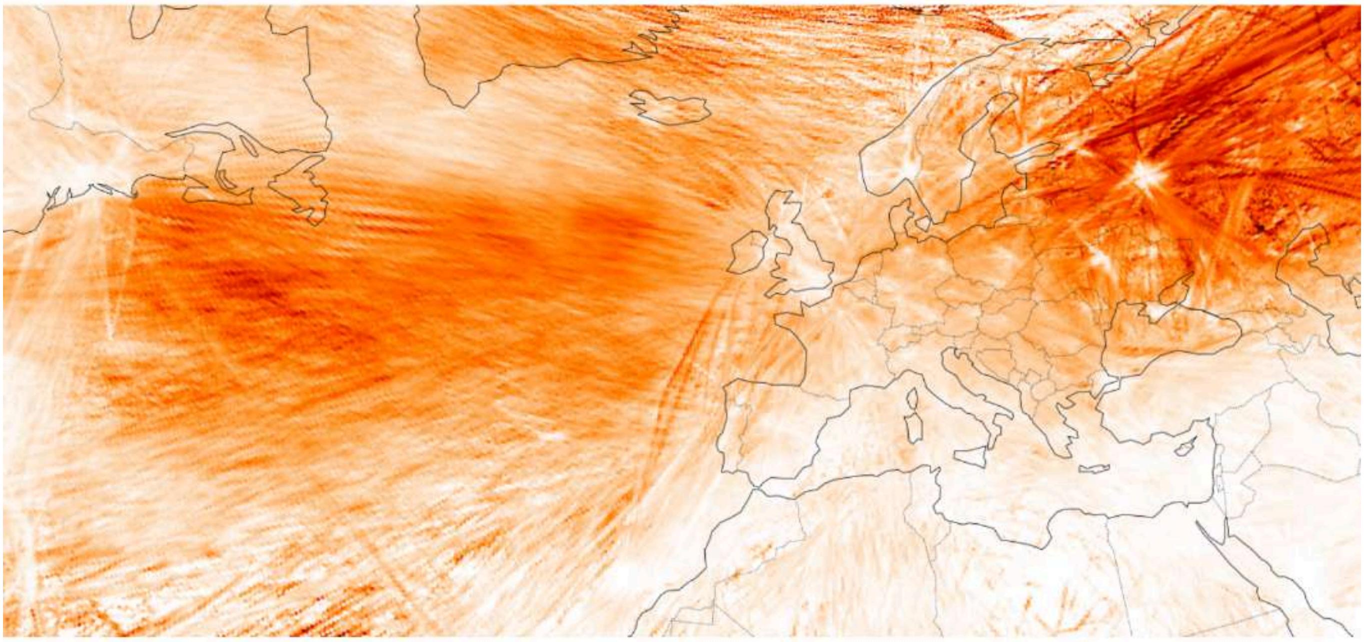
It turns out that the areas with significant air traffic over North America, the North Atlantic and Europe generally correspond to areas with high contrail warming. The above map illustrates this by showing where contrail warming is caused over Europe and the Atlantic. **Most European contrail warming originates over continental Europe and the UK**. Overall, the map covers around **45% of global contrail warming in 2019, despite representing only about 25% of global air traffic**. Of this warming, roughly 20% occurs over continental Europe and about 10% over the North Atlantic. This reflects the fact that the weather conditions at these latitudes favour contrail formation precisely where air traffic densities are high. Contrail warming over the North Atlantic is also significant despite lower air traffic densities.

The **map represents contrail warming in 2019**. Since Russia's invasion of Ukraine, aircraft have largely avoided Russian airspace, and many flights to Asia are now rerouted via the Middle East. As a result, **current contrail patterns in Eastern Europe may differ from those shown here**.

Contrail warming is quantified here and in the rest of the report using contrail energy forcing, and key methodological limitations of this report are detailed in the appendix.

Eastern Europe and North Atlantic are major contrail hotspots

Contrail warming per flown distance in 2019. Darker cells indicate where aircraft produced more warming per flown distance.

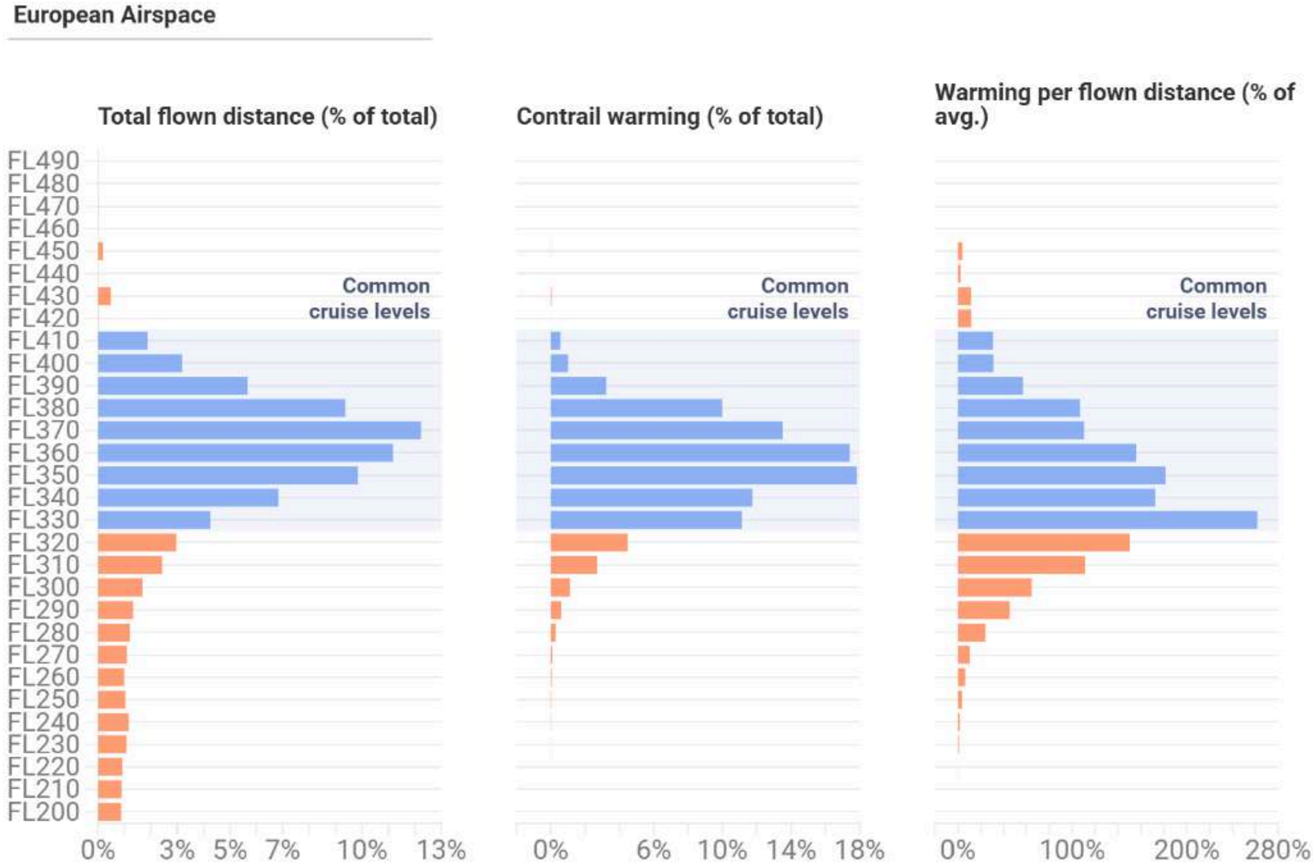


Source: T&E (2025), based on Teoh et al. (2024), re-run by ICL with an updated version of pycontrails (v0.54.8) • Using Albers equal-area projection.

Not all flights cause the same amount of contrail warming. Some regions create much stronger contrail warming than others. The above map highlights these areas: darker regions show where avoiding a contrail would bring the greatest climate benefit. **In this view,** the **North Atlantic** appears as a major **contrail hotspot**, despite lower overall traffic than Central Europe. For this reason, contrail warming over the North Atlantic receives special attention from research and is also considered for contrail avoidance trials. **Eastern and Northern Europe** show similarly elevated values - indicating potential for scaling up contrail avoidance. It is important to note that high traffic density does not preclude contrail avoidance, as trials in some of Europe's busiest airspaces demonstrate.

Contrail warming is mainly caused by flights at cruise altitudes

Total flown distance, contrail warming (both share of 2019 European total) and contrail warming per flown distance (share of 2019 European average) by flight level (FL)



Source: T&E (2025), based on Teoh et al. (2024), re-run by ICL with an updated version of pycontrails (v0.54.8)

Beyond geographical patterns, it is equally crucial to **understand at which altitudes contrails are most likely to form**. The chart above shows traffic and contrail warming by flight level (FL) in European airspace. A flight level is an altitude reference, where the number indicates the altitude in hundreds of feet (roughly 30 metres). For example, FL340 corresponds to an altitude of 34,000 feet, or around 10,200 metres.

Flight levels are based on barometric altitude: aircraft measure air pressure and convert it into an equivalent altitude using the International Standard Atmosphere. The chart highlights that most flights spend the majority of their time at cruise altitudes, typically at FL330 to FL410 corresponding to roughly 10,000 to 12,000 metres above sea level. These are also the altitudes where persistent contrails most often form and where most contrail warming originates.

The above chart shows that, in European airspace, flights at common cruise levels were responsible for more than 60% of the total flown distance and more than 80% of contrail warming in 2019. **In other words, contrail-sensitive regions frequently overlapped with the**

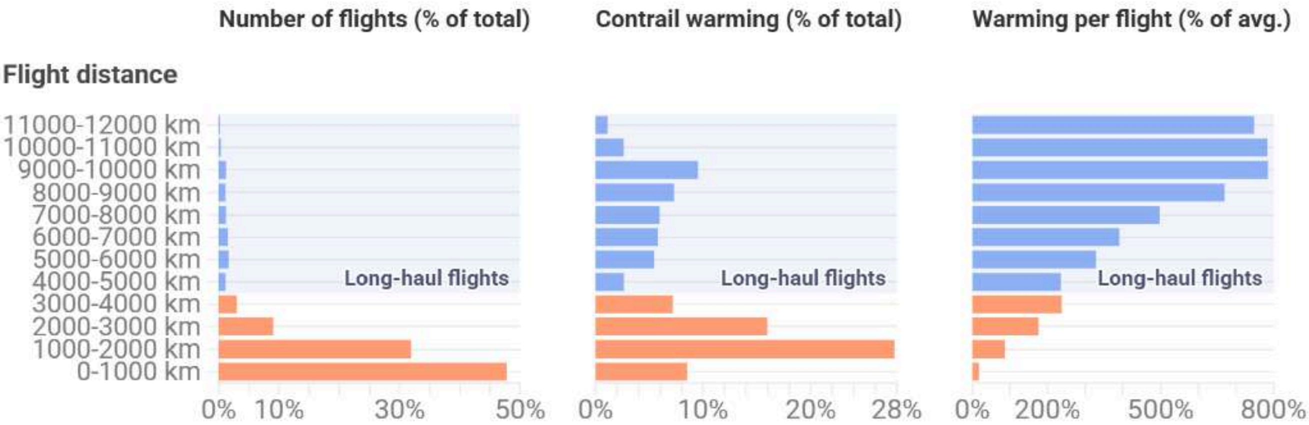
most common cruise levels, helping explain Europe's disproportionate share of global contrail warming.

Flights at FL370, for example, accounted for around 12% of total flown distance and generated more than 14% of contrail warming. Their contrail climate impact per kilometre flown was therefore roughly 110% of the European average.

Crucially, the chart shows that aircraft operating **above roughly FL370 or below roughly FL330** tend to have a significantly lower contrail climate impact on average. This vertical pattern underpins why **small altitude changes can often avoid contrail-forming regions altogether**, making vertical deviations a highly effective avoidance strategy.

Long-distance flights have an outsized contrail climate impact

Number of flights, contrail warming (both share of 2019 European total) and contrail warming per flight (share of 2019 European average) by flight distance for European departures

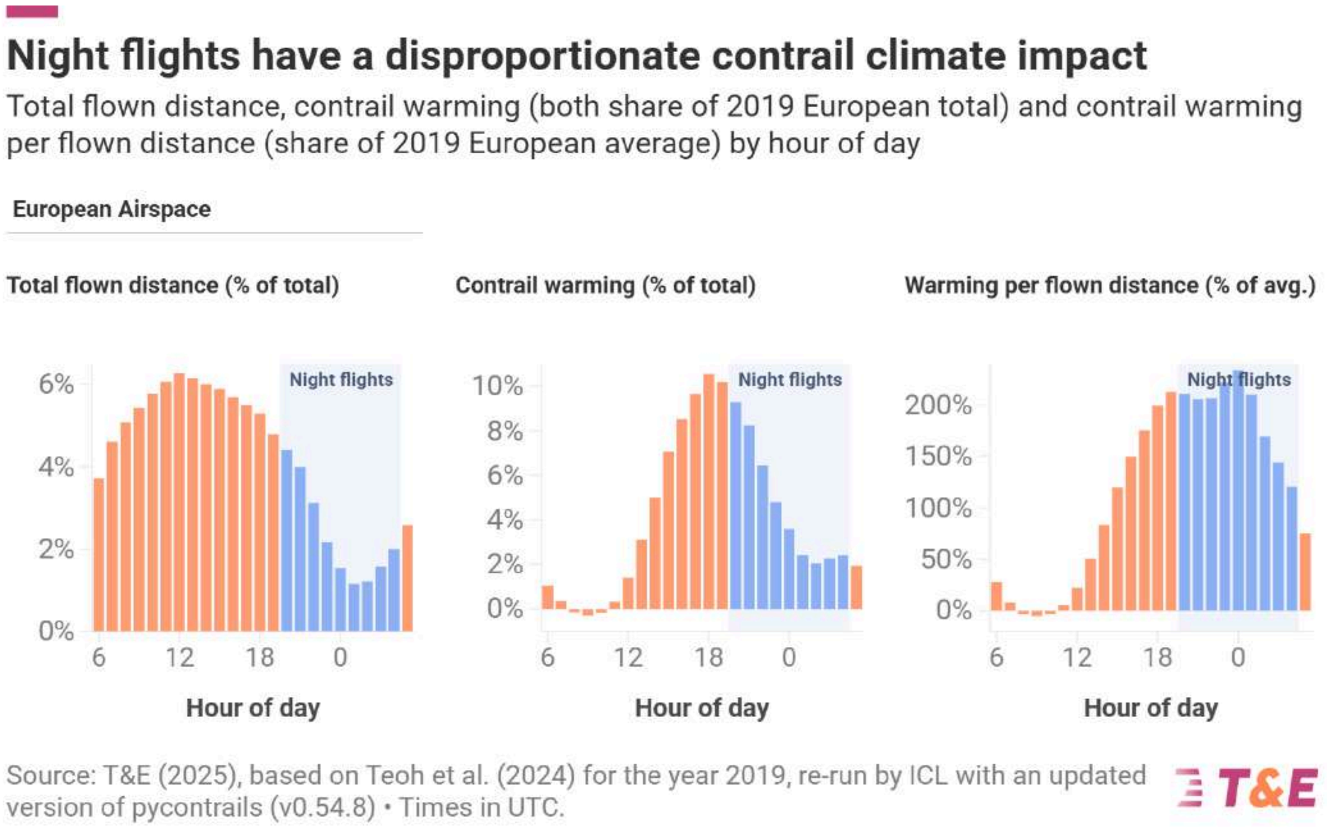


Source: T&E (2025), based on CoCiP simulation for 2019 from Teoh et al. (2024)

Finally, it is important to identify which types of flights generate the most contrail warming. The chart above shows that long-haul flights accounted for less than 10% of departures, yet they were responsible for around 40% of total contrail warming from European departures in 2019. This highlights the highly **disproportionate contrail climate impact of long-haul flights**.

This is essentially because contrail warming grows with flight distance just like CO_2 emissions. As a result, a small number of very long flights can dominate total warming. For example, flights covering 9,000 to 10,000 km represented only about 1.2% of departures, but they generated roughly 10% of contrail warming. Their contrail climate impact was therefore around 800% of the contrail climate impact of the average European departure.

1.3 When to do contrail avoidance?



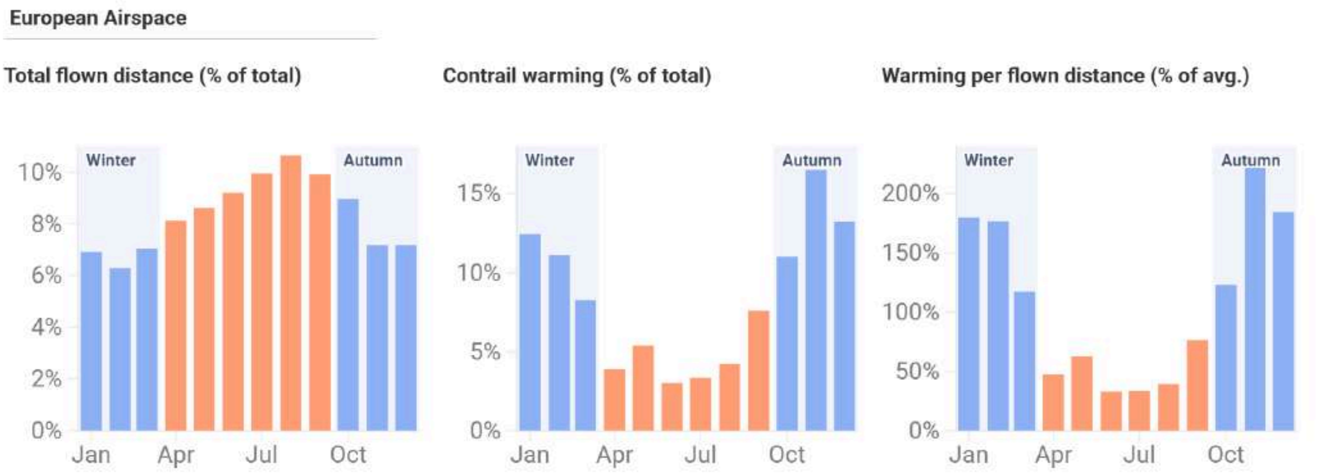
The above chart shows air traffic and contrail warming by hour of the day in European airspace. It shows that **traffic as measured by the flown distance (i.e. the number of aircraft in the air times the distance each aircraft flies) peaks around noon, whereas formation of warming contrails is highest in the evening.** What stands out is that night flights have a disproportionate contrail climate impact - the number of aircraft in European airspace is low and still, contrail warming is significant.

Flights around midnight (00:00 UTC), for example, accounted for only about 1.5% of total flown distance, yet they were responsible for more than 3% of total contrail warming. Their contrail impact per kilometre flown was therefore roughly 200% of the European average.

Overall, around 40% of European contrail warming was caused by flights from 8 pm to 4 am that accounted for 20% of traffic in 2019. This suggests that **targeting late-evening and night flights yields a disproportionately large reduction in warming**. Many warming contrails are produced at times when overall traffic is already lower, reducing congestion concerns. In addition, there is evidence that different contrail models as well as observations also provide better agreement for night flights, increasing the chance of maximum climate benefits and reducing uncertainties for avoidance at night.

Autumn and winter flights have a disproportionate contrail climate impact

Total flown distance, contrail warming (both share of 2019 European total) and contrail warming per flown distance (share of 2019 European average) by month



Source: T&E (2025), based on Teoh et al. (2024) for the year 2019, re-run by ICL with an updated version of pycontrails (v0.54.8)

Contrail avoidance at night is a clear opportunity, so what about the season? The above chart shows air traffic and contrail warming by month in European airspace. Again, there is a clear opportunity: **Flights from October to March accounted for 45% of European traffic in 2019, but for 75% of contrail warming**. This seasonal pattern holds true for other mid-latitude regions. In other words, flights in autumn and winter show significantly higher warming potential than in summer.

For example, flights in November accounted for only 7% of traffic, but for around 15% of contrail warming. Their contrail climate impact per kilometre flown was therefore more than 200% of the European average.

This means that most of the peak contrail climate impact occurs when traffic levels are lower, enabling avoidance to be done with fewer capacity constraints and supporting a seasonal mitigation strategy for scaling up contrail avoidance: **avoidance in autumn and winter is higher-impact and operationally easier than in late spring and summer.** Additionally, there is evidence that the uncertainty of the climate impact of contrails in winter may be smaller - making avoidance in winter an attractive first step towards scaling up contrail avoidance from a scientific perspective as well.

Section 2

2. How is air traffic managed?

2.1 Who decides flight routes?

Responsibility for shaping a flight route is shared among several actors, at different phases of the flight. Before departure, the **airline's operations control centre plans the flight**, selecting the route, flight levels, and timing, with the aim of optimising fuel use, flight time, weather conditions, charges, and airspace restrictions.

In parallel, the **Network Manager (i.e. EUROCONTROL) oversees flight plan processing and demand-capacity balancing.** It checks the proposed flight plans, addresses potential overloads in specific sectors, and assigns departure slots where needed. The Network Manager may also propose network-level measures such as altitude restrictions or reroutes to maintain overall traffic flow.

During the flight, air navigation service providers (ANSPs) manage the aircraft's movements. Area control centres (ACCs), operated by entities such as NATS (UK), DFS (Germany), DSNA (France), ENAIRE (Spain) or MUAC (Belgium, Netherlands, Luxembourg, and North-West Germany), manage climbing, descending and en-route traffic. Controllers are responsible for maintaining safe separation and may issue tactical instructions like altitude changes or route changes to keep traffic flowing.

Pilots are responsible for executing the approved route. They may also request changes mid-flight when conditions such as turbulence, weather or fuel efficiency justify or require a deviation.

At either end of the **journey, airports and local ATC units manage runway use and sequencing of departures and arrivals**.

Military airspace managers can release or restrict specific zones, which can in turn affect the routing options available to civil traffic.

The role of the Single European Sky initiative

The **Single European Sky (SES) initiative**, established through the SES legislative package in 2004, plays a significant role in how flights are planned. SES aims to **de-fragment European airspace**, which was historically segmented by national borders, to make flight paths more direct. This allows airlines to plan routes closer to the shortest distance or the most economically efficient trajectory, thereby reducing fuel burn and environmental impact.

The SES underwent the SES II reform in 2009. The SES II introduced a **performance scheme** that formally assesses the efficiency of both the Network Manager and the ANSPs. It uses **Key Performance Indicators (KPIs)** across four main areas:

- **Safety:** The primary objective.
- **Capacity:** The ability to handle air traffic volumes (e.g., measuring delays).
- **Cost-Efficiency:** The cost of air navigation services for users.
- **Environment:** Measured primarily by **horizontal flight efficiency** (the extent to which the actual flight path deviates from the shortest route).

In practice, the cost and environmental KPIs mean that flights today **are mostly cost-optimised and not climate-optimised**. This is also true for airlines, which plan cost-optimised trajectories as opposed to fuel-optimised or climate-optimised.

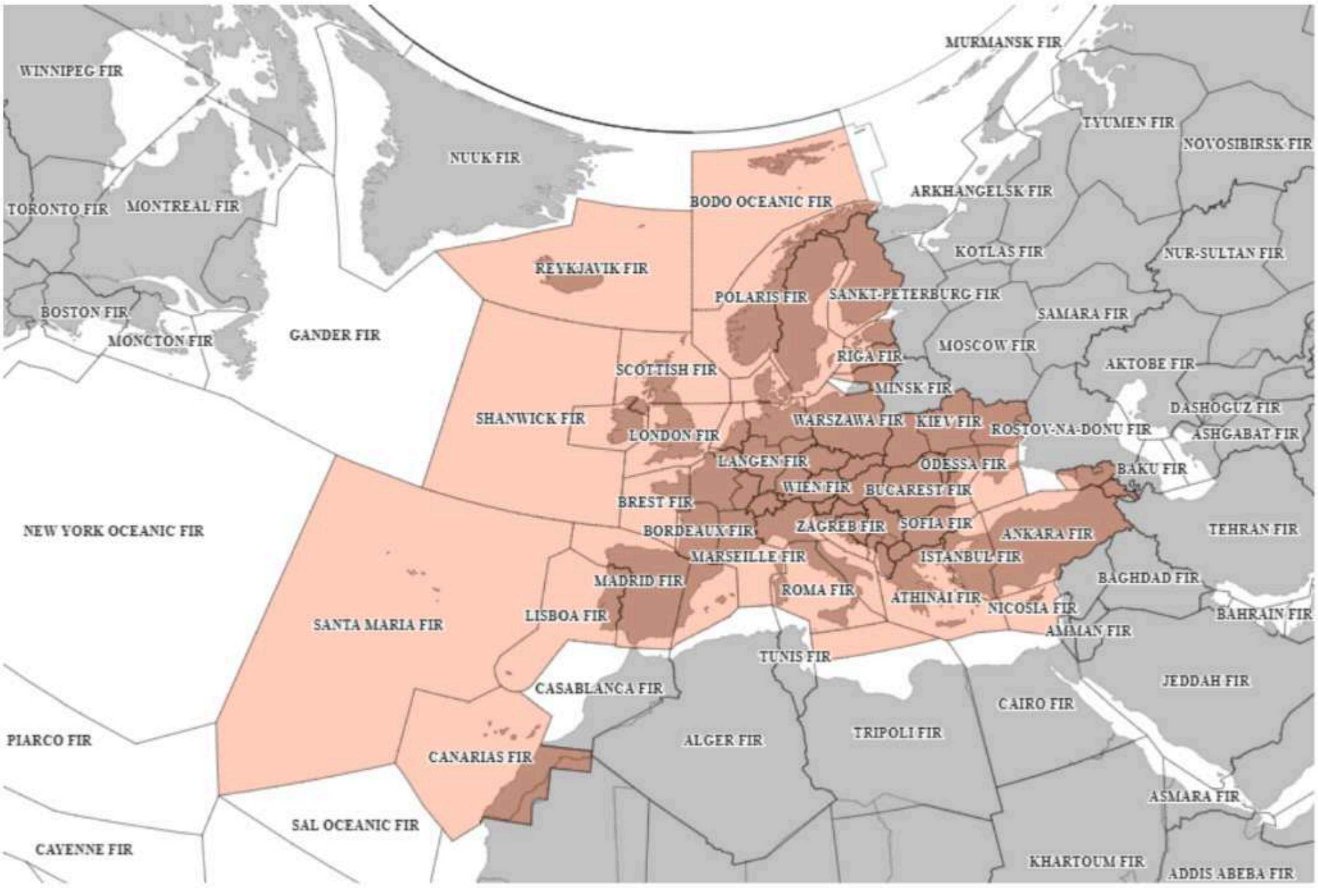
Policy recommendation

Following the SES 2+ reform adopted in 2024, there should be a dedicated **climate KPI in EU and national performance schemes** that explicitly covers non-CO_2 effects, including contrails, so that climate performance becomes a core objective for ATM, and no longer only measures CO_2 burn. Studies on a dedicated climate KPI should happen as early as 2026 to ensure the Performance Indicator (PI) is included in the next reference period of the SES - RP5, starting in 2029, gradually becoming a KPI for ANSPs.

2.2 How is Europe's airspace organised?

Eurocontrol airspace stretches beyond continental Europe

Lower flight information regions (FIRs) - Eurocontrol FIRs in orange



Source: T&E (2025), based on Eurocontrol and Open Aviation • Using Albers equal-area projection

Europe's skies are divided into a structured hierarchy designed to ensure the safe and efficient management of air traffic. At the highest level, the airspace is split into Flight Information Regions (FIRs). Each FIR covers a defined portion of national or multinational airspace and is managed by one or several designated ANSP(s). These regions are the basic building blocks of the air traffic control system. In the context of this report, we refer to the ensemble of all EUROCONTROL FIRs (orange in the above map) as *European airspace*.

Within each FIR, responsibility is handed over to one or more Area Control Centres (ACCs), which are responsible for managing aircraft as they transit through en-route airspace. Each ACC oversees a number of smaller subdivisions called sectors.

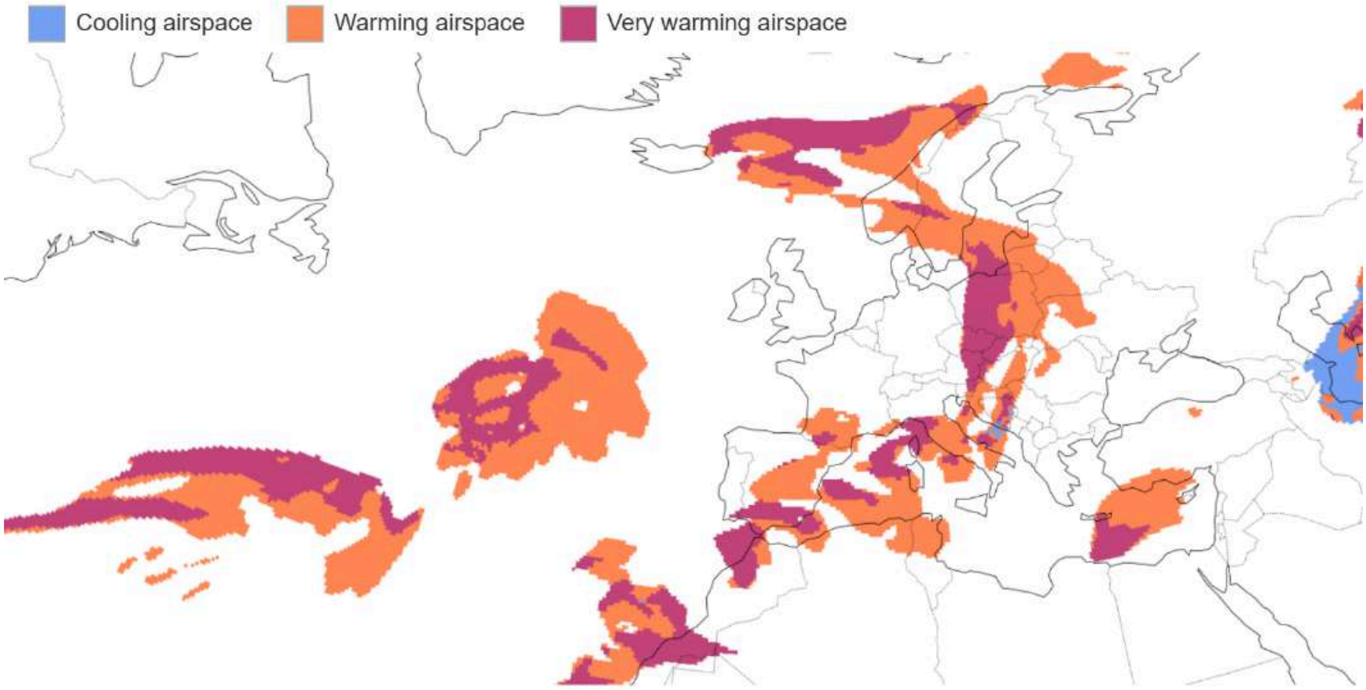
Sectors are the operational units of air traffic control. Each one handles a defined volume of airspace and is staffed by a team of controllers who monitor and direct aircraft using radar, for instance. Sectors are structured vertically and horizontally to reflect traffic flows and controller workload. In busy areas, airspace is sliced into multiple vertical levels to allow for more efficient handling of climb, cruise and descent phases.

The configuration of sectors is not static. During peak periods, sectors can be split into smaller units to spread the workload across more controllers. At night or in quiet regions, sectors may be merged to reduce staffing requirements. Sector design also considers navigational complexity, including the density of crossing traffic, the volume of altitude changes, and proximity to restricted or military airspace. This is also one of the reasons why low air traffic density does not necessarily imply low controller workload.

2.3 How to avoid contrails?

Persistent contrail regions can stretch across hundreds of kilometers

Persistent contrail regions on flight level 360 at midnight on 01/01/2024



Source: T&E (2025), based on gridded CoCiP data for Airbus A320 from contrails.org • Using Albers equal-area projection. "Very warming" indicates airspace with contrail radiative forcing of at least 5×10^8 J m^{-1} per flight distance. T&E

The map above illustrates that contrail-sensitive regions can extend over several hundred kilometres horizontally. These are the layers of cold, moist air in which persistent, warming contrails are most likely to form. The core objective of contrail avoidance is therefore intuitive: **minimise the distance an aircraft spends inside such regions while also keeping the additional fuel burn low**. This is because the warming impact of a flight generally depends on the distance flown through the contrail-sensitive airspace. An aircraft traversing roughly 600 km of "very warming" airspace as indicated in the map can generate enough contrail warming to place it among the 5% of European departures responsible for about 80% of total contrail warming in 2019. At the extreme, the most warming flights may form persistent contrails for many thousands of kilometres along their route.

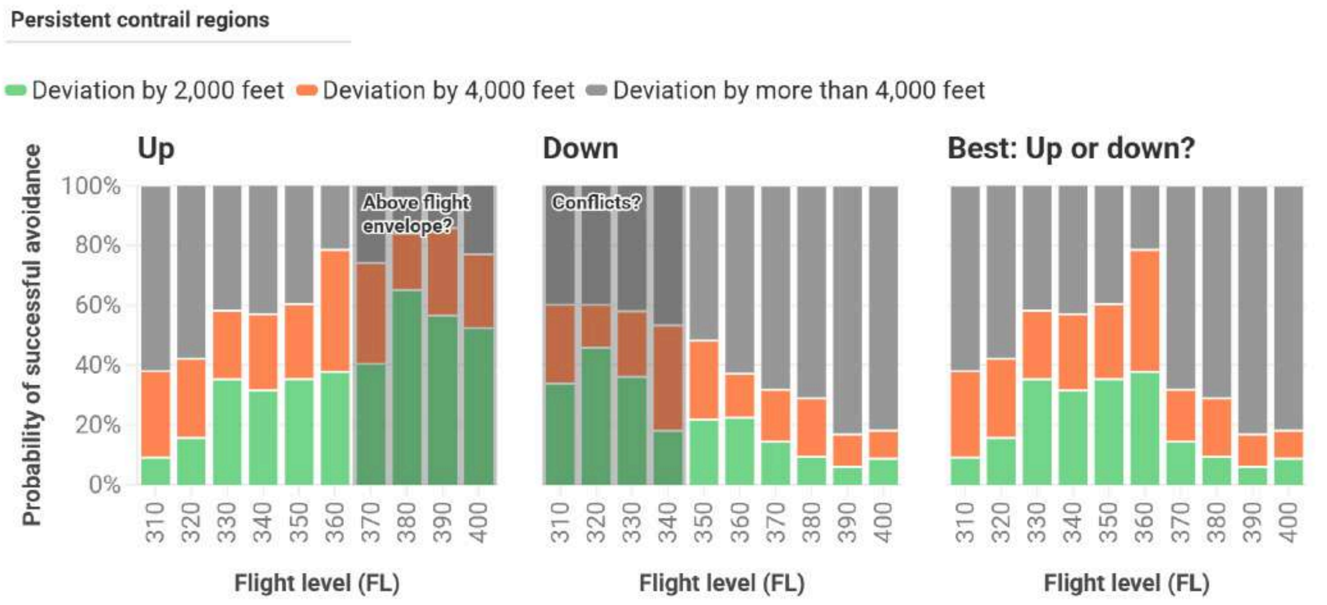
Reducing the distance flown through contrail-sensitive airspace can be achieved in three ways:

- **Lateral deviations**, where the aircraft flies around the region horizontally;
- **Vertical deviations**, where it climbs above or descends below the contrail-forming layer;
- **Hybrid deviations**, combining both small horizontal and vertical adjustments.

Any of these strategies require coordination among ATM stakeholders, as they all constitute changes to the planned flight trajectory. However, because contrail-sensitive regions are typically limited in depth and because lateral manoeuvres can add significant distance or route complexity, **vertical deviations are often operationally the simplest option**. Additionally, they can often reduce contrails at [minimal additional fuel burn](#).

Many contrails can be avoided through small vertical deviations

Probability of successful contrail avoidance through vertical deviation over Europe, North America, and the North Atlantic



Source: T&E (2025), based on gridded CoCiP data for Airbus A320 from contrails.org • Likelihoods are based on the annual average area occupied by contrail-sensitive regions and do not reflect actual traffic patterns.

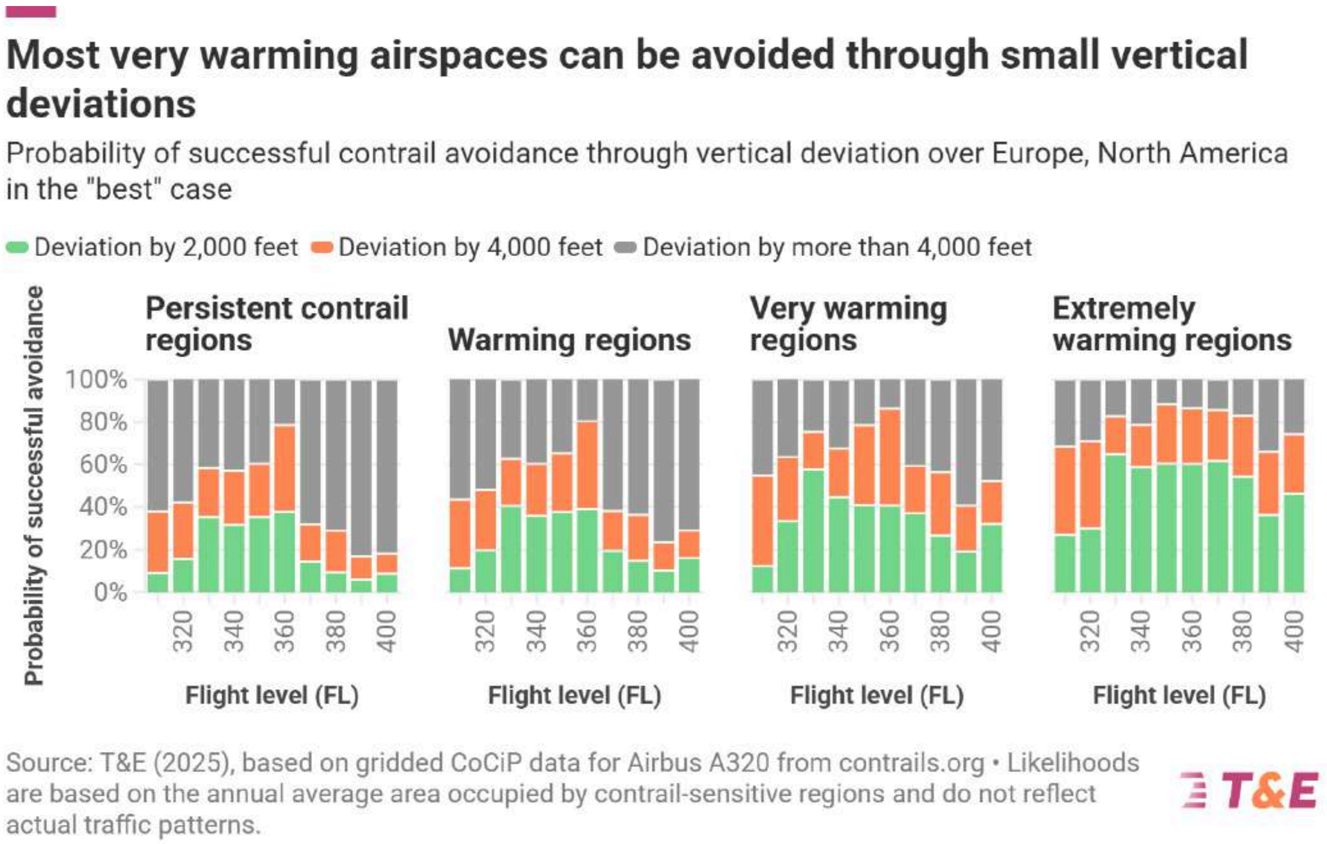
The fact that many contrails can be avoided with a vertical deviation raises the question of **how large a change in altitude is actually needed**. The above chart shows how likely a vertical manoeuvre is to successfully steer an aircraft clear of a contrail-sensitive region at different flight levels. For each altitude, it displays three options: climbing, descending, or choosing the optimum of the two, assuming climbs below FL350 and descents above FL360. The chart highlights that **persistent contrails can often be avoided with relatively modest vertical deviations.**

At FL350, for example, climbing by 2,000 feet avoids a persistent contrail region in about 35% of cases, while climbing by 4,000 feet increases this to around 60%. A descent of 4,000 feet also avoids contrails in roughly 50% of cases.

Overall, this shows that a vertical deviation of 2,000 feet (around 600 metres) is often sufficient, while in other cases a 4,000-foot deviation (around 1,200 metres) is needed to avoid contrails. These steps align with aviation's standard separation rules: in Europe **eastbound aircraft fly on odd flight levels** such as FL310, FL330, FL350 and westbound aircraft fly on even flight levels FL320, FL340, FL360 etc. This is why vertical deviations typically come in increments of two or more flight-level steps. Note that current **weather forecasts tend to overestimate the vertical thickness of contrail-sensitive regions**. Therefore, as forecasts improve, the required vertical deviations for contrail avoidance will likely become smaller.

However, the chart also highlights that **climbing or descending may not always be a viable option**. Commercial aircraft operate within a so-called **flight envelope specified by the altitudes and other conditions in which an aircraft can be safely operated.** Most aircraft cannot safely cruise above a certain altitude which is often around **FL390 to FL410**, depending on aircraft weight, temperature, and performance.

While the chart extends to FL400 and suggests that climbing to levels such as FL420 or FL440 could theoretically avoid some ISSRs, these altitudes lie **beyond the operational ceiling of most airliners**. In such cases, the only practical vertical avoidance manoeuvre is to **descend to a lower flight level**. This constraint is particularly relevant for long-haul aircraft already operating near their performance ceiling during parts of the flight. In addition, descending below typical cruise altitudes **may interfere with normal climb and descent phases of other aircraft.**

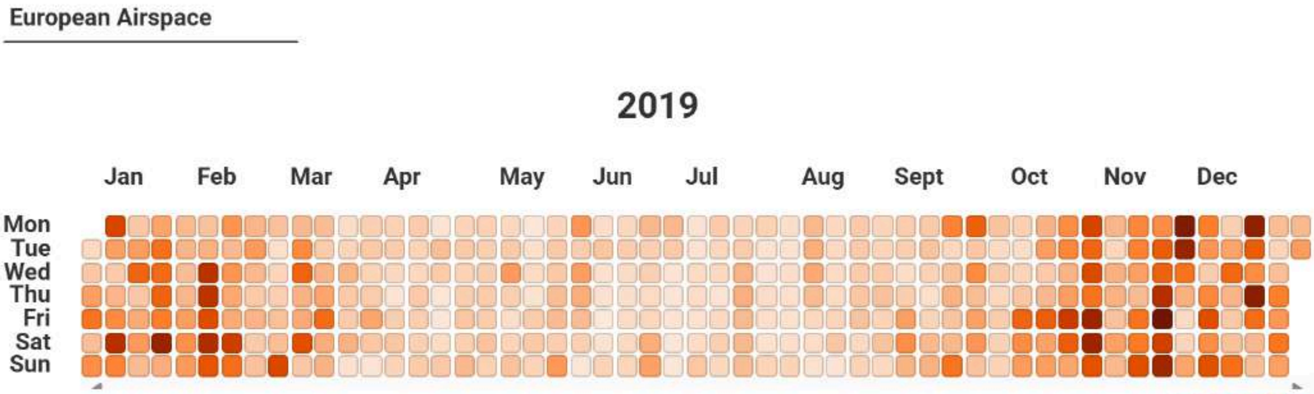


While persistent contrail regions cannot always be avoided with vertical deviations of 2,000–4,000 feet, especially when taking into account typical flight envelopes, targeted contrail avoidance can rely on modest vertical deviations much more frequently. The above chart shows that **increasingly warming contrail-sensitive regions are easier to avoid**, with most very warming and extremely warming regions requiring only small altitude changes.

In practice, **vertical deviations can be implemented in several ways**: delaying the climb to the planned cruise altitude, initiating an earlier descent, maintaining a lower cruise level for a segment of the flight, or climbing to a slightly higher level when aircraft performance allows. Which option is chosen depends on aircraft capabilities, weather conditions, and the capacity and complexity of the surrounding airspace. In the end, the air traffic management system determines whether such deviations can be safely accommodated. There may also be differences depending on whether the airspace in question is oceanic or continental: **Over the North Atlantic, lateral deviations in the form of switching to a different North Atlantic track may be preferable to vertical deviations**, for example.

Performing contrail avoidance only a few weeks a year could already have significant climate benefits

Contrail warming per day caused by flights in airspace. Darker cells indicate days where aircraft activity produced contrails that caused the most warming.



Source: T&E, based on Teoh et al. (2024) for the year 2019

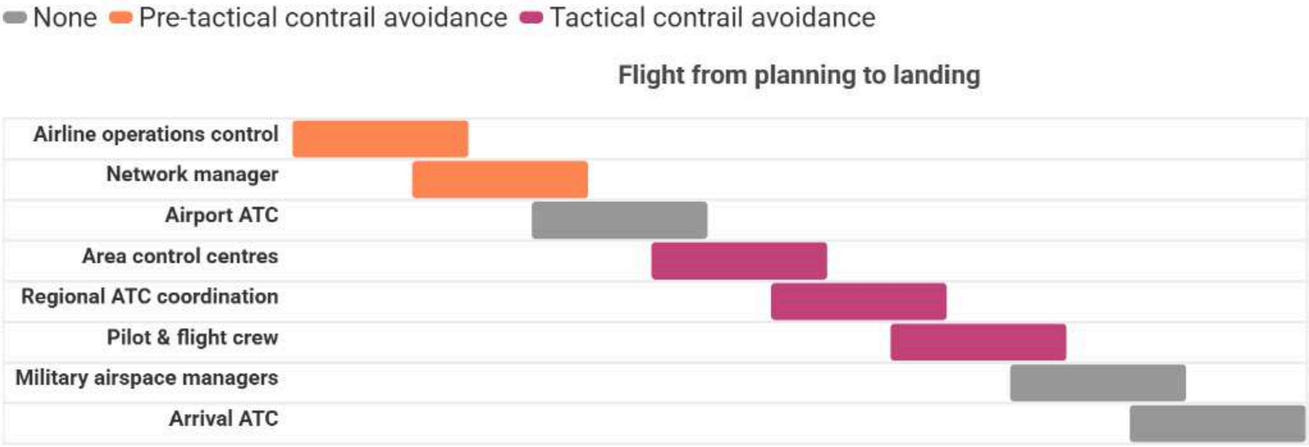
In terms of **how often contrail avoidance is required**, it is important to highlight that contrail warming is highly clustered in time. The above chart shows the contrail warming caused per day in European airspace (for more airspaces, please consult the interactive charts here). Many days in autumn and winter exhibit little or no contrail warming, while a small number of "big-hit days" account for a disproportionate share of the total impact.

This pattern is even more striking in many FIRs: 80% of contrail warming is caused during less than 10% or even 5% of the hours of the year. This means that **the bulk of contrail avoidance can be performed in the equivalent of a few weeks a year - contrail avoidance can be effective even if applied only in targeted windows**.

This has important operational implications. **ANSPs and airlines are unlikely to face a constant daily workload from contrail mitigation**. Instead, they will encounter sporadic periods of higher activity, during which some days require adjustments to only a limited number of flights, while a smaller number of days may require more extensive action. This highlights the **need for having integrated planning tools that allow the prioritisation of the contrail avoidance manoeuvres with the highest climate benefits** and minimum impact on air traffic management.

2.4 When can avoidance happen?

Contrail mitigation measures may be applied either during flight planning or via in-flight trajectory adjustments



Source: T&E • Responsibilities may overlap across actors and phases. The diagram highlights the primary role in contrail avoidance.

Planning and performing contrail avoidance can happen at different points in the operational timeline: **pre-tactical** planning, which takes place before departure, **tactical** decision-making during the flight itself, or a combination of both. It is worth noting that airlines and ANSPs may apply the terms “pre-tactical” and “tactical” differently. For example, a flight after take-off may still be considered “pre-tactical” by an ANSP if it has not yet entered that provider’s airspace. In this report, however, we use the definition that **pre-tactical avoidance refers exclusively to actions taken before take-off**.

2.4.1 What is pre-tactical avoidance?

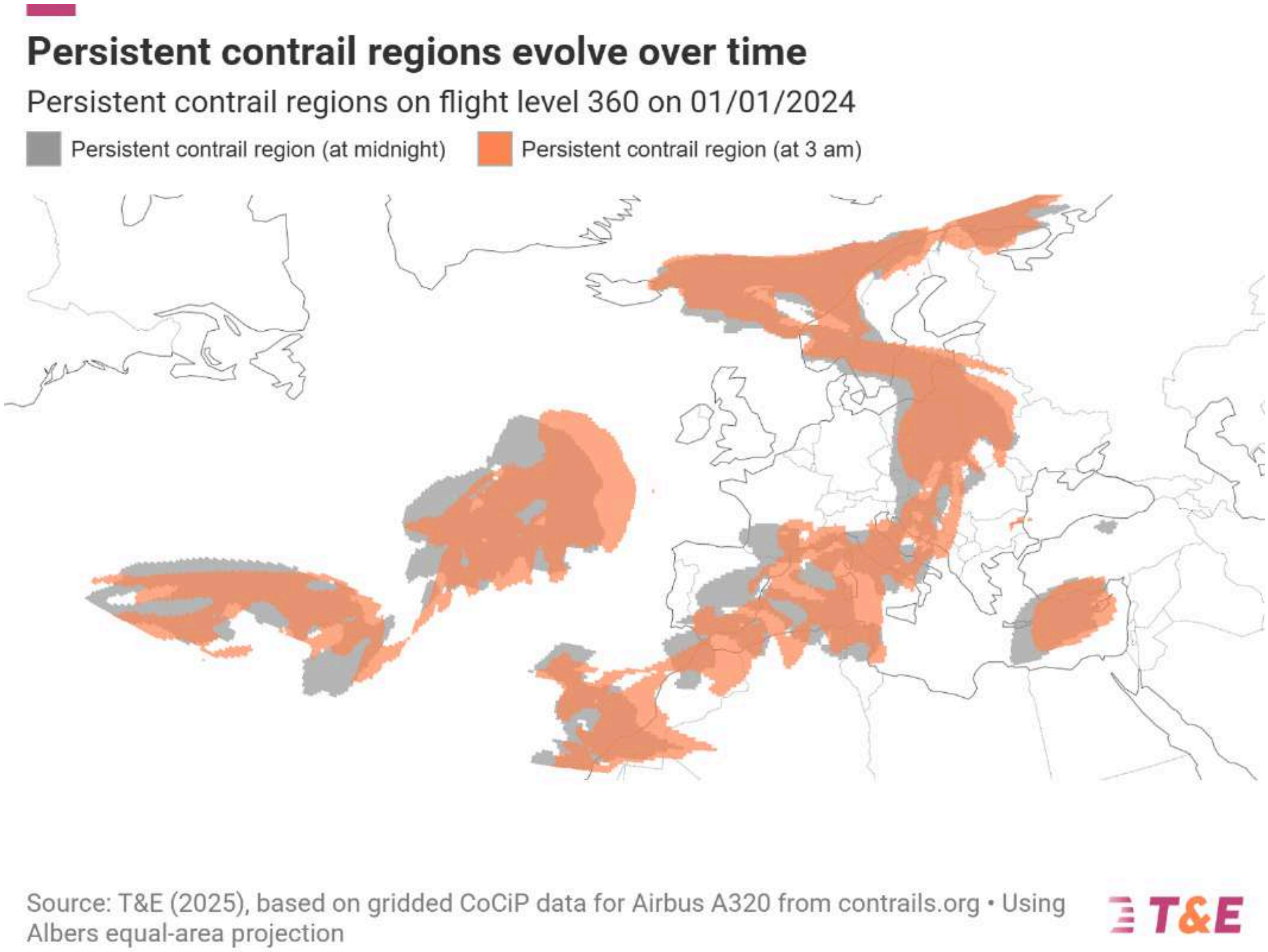
Many contrails can be avoided before the flight ever takes off. Airline dispatchers would **adjust flight plans to avoid contrail-forming regions** when the climate benefit is high and the operational cost is low. This could involve minor changes to routing, requested flight level, or departure timing. At the network level, the Network Manager would manage these requests to reduce contrail formation without overloading key sectors. Therefore, pre-tactical avoidance means **low additional workload for ANSPs** since their workflows remain unchanged.

Given that flight schedules are filed up to 48 h before the contrail avoidance manoeuvre, accurate and stable weather forecasts are key to making pre-tactical avoidance effective. Fortunately, recent research shows that **current weather forecasts with 8–24 h lead times relevant to flight planning are stable enough to be used for pre-tactical contrail avoidance**. Still, they may require more generous avoidance manoeuvres than strictly necessary to take into account the inherent uncertainty of these long forecasts.

To integrate pre-tactical avoidance in dispatcher workflows, updated operational tools that incorporate contrail forecasts in flight planning are essential. They can assess the full airspace impact flight-by-flight and select only the contrail avoidance manoeuvres with the highest climate benefits and the least air traffic management impact. **This capability allows pre-tactical planning to consider both lateral and vertical deviations**. For instance, a substantial lateral adjustment can be implemented simply by filing an alternative route in the flight plan. Because lateral changes may shift traffic into neighbouring ACCs, these tools help ensure that only reroutes compatible with sector capacity are proposed. In practice, this means pre-tactical planning can enable **disruption-free lateral deviations** where airspace allows, while automatically favouring vertical adjustments where lateral rerouting would risk overloading busy sectors.

Over oceans, pre-tactical contrail avoidance becomes a core lever since real-time flexibility is limited. Away from land, aircraft do not operate under radar-based surveillance, which traditionally meant long gaps between position reports and limited communication with air traffic control. This has led to the utilisation of structured paths such as the North Atlantic Tracks. By **using different tracks, flights could be planned to bypass warming contrail regions altogether** where capacity permits.

2.4.2 What is tactical avoidance?



Like weather fronts, contrail-sensitive regions evolve over time, sometimes moving hundreds of kilometres in just a few hours. This means **contrail forecasts must be accurate and frequently updated for avoidance to deliver maximum climate benefits**. Meteorological service providers play a key role here by providing accurate weather forecasts. Yet, these forecasts are only fully useful when the flight trajectory can still be adapted. In pre-tactical planning, avoidance manoeuvres must be decided hours, sometimes up to 24 hours or more, before departure. Even if recent research shows forecasts have good stability with time, in some cases they may already have shifted by the time the aircraft reaches the region of interest. This is where **tactical contrail avoidance** comes in: decisions are made in real-time during the flight, allowing pilots and controllers to use the latest information.

For this to work, air traffic controllers and/or pilots need to be able to assess contrail risk quickly and confidently. **Sector tools for air traffic controllers could display a visual indicator of contrail-sensitive regions** that would support fast decision-making. Controllers can use this information to allow minor level changes or reroute traffic dynamically to optimise the flight trajectory for contrails. However, this flexibility is not unlimited. During peak hours, high workload and complex sector geometry, especially where climbing, descending, and crossing traffic intersect, can reduce the ability to make changes.

If sector capacity allows and safety is not compromised, **controllers can suggest a contrail avoidance manoeuvre to the pilot** who then takes the final decision on whether to implement the avoidance manoeuvre. Before the flight, dispatch teams could brief crews on whether contrail avoidance is being prioritised, depending on the expected climate impact and the trade-off in time or fuel.

In practice, **vertical deviations are often the most feasible option for tactical contrail avoidance.** Small altitude changes tend to remain within the same sector or the same ACC, meaning their operational impact is more localised. In contrast, even modest lateral deviations can shift a flight into neighbouring sectors or across ACC boundaries, triggering coordination between units and increasing workload. This makes tactical lateral deviations more difficult to approve, whereas vertical changes typically require fewer coordination steps, affect fewer controllers, and can usually be implemented more quickly.

Tactical avoidance must remain **subordinate to core safety and capacity constraints**. Clear guardrails would help: airlines and ANSPs could agree thresholds such as only acting on the most warming contrails and revert changes if workload spikes.

Despite its benefits, **tactical avoidance is likely more challenging to implement than pre-tactical avoidance**. Pilots may prefer not to implement avoidance manoeuvres to avoid incurring extra fuel penalties and the risk of small delays. Moreover, ANSPs cannot evaluate the full airspace impact of rerouting a flight in real time.

2.5 Who leads on contrail avoidance?

Contrail avoidance can in principle be driven by airlines, by ANSPs or in a hybrid approach by both.

2.5.1 What is airline-led contrail avoidance?

In an **airline-led** approach, the airline analyses atmospheric conditions and plans each flight to minimise its climate impact, taking both CO_2 and contrails into account. This allows optimisation at the individual flight level and can be integrated into existing dispatch processes. However, if many airlines run their own contrail optimisation, it becomes harder for ANSPs to anticipate traffic patterns. Different operators may also rely on different models or forecasts, leading to inconsistent avoidance strategies within the same airspace.

2.5.2 What is ANSP-led contrail avoidance?

In an **ANSP-led** approach, contrail avoidance is coordinated at the air traffic management level. This offers a more coherent picture of the network and is easier to manage from a capacity point of view, as the ANSP and the Network Manager can ensure that climate-motivated deviations remain compatible with sector workload. The downside is that fully centralised optimisation for all flights would create a high workload for ANSPs and the Network Manager, and closing large airspace volumes for contrail reasons would be impractical for airlines.

2.5.3 How to incentivise airlines and ANSPs to do contrail avoidance?

In practice, any large-scale deployment of contrail avoidance is likely to require a balanced model where airlines and ANSPs work together.

From an ANSP's perspective, it is important that the KPIs in the SES Performance Scheme are updated to reflect that a **climate-optimal flight trajectory is not always a fuel-optimal or cost-optimal flight** trajectory. This is because the climate benefit from avoiding contrails can be dozens or even hundreds of times larger than the climate penalty of burning slightly more fuel and thereby emitting more CO_2. Climate KPIs in the Performance Scheme will ensure that contrails become part of the ANSP's mission to deliver a safe, efficient and sustainable European airspace. Additionally, regulators such as EASA and national authorities will need to endorse the operational procedures, and ensure any safety implications are fully assessed. Finally, the integration of contrail management into ATM procedures would need to be tested and fine-tuned in real environments through large-scale simulations and trials.

From an airline's perspective, performing contrail avoidance may lead to extra operational costs. Although these costs are estimated to be limited compared to the expected climate benefits from contrail mitigation, an incentive scheme based on the EU ETS would make sure that airlines starting to deploy contrail avoidance get their extra costs compensated. The incentives should be based on verifiable information regarding the cost of the intervention and the reduced climate impact of flights.

The role of flight trials

Flight trials are essential for moving contrail avoidance from modelling studies to operational reality. They provide evidence on whether avoidance can be integrated safely, predictably, and with acceptable workload and fuel implications, and should be performed in parallel to scientific research.

Airline-led trials such as Lufthansa's, TUI's, Condor's and DHL's D-KULT campaign focus on route planning, onboard execution, and dispatcher procedures and typically test pre-tactical avoidance. However, tactical avoidance is an option if contrail forecasts are available in near-real-time and operational adjustments can be made safely during flight.

ANSP-led trials such as MUAC's trials, conducted in collaboration with the German Aerospace Center DLR, explore how contrail avoidance can be handled tactically within the air traffic management system in dense airspaces. These trials assess real-time controller support tools, integration with normal sector operations, and the extent to which tactical clearances can be issued without adding complexity or reducing capacity. They also help determine how avoidance requests should be prioritised during busy periods and how last-minute vertical or lateral changes interact with crossing flows. NATS's trial as part of CICONIA explicitly explores the role of contrail avoidance in low-density airspaces such as over the North Atlantic. Trials under the CONCERTO project aim at pre-tactical avoidance, with ANSPs analysing the potential contrail impact of flights in their control area, and prioritising the most effective avoidance manoeuvres - high climate benefits, low operational impact on airlines and ATM.

Policy recommendation

For now, trials have focused on a small number of airspaces and been led by a small number of frontrunners. To test contrail avoidance at scale, **T&E calls upon the EU to fund a large-scale contrail avoidance trial, through the EU Innovation Fund or Horizon Europe.**

Section 3

3. How to make contrail avoidance work?

Both pre-tactical and tactical avoidance require making changes to air traffic flows. Whether they are **feasible depends on airspace capacity** - how many aircraft can safely fly in a given airspace at the same time - as well as on **air traffic control workload.** During peak traffic hours, for instance, high workload and complex airspace sector geometry and traffic flows, especially where climbing, descending, and crossing traffic intersect, can reduce the ability of air traffic controllers to perform tactical avoidance manoeuvres. This chapter assesses **when and where there are opportunities for successful contrail avoidance with a low impact on air traffic.**

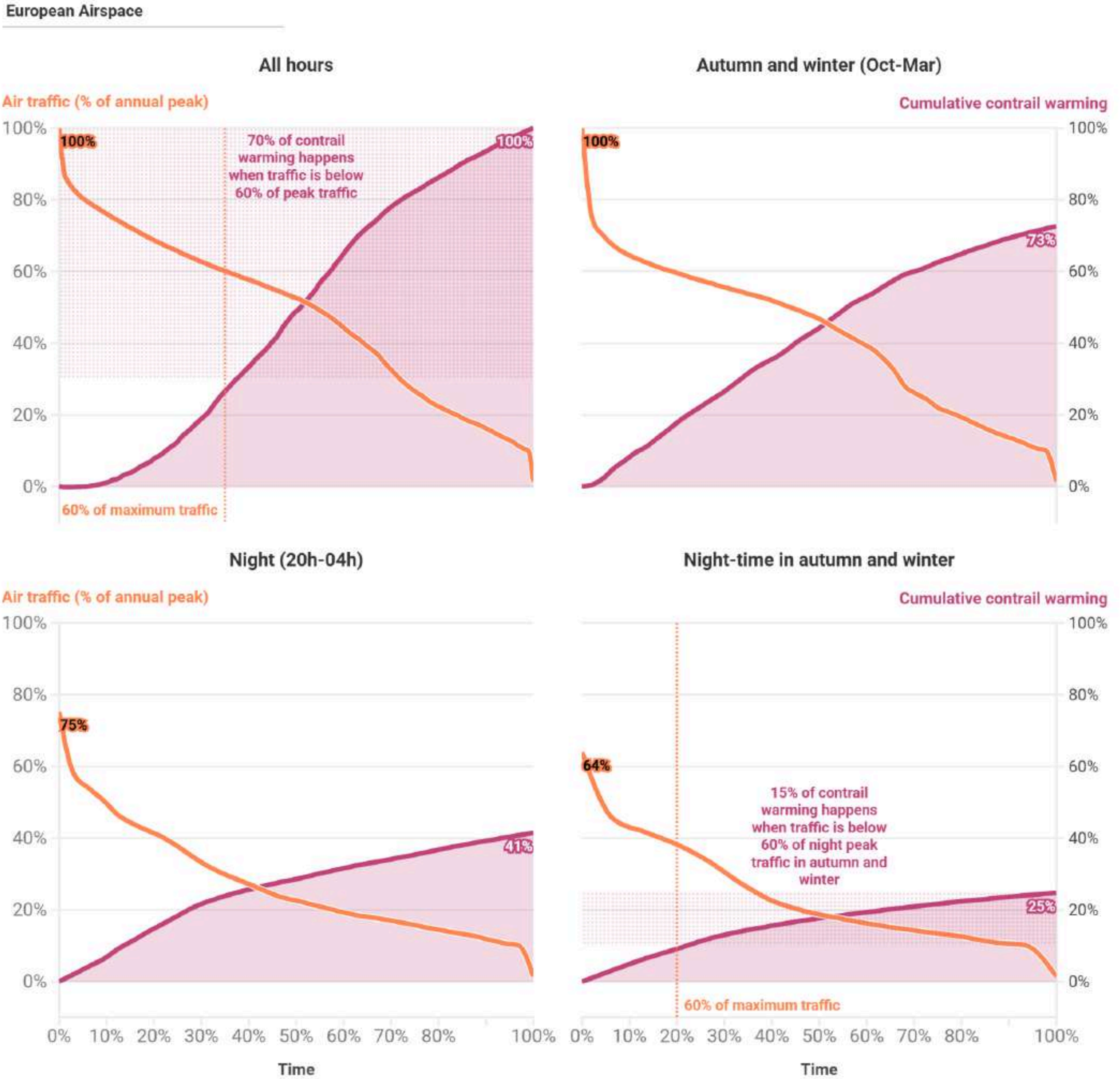
3.1 When are opportunities for contrail avoidance?

Critics sometimes suggest that contrail avoidance is impossible to implement effectively due to the **significant impact** it could have on air traffic control when performed at scale, particularly during **busy periods** such as peak summer travel days.

We argue, however, that the focus should shift from where contrail avoidance is hardest to where it is **arguably easiest and most impactful**. Therefore, contrail avoidance should be scaled up **gradually**, starting from less busy periods and less complex airspaces. This allows science, legislation, and operational experience to co-evolve responsibly.

Large share of contrail warming occurs during periods with lower traffic volumes

Traffic (hourly flight distance) versus cumulative contrail warming in 2019



Source: T&E (2025), based on Teoh et al. (2024) for the year 2019, re-run by ICL with an updated version of pycontrails (v0.54.8) • Time = Hour of year sorted by flight distance

The above chart shows when contrail warming happens compared with how busy air traffic is. The orange line shows air traffic, measured as total flight distance per hour, compared to the busiest hour of the year. The pink line shows how contrail warming adds up over time. Time in the chart is ordered from **very busy traffic periods on the left** to **quieter periods on the right**. As you move to the right, air traffic falls, but contrail warming continues to increase.

The key message is that **most contrail warming does not happen during the busiest flying hours**. Instead, a large share occurs when traffic levels are lower, especially in autumn and winter, and at night.

For example, the chart shows that **around 70% of contrail warming occurs when air traffic is below 60% of its annual peak level**. This is because the busiest flying hours mostly happen during summer days, while contrail warming is strongest in cooler, darker conditions typical of autumn and winter. Focusing on the quietest periods such as autumn and winter nights where traffic is below 40% of the annual peak would still allow for addressing 15% of total annual contrail warming in European airspace.

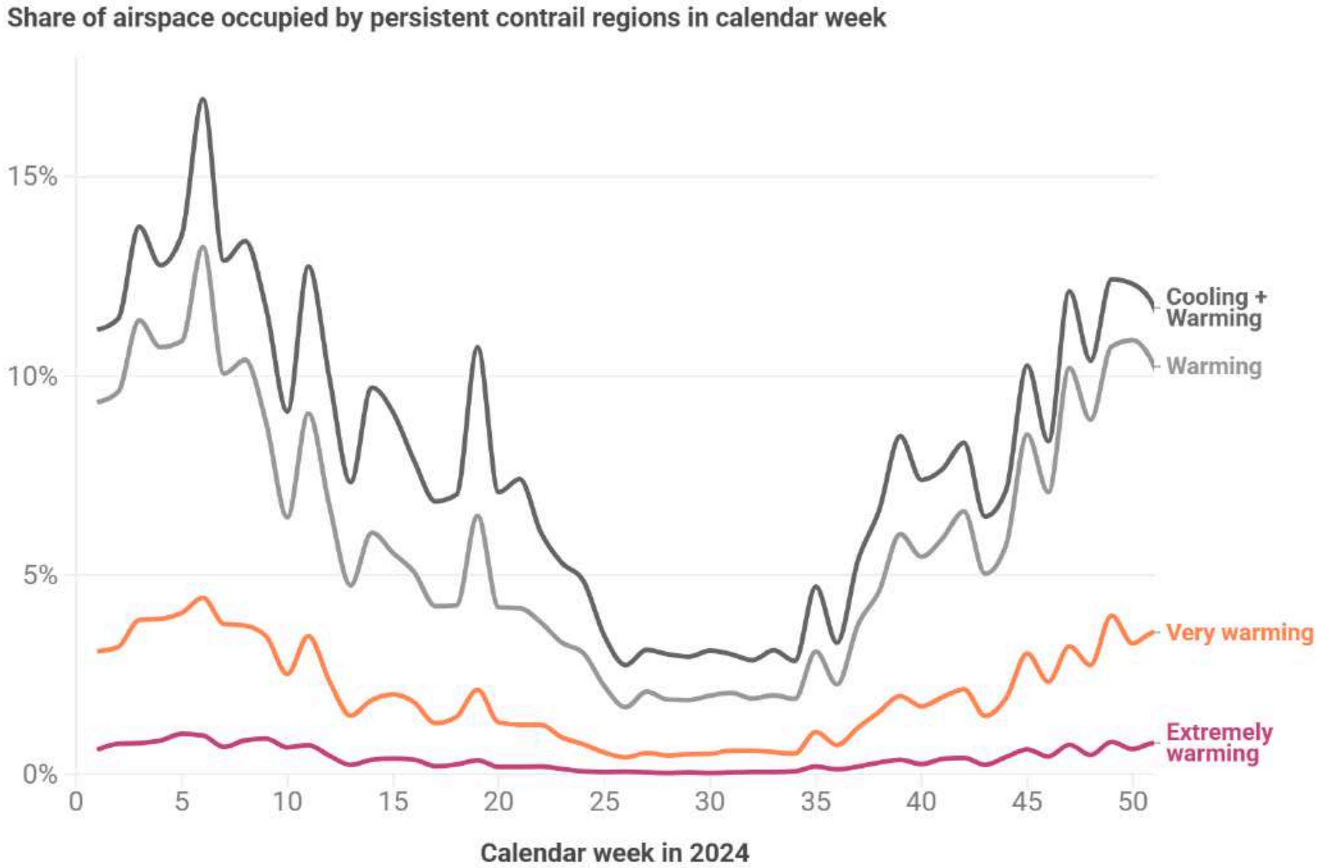
This highlights the **opportunity for scaling up contrail avoidance where traffic is low**. Simulations conducted by MUAC confirm that contrail mitigation at night time with low traffic levels, for instance, can be possible without a reduction in traffic capacity whereas the impacts of contrail avoidance at medium and high traffic levels were higher. Note that traffic should not be interpreted as a direct measure of airspace busyness or complexity in an ATM sense that depends on factors such as sector load and the number of conflicts. Still, low traffic levels tend to imply that more physical airspace is available for rerouting flights and that avoidance manoeuvres will create fewer conflicts. This means that they will likely create **less additional workload for controllers**. However, **low traffic levels do not necessarily imply low overall controller workload or large spare staff capacity**. This is because staffing at air traffic control centres varies by season and time of day as ANSPs already scale staff by expected demand.

3.2 How does contrail avoidance affect airspace efficiency?

Avoiding only the most warming contrails impacts air traffic significantly less than avoiding all contrails

Very warming and extremely warming contrail regions occupy only a limited share of airspace. Therefore, targeted avoidance sharply reduces impacts on traffic.

European Airspace



Source: T&E (2025), based on gridded CoCiP data for Airbus A320 from contrails.org • "Very warming" indicates airspace with contrail radiative forcing of at least 5×10^8 J m⁻¹ per flight distance; "Extremely warming" corresponds to ≥ 1.54×10^9 J m⁻¹. Airspace volume in this chart from FL270 to FL440.

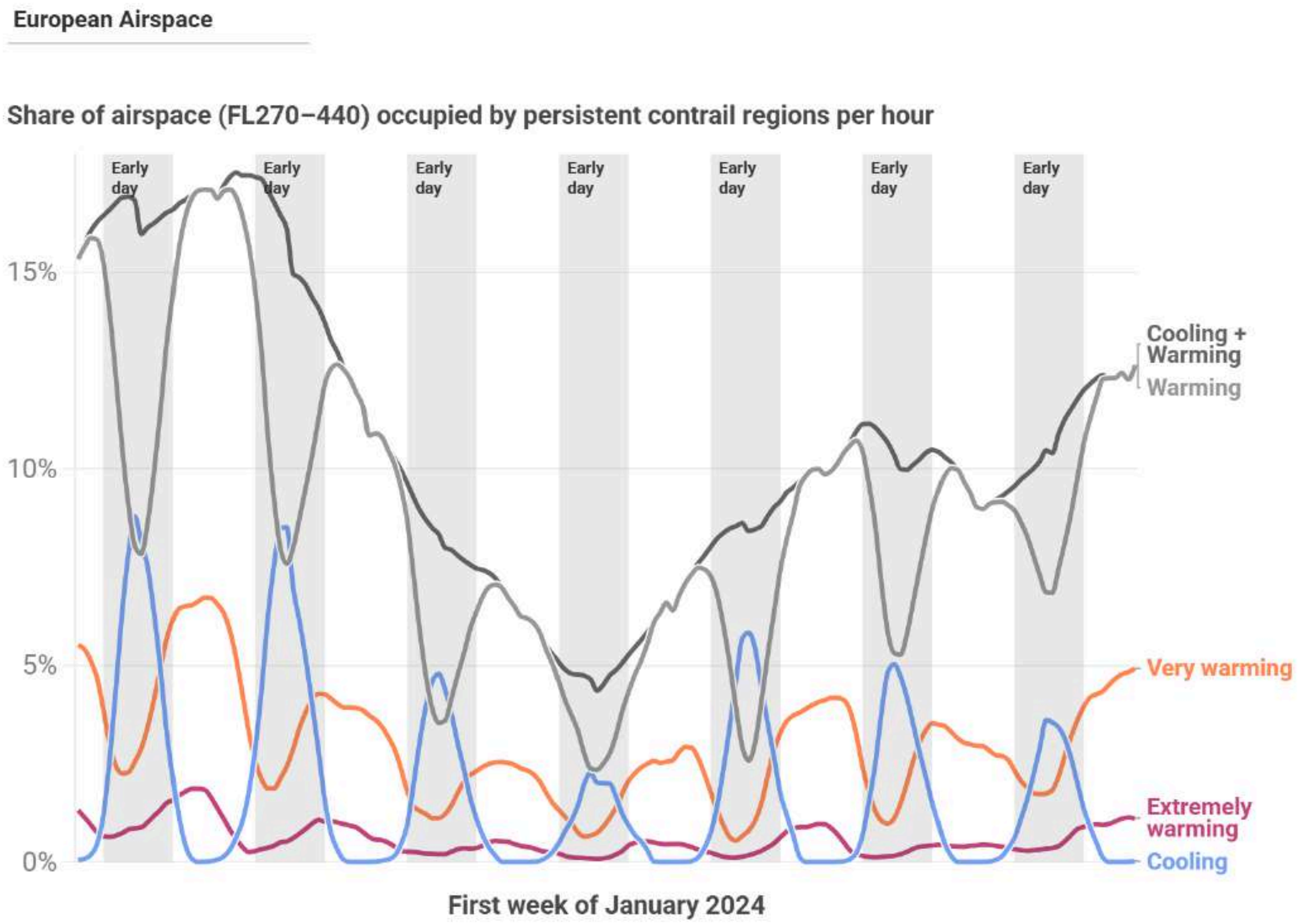
The fact that many of the highest-impact opportunities for contrail avoidance arise precisely when traffic densities are already well below their daily and seasonal peaks raises an important question: even when contrail-forming conditions are present, how much airspace is actually affected at any given moment? The above chart answers this question by assessing the spatial extent of contrail-sensitive regions over time. Contrail-sensitive areas typically cover only a limited fraction of upper airspace at any one time. Moreover, **targeting only the most warming share of airspace significantly improves the available manoeuvring space for contrail**

avoidance and reduces operational constraints. It is worth highlighting that even the most warming airspace does not necessarily need to be closed.

Restricted airspace blocks could be one model to implement contrail avoidance. ANSPs would treat a given section of warming airspace like a military airspace, for instance, and strictly reroute all flights around it. Alternatively, contrail avoidance **can be performed through a flight-by-flight ranking** without imposing airspace closures. Both approaches exist and neither is inherently superior. The preferred approach will depend on ANSP preferences and the nature of the airspace in question.

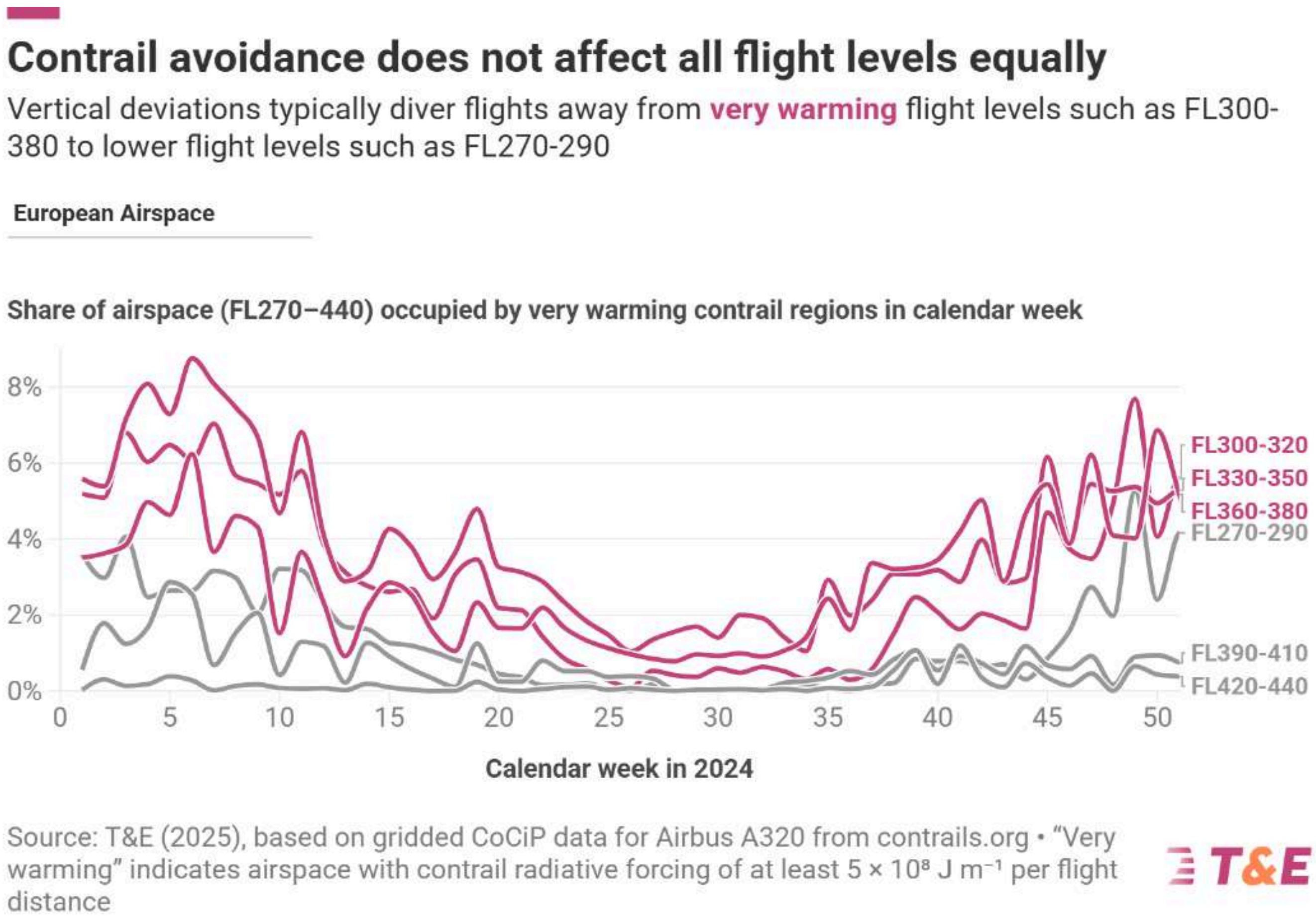
Contrail avoidance impacts air traffic least during the early day

During the early day (5 am to 3 pm), many contrails formed are cooling.



Source: T&E (2025), based on gridded CoCiP data for Airbus A320 from contrails.org • "Very warming" indicates airspace with contrail radiative forcing of at least 5×10^8 J m^{-1} per flight distance; "Extremely warming" corresponds to $\geq 1.54 \times 10^9$ J m^{-1}.

Zooming into a single week, it is clear that the **available airspace for contrail avoidance manoeuvres is dominated by daily cycles**: a larger share of airspace produces cooling contrails during the early day. From the late afternoon through the early morning, a larger share of airspace produces warming contrails. This highlights that early morning flights can create *cooling* contrails, reducing the need for avoidance. Furthermore, there is some variation within the week that is likely due to natural weather variations.



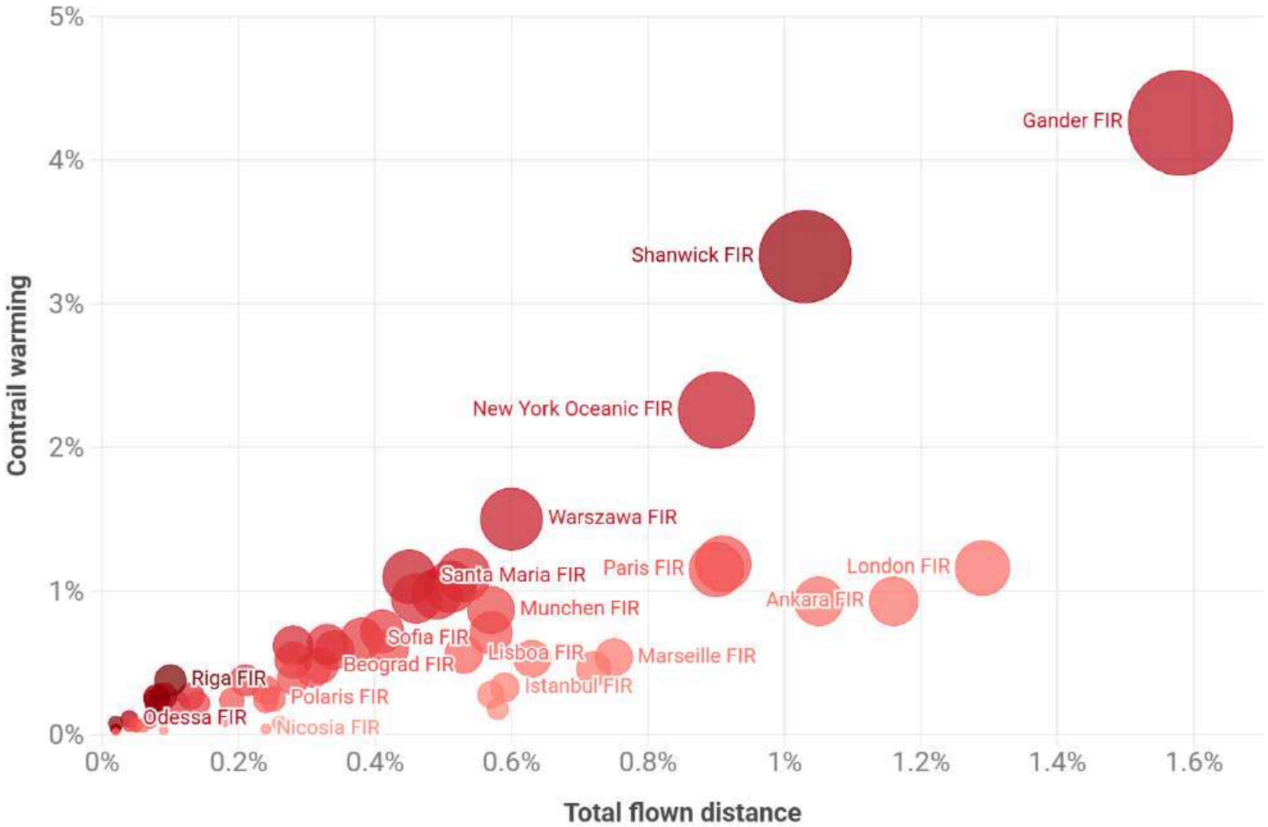
As discussed before, flights are more likely to form persistent contrails at certain altitudes. The above chart highlights that this is because a large share of these flight levels is typically occupied by contrail-forming regions. At the same time, there is a clear opportunity. Lower and higher flight level bands such as FL270-290 or FL390-440 typically **have less traffic and more available space for contrail avoidance manoeuvres.** Nonetheless, as previously noted, FL 270-290 are typically transition levels for flights climbing to cruise level or descending to lower airspaces, and FL390-440 may be higher than the ceiling of many commercial airliners. In practice, this limits the usability of these flight level bands for avoidance manoeuvres.

In any case, the **primary challenges for vertical contrail avoidance** are often less about hard physical limits of airspace availability, and more about **operational coordination, workload distribution, and the timely detection and prioritisation of avoidance opportunities.**

3.3 Where are opportunities for contrail avoidance?

Airspaces with high traffic account for high contrail warming

Traffic (total flown distance as share of 2019 global total) versus contrail warming (share of 2019 global total). Circle sizes proportional to contrail warming, darker colours stand for more contrail warming per flight distance.

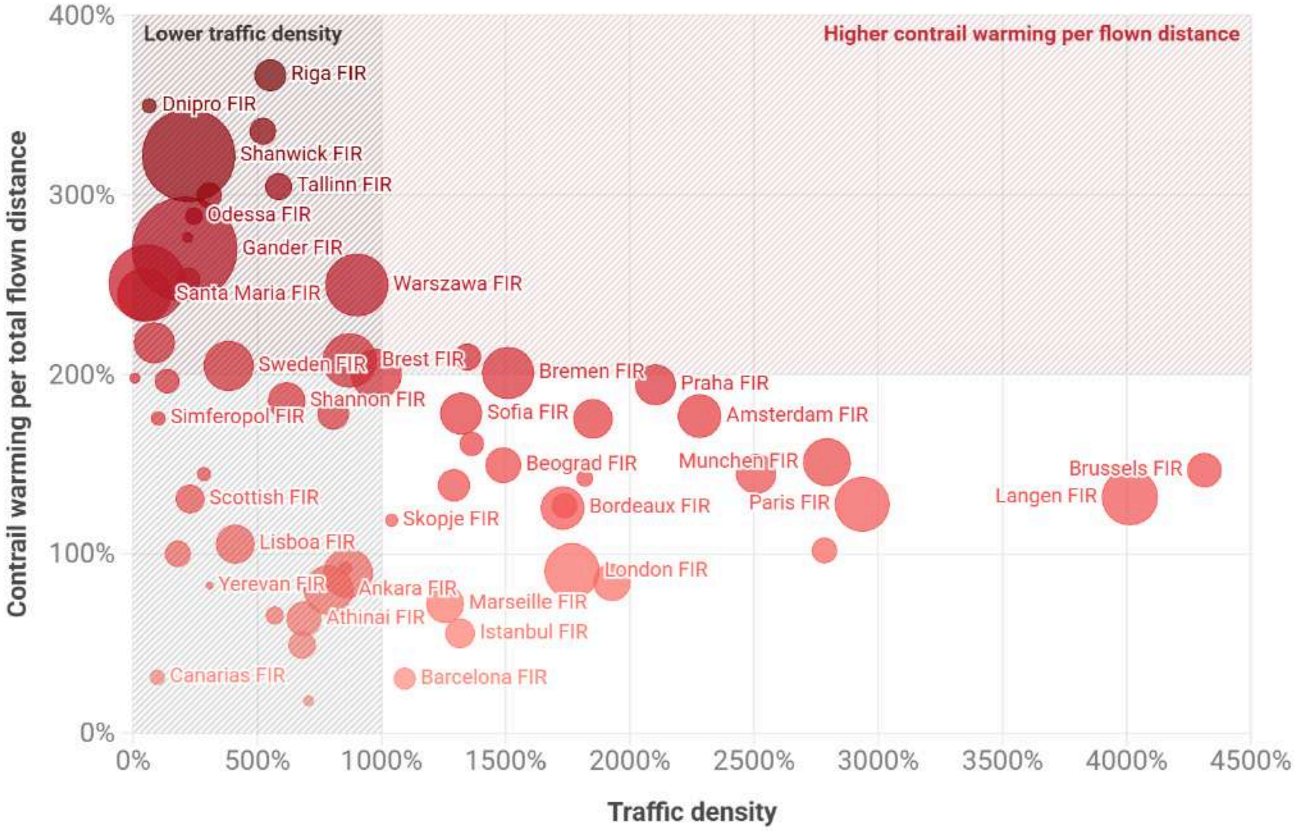


Source: T&E (2025), based on Teoh et al. (2024) for the year 2019, re-run by ICL with an updated version of pycontrails (v0.54.8)

In the previous section we looked at *when* there may be opportunities for contrail avoidance. However, where flights take place also matters: different airspaces have different characteristics, which may call for different approaches to contrail mitigation. The above chart highlights that **more traffic generally means more contrail warming** in Europe and above the North Atlantic. This suggests that, in the long run, even busier airspaces might need to eventually adopt avoidance procedures.

Eastern European and oceanic airspaces have higher contrail warming at lower traffic levels

Traffic density (total flown distance distance per area as share of 2019 global mean) versus contrail warming per flown distance (share of 2019 global mean). Circle sizes proportional to contrail warming, darker colours stand for more contrail warming per flown distance.



Source: T&E (2025), based on Teoh et al. (2024) for the year 2019, re-run by ICL with an updated version of pycontrails (v0.54.8)

However, examining the concentration of this warming provides a different perspective: The above chart **highlights airspaces with high contrail warming per flown distance and low traffic density**. Flight Information Regions (FIRs) in **Northern and Eastern Europe, as well as North Atlantic FIRs such as Shanwick (UK and Ireland), Gander (Canada), New York (USA) and Santa Maria (Portugal)**, stand out. This reflects the fact that colder or oceanic climates may be more prone to contrail formation, and that planes flying in these airspaces, particularly long haul aircraft, tend to form more contrail warming per distance flown.

These regions have less traffic than FIRs such as Brussels or Langen, making them interesting for contrail avoidance. At the same time, it is important to stress that low traffic density does not necessarily imply low traffic complexity. In oceanic airspaces, for instance, traffic densities are lower but radar coverage is limited which is why each aircraft requires larger separation and more strategic planning and coordination with fewer available routes.

These findings illustrate that different airspaces have different contrail and traffic profiles, and contrail-avoidance strategies may need to be tailored to local conditions. These strategies will also depend on workload and staffing levels at ANSPs among other things. This is why **collaboration between airlines, the Network Manager, ANSPs and other aviation stakeholders is essential** to better understand how to best scale up contrail avoidance.

Recommendations

Contrail avoidance is a key opportunity to reduce aviation's climate impact. **Air traffic management has a key role to play in making it a reality**. As shown above, contrail avoidance can be efficiently integrated into air traffic management when designed carefully. Still, it is paramount to state that **safety always has priority** and changes to flight trajectories must not compromise safety. Contrail avoidance could start with night flights in autumn and winter in airspaces with low traffic density such as the North Atlantic and focus on vertical deviations. Wherever possible, **decisions should be shifted to the pre-tactical planning phase**, reducing controller burden. The climate benefits are already significant with pre-tactical contrail avoidance and as satellites, weather forecasts and the familiarity of air traffic controllers with these types of manoeuvres improve, tactical avoidance can gradually be increased. In this regard, T&E recommends the following:

1	Perform **large-scale contrail avoidance trials** in live operations to better understand their network-scale impact on air traffic management. The EU and the UK should substantially increase funding for contrail-related research and innovation. For the EU, this includes a **dedicated SESAR workstream that covers both fundamental science and applied operational trials** as well as funding through the EU Innovation Fund. For the UK, building on the JetZero strategy, continue allocating and increasing funds for a large-scale trial in the UK airspace and for non-CO_2 research, such as the non-CO_2 programme.
2	Include a **dedicated climate KPI in SES II+ and national performance schemes** that explicitly covers non-CO_2 effects, including contrails, so that climate performance becomes a core objective for ATM. For the UK, a climate KPI should be included into the 3-Dimensional Efficiency Score. Dedicated studies on how to implement a dedicated climate KPI should happen as early as 2026. The climate KPI should be introduced first as a PI in the next reference period of the Single European Sky (RP5, starting in 2029), while the KPI should be gradually phased in: it could, for instance, first be implemented in contrail-prone regions with low traffic density, such as the North Atlantic, already in RP5.
3	**Maintain the automatic extension of EU non-CO_2 MRV**, which currently excludes two thirds of contrail warming, **to extra-EEA flights** and set up a non-CO_2 MRV **covering UK departure flights** to build the evidence base for robust policy measures around contrail impacts.

4	Consider **incentivisation mechanisms within the ETS scheme through the use of ETS allowances**, to support airlines financially when performing contrail avoidance manoeuvres.
5	Accelerate European airspace modernisation to **enable more flexible, dynamic, climate-optimal flight trajectories**. A more modern ATM system will lead to reduced airspace complexity and ATM workload which in turn increases controller capacity for contrail avoidance.
6	**Raise awareness of contrails as one of ATM's key levers to reduce aviation's climate impact**. Integrate non-CO_2 impacts and contrail mitigation into initial and recurrent ATCO training and other ATM training programmes for supervisors, flow controllers, flight data operators, ATCOs, dispatchers and pilots and equip the Network Manager and ANSPs with contrail-aware tools.
7	Integrate **contrail management as Strategic Development Objective (SDO) into Europe's ATM masterplan** and standardisation roadmaps, with a concrete action plan to scale up across the network by 2035.

Bibliography

- **Quantification of climate impact of contrails**
    - The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018
    - Global aviation contrail climate effects from 2019 to 2021
    - Aviation contrail climate effects in the North Atlantic from 2016 to 2021
    - Reanalysis-driven simulations may overestimate persistent contrail formation by 100%–250%
    - The effect of uncertainty in humidity and model parameters on the prediction of contrail energy forcing
    - Satellite-Based Quantification of Contrail Radiative Forcing over Europe: A Two-Week Analysis of Aviation-Induced Climate Effects
    - Trade-offs in aviation impacts on climate favour non-CO2 mitigation
- **Contrail avoidance**
    - Feasibility test of per-flight contrail avoidance in commercial aviation
    - Impact of forecast stability on navigational contrail avoidance
    - Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?
    - Contrail, or not contrail, that is the question: the "feasibility" of climate-optimal routing
    - Concept of robust climate-friendly flight planning under multiple climate impact estimates
    - Climate-aware air traffic flow management optimization via column generation
    - Conflict assessment and resolution of climate-optimal aircraft trajectories at network scale
    - Forecasting contrail climate forcing for flight planning and air traffic management applications: the CocipGrid model in pycontrails 0.51.0
    - Implementation of contrail avoidance in commercial flight planning
    - Feasibility of integrating multiple climate impact estimation models to enhance confidence in environmentally-friendly aircraft trajectory optimization
    - Beyond Contrail Avoidance: Efficacy of Flight Altitude Changes to Minimise Contrail Climate Forcing
    - Energy Efficient Contrail Mitigation Strategies for Reducing the Environmental Impact of Aviation
    - Contrail Regions 101 (Part I)
- **Trials**
    - American Airlines participates in first-of-its-kind research on contrail avoidance
    - From research to operations: MUAC is pioneering ATM Condensation Trail (CONTRAIL) avoidance measures | EUROCONTROL
    - Contrail avoidance - Research & development - NATS
    - Joint Research-Project: D-KULT
    - SESAR Joint Undertaking | CONCERTO- Dynamic Collaboration to Generalize Eco-friendly Trajectories
    - CICONIA - Climate effects reduced by Innovative Concept of Operations
    - How can ANSPs prepare to mitigate aviation's impact on global warming, with a focus on non-CO_2 emissions?

Appendix

Methodology

Data sources

We combined flight traffic data, global emissions inventories and high-resolution contrail simulations to estimate the climate impact of aviation contrails and to explore the scope for contrail avoidance.

We used four main datasets:

- **Flight-by-flight contrail simulations for 2019** for all European arrivals and departures, based on CoCiP simulations driven by Spire ADS-B data and documented in Teoh et al. (2024). This dataset included, for each flight, fuel burn, flight distance, contrail length, contrail lifetime and total contrail energy forcing.

- **Gridded output of the flight-by-flight forcing simulations for 2019**, re-run by Imperial College London with an updated version of pycontrails. These provided global hourly fields of flight distance and contrail energy forcing on a regular three-dimensional grid with 0.25° x 0.25° lateral resolution and 100 m vertical resolution. The data is consistent with the Global Aviation emissions Inventory based on ADS-B (GAIA) for 2019.

- **Gridded CoCiP outputs for 2024** from contrails.org, giving global hourly fields of contrail energy forcing by longitude, latitude, flight level and time.

We defined European and other regional airspaces using FIR boundaries from Open Aviation together with information about which FIRs are governed by EUROCONTROL member states. We chose to use lower flight information region boundaries (FIR) and not upper information region boundaries (UIR) because their lateral extent generally more closely matches that of ACCs. Note that contrail warming is relevant at high altitudes where UIR boundaries apply.

In addition to FIR boundaries, we used rectangular regions proposed in Teoh et al. (2024). We combined these with airport and country information to attribute traffic and contrail impacts to specific airports, regions and airspaces.

Unless otherwise stated, all hours in this report are given in Coordinated Universal Time (UTC), and all altitudes refer to barometric flight levels.

Analytical approach

For detailed Python notebooks containing the calculations for all results shown in this report as well as a Google sheet that contains most of the data shown in the charts, please refer to the corresponding GitHub repository.

We analysed the **2019 European departures dataset** on a flight-by-flight basis to understand contrail climate impact as a function of aircraft type and flight distance as well as to derive general statements about European contrail warming such that 5% of flights generated 80% of contrail warming from European departures in 2019. In the context of this report, **contrail warming is quantified using energy forcing as a proxy**. Energy forcing is defined as the time integral of radiative forcing over the lifetime of contrail cirrus. This metric is **useful and transparent for comparing where and when contrails are most climate-relevant**

We used the **2019 gridded contrail forcing simulations to move from individual flights to a full three-dimensional picture of contrail warming**. We processed the hourly model outputs into annual, monthly and hourly aggregates, both on the native three-dimensional grid and by region. This gave us maps and profiles of flight distance and contrail forcing by time, location and altitude. In this report we do not use air traffic complexity metrics. These metrics aim to describe how "busy" or challenging an airspace is for controllers. They can include the number of aircraft in a given volume, entry and exit rates, traffic density and more complex composite scores based on traffic flow characteristics. They also depend on the geometry of sectors and constraints such as military airspace and weather. Because complexity metrics are still the subject of ongoing research and are not standardised, we instead use a **simpler and more transparent measure of traffic: the total distance flown in a given airspace over a fixed period.**

The **2024 gridded CoCiP outputs** were used for two main purposes. First, we **identified and characterised persistent contrail regions**, defined as contiguous three-dimensional clusters of grid cells where contrail energy forcing exceeded threshold values derived for 2019. Since they were derived from a different contrails simulation, these thresholds should be understood as approximate. We restricted the identification to a bounding box focused on the North Atlantic and European sector for computational reasons and calculated, for each region, its area, volume, mean and maximum forcing, typical flight level, thickness and geographical extent. This provided a set of "contrail hotspot" regions for 2024 that we analysed to understand the extent of typical vertical deviations.

Second, we used the same **2024 gridded CoCiP outputs to quantify airspace capacity in terms of contrail warming potential**. For each hour of the year, region and flight level band, we classified grid cells according to whether they produced cooling contrails, warming contrails, or highly warming contrails based on percentile thresholds of energy forcing. We then calculated the fraction of the available airspace volume falling into each category and aggregated these shares by week and flight level. This gave a time- and altitude-resolved view of which share of airspace is occupied by warming, very warming or extremely warming contrail-sensitive regions.

Notes on specific charts and sections

Section 1.2 - Maps

- We use linear colour scales with a cutoff for high values to prevent single points with very high traffic or contrail warming from dominating the colour scheme

    - Colour scale for flight distance: [0, 5e9 m]
    - Colour scale for contrail warming: [0, 1e17 J]
    - Colour scale for warming per flight distance [0, 2e8 J/m]
- Grid resolution: 0.25° x 0.25° lateral resolution vertically summed
- Bounding box shown in the maps: Longitude [−70°,45°] and Latitude [25°,60°]

Section 1.2 - Contrail warming and traffic by region

- Bounding boxes for regions defined here

Section 1.3 - Typical required vertical deviations

The analysis for this chart is divided into two steps: In the first step, we identify and characterise persistent contrail regions in 2024. In the second step, we simulate the required vertical deviation manoeuvres to avoid them.

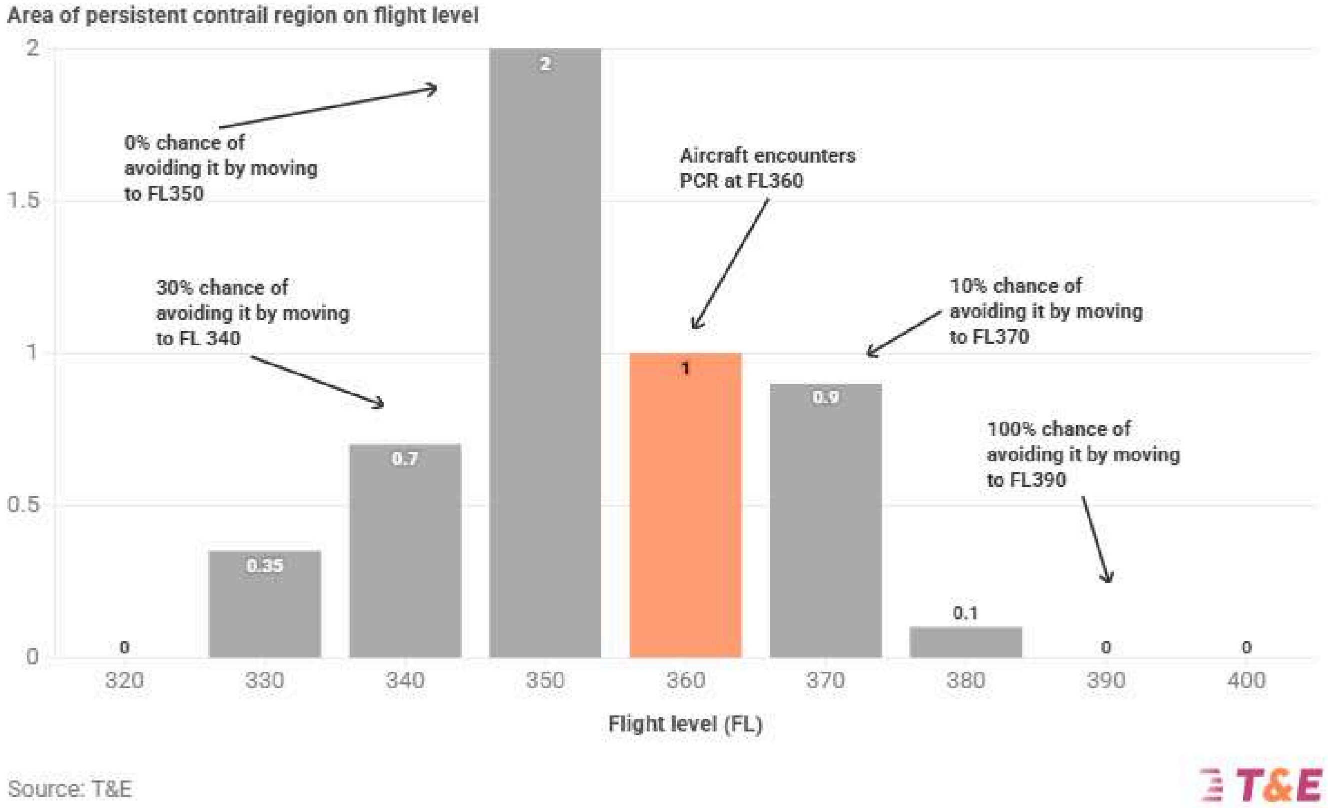
Persistent contrail region identification

- Input data: gridded CoCiP outputs for a representative Airbus A320 aircraft with an assumed engine efficiency of 0.32 for 8,760 hours in 2024 for flight levels 270 to 440
- Note that contrails can also form at flight levels lower than 270.
- For every hour, identify 3D-connected areas where the energy forcing per flight distance exceeds a given threshold.
- We only retain these areas if they fully lie within the bounding longitude=(−90.0°,40.0°) and latitude=(30.0°,80.0°). This focus speeds up the data processing and leads to results relevant for contrail avoidance of Europe and the North Atlantic.
- For every single contrail-sensitive region, we compute key metrics such as the mean latitude, longitude, the area occupied per flight level etc.
- This hourly snapshot approach means we do **not track the evolution** of individual ISSRs over time. The results characterise the **annual average statistical properties** of these regions, not the life cycle or persistence of specific contrail clouds. Furthermore, the geographical filtering may cause us to **miss very large ISSRs** with high longitudinal or latitudinal elongation.

Required vertical deviations

- Our model determines the probability of needing N consecutive vertical steps (where 1 step = deviation by 1,000 feet) to exit the contrail area, conditioned on the aircraft already being inside the persistent contrail region at its current flight level
- It is a **probabilistic** model that only takes into account the areas occupied by each persistent contrail region at each flight level

How do we assess whether a persistent contrail region can be avoided by a vertical movement?



- Suppose an aircraft encounters a persistent contrail region that occupies an area of 1 at FL360. If that same persistent contrail region occupies an area of only 0.9 on FL370, we assume that there is a 10% chance of avoiding the persistent contrail region by moving up to FL370.
- We assume that an aircraft can only avoid a persistent contrail region by moving to flight levels where it occupies a smaller area than on the flight level where the aircraft encounters it. In the above chart, it means that the avoidance probability for a move to FL340 is only 30% and not 75% as for a classical Markov chain. Therefore, our approach is more conservative than a Markov chain model. This is because we assume there is vertical coherence for the ISSR.
- By performing this simulation for both upward and downward deviation directions, we provide an estimate of the required deviation magnitude.
- We then compute a weighted sum of the deviation probabilities for every persistent contrail region for all hours of the year and weigh them by the PCR areas on the respective flight levels to get an estimate of the avoidance probability for a generic, representative PCR at a given flight level.

Limitations and caveats

The analysis relied on state-of-the-art but still uncertain contrail models and on several simplifying assumptions. **The results should therefore be interpreted as indicative of patterns and orders of magnitude rather than precise estimates of contrail warming.**

Key limitations include:

- **Meteorological data**
  All contrail simulations and airspace capacity estimates in this report are based on the ERA5 meteorological reanalysis. While ERA5 is a widely used, state-of-the-art dataset, it has known limitations for representing ice-supersaturated regions (ISSRs), which are where persistent contrails form. In particular, ERA5 tends to predict air that is too humid at cruise altitudes. In practice this means that model grid boxes remain ice-supersaturated more often and over a deeper vertical range than may occur in reality. As a result, the simulations are likely to overestimate the thickness and extent of ISSRs.
    - This has two important implications for our results:
        - The vertical range of airspace flagged as “at risk” of producing warming contrails may be too wide, and the typical size of required vertical deviations may be overstated.
        - Our estimates of the share of airspace volume affected by warming contrails are therefore likely to be pessimistic, in the sense that they err on the high side.
        - The overall patterns we describe, for example, which flight levels and times of year are most affected, are still informative. However, the absolute depth of ISSRs and the implied vertical deviation distances should be interpreted with caution, and as conservative estimates rather than precise values.

- **Model and parameter uncertainty**
  The CoCiP simulations depend on meteorological reanalysis data, aircraft performance assumptions and microphysical parameterisations. The rerun of the 2019 forcing dataset produced about 20% lower total forcing than the original publication and did not include additional warming from volatile particulate matter activation.
- **Contrail warming**
  All references to contrail warming in this report refer to energy forcing, defined as the time integral of radiative forcing over the lifetime of contrail cirrus. This metric is a **useful and transparent proxy for comparing where and when contrails are most climate-relevant. However, energy forcing does not translate directly into surface temperature change**, because the temperature response depends on complex atmospheric processes (including the altitude of the forcing, background cloudiness, timing, and circulation). Results should therefore be interpreted as indicating relative patterns and mitigation potential, rather than direct temperature impacts in degrees.
- **Geographical and vertical simplifications**
  We represented FIRs and other regions using two-dimensional boundaries and did not explicitly model their finite vertical extent. The identification of persistent contrail regions was limited to a fixed latitude-longitude box, which may exclude some very long regions

that stretch beyond this area. As a result, regional totals and hotspot locations are approximate rather than exact.

- **Temporal coverage and tracking**
  The 2024 gridded CoCiP dataset had a small number of missing hours despite repeated data requests. We treated the remaining data as representative of the year. When analysing persistent contrail regions, we treated each hour independently and did not track the full life cycle of individual regions over time. The statistics therefore describe typical region properties over a year rather than detailed evolution of specific events.
- **Representativeness of traffic patterns in 2019 versus 2025**
  The core traffic year in the analysis is 2019, which predates the Covid-19 shock and recent structural changes in aviation. Subsequent shifts in routes, fleets and operations mean that absolute levels of contrail forcing today may differ from the 2019 baseline, even if many spatial and temporal patterns remain similar.
  Having said that, we did **compare our results with results based on unpublished CoCiP simulations for 2024 traffic data** using a newer pycontrails version taking into account vPM activations and they generally **showed good agreement.**