IN-DEPTH

Aviation contrails and their climate effect

Tackling uncertainties and enabling solutions

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The aviation community, formed by industry, governments, universities, and research institutions are actively researching ways to minimize the warming impacts of contrails. This report addresses the urgent need to further understand and mitigate the formation of persistent warming contrails.

This report was developed with the following organizations and companies:

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EXECUTIVE SUMMARY

Aviation's impact on climate extends beyond CO_2 emissions, with non-CO_2 effects such as contrails and nitrogen oxides (NO_x) contributing to global warming. Persistent contrails, formed in ice-supersaturated regions, can transform into cirrus clouds which reflect incoming solar radiation (during the day) as well as trap outgoing heat. On balance, it is understood that they have a warming effect on the climate, with diurnal, seasonal and geographical variations. However, despite extensive studies, significant uncertainties exist in predicting individual contrail formation, and their climate impact.

The aviation community, formed by industry (airlines, manufacturers, air navigation providers), governments, universities, and research institutions are actively researching ways to minimize the warming impacts of contrails. This report addresses the urgent need to further understand and mitigate the formation of persistent warming contrails. Strengthening the synergy between, research, technological innovation and enabling policy frameworks will be crucial in reducing aviation's climate footprint effectively.

The report first explains contrails and the regions in the atmosphere where they form. Then, initiatives looking at reducing contrail formation are highlighted along with the existing limitations. The use of humidity sensors on a limited population of aircraft is then explored as a potential enabling lever to tackle some of the existing scientific uncertainty gaps by improving and validating numerical weather prediction models.

Current Understanding and Challenges

The report highlights the complexity of contrail science, noting gaps in understanding how contrails form, persist, and impact climate. The lack of high-resolution, real-time data on atmospheric conditions (particularly humidity and temperature at cruising altitudes) hinders precise contrail forecasting.

Initiatives and Trials

Recent collaborations among meteorologists, climate researchers, airlines, and aircraft manufacturers have yielded new insights but underscored the need for enhanced data collection and air traffic network complications. Trials with modified flight paths and alternative fuels have shown potential yet limited efficacy due to the variability of atmospheric conditions and the localized nature of where contrails do occur.

Technological Advances and Future Directions

Advancements in humidity sensors on aircraft have been proposed as critical for better contrail prediction and avoidance strategies. Although the current sensor technology on commercial aircraft lacks the required sensitivity and response time, ongoing research aims to develop more accurate and robust solutions. The use of sensors on a limited population of aircraft would allow the necessary improvement and validation of numerical weather prediction models.

Recommendations

The report advocates for short, medium and long-term approaches to tackling the climate effect of contrails.

- In the **immediate term** (2024-2030), prioritizing the reduction of CO_2 emissions should take precedence over uncertainties in contrail detection and climate impact. Actions now include:
  - increasing airline participation in sensor programs;
  - continuing scientific research; and
  - improving humidity and climate models.
- **Mid-term actions** (2030-2040) involve:
  - establishing standards for data transmission;
  - continuous validation of models; and
  - encouraging aircraft manufacturers to include provisions for meteorological observations.

- **Longer-term actions** (2040-2050) focus on increasing the world fleet providing data and having a full understanding of the non-CO_2 effects of alternative fuels. These action items collectively aim to mitigate the climate impact of aviation while advancing scientific understanding and technological capabilities.

The industry and its stakeholders are working to tackle non-CO_2 emissions. It is clear that significant progress has been made in understanding non-CO_2 impacts of aviation, however considerable work remains. In the short term, this means developing more experimentation, raising awareness and increasing understanding around non-CO_2 emissions. Based on these learnings, design and operational decisions will need to be taken.

Strengthening the synergy between technological innovation and regulatory frameworks will be crucial in reducing aviation's climate footprint effectively. Due to current limitations in measuring the impact of individual contrails, Monitoring Reporting and Verification (MRV) schemes for non-CO_2 emissions today, will be incomplete and unlikely to represent reality or result in a reduction of aviation's climate impact. Instead, all stakeholders must work together to resolve current gaps in the science so effective action can be progressed for aviation.

1. INTRODUCTION

The climate impact of aviation is generated from direct aircraft emissions and the resulting atmospheric effects which happen as a consequence of those emissions. Carbon dioxide (CO_2) and water vapor (H_2O) are natural by-products of the combustion of jet fuel and have a direct warming effect. Other emissions like soot particles or nitrogen oxides (NO_x) have an indirect effect by causing processes in the Earth's atmosphere, including direct warming by the absorption of radiation by soot particles, and the formation of ice crystals and ozone. The combined effect of emissions other than CO_2, and their resulting climate impacts are commonly known as non-CO_2 effects of aviation. It is believed that the highest contributor to climate change of those non-CO_2 effects could be the creation of persistent contrails in the upper troposphere, followed by NO_x and their indirect atmospheric effects.

While scientific consensus exists that these effects on average have a warming impact, there is much less consensus as to just how warming they are, and on which timescales the effects occur. Furthermore, there is scientific disagreement as to how accurately, or if at all, we can predict contrail formation on a flight-by-flight basis. These two aspects are still subject to large uncertainties, particularly when assessing individual flights.

The existing uncertainties have created opposing views amongst the aviation and scientific community as to whether we know enough to act now, or whether the knowledge and scientific gaps are too large and immediate action could result in unintended consequences and a worsening of the aviation's climate impact.

The need to increase the understanding on these complex atmospheric effects, has undoubtedly accelerated related research in the last few years. Initiatives involving meteorologists, climate researchers, airlines, air navigation service providers and aircraft/engine manufacturers are increasing and while the understanding of the issues has evolved, there are still gaps.

Improving the knowledge on climate and surface temperature effects of aviation-related gaseous and particulate emissions is paramount for these gaps to be closed, and the existing uncertainties to be reduced. This assessment addresses actions that the international aviation community is taking in this respect now, as well as future steps which could put airlines at the forefront of the scientific research on non-CO_2 emissions and effects.

NO_x emissions could have the second largest non-CO_2 climate effect, after contrails. Their air quality and climate impact are the subject of active scientific research, and the science is continuously maturing. Engine manufacturers have worked for decades on technology developments for their reduction. However, the scope of this report is on contrail formation. The report first introduces contrails and the regions in the atmosphere (ISSR) where they form. Then, initiatives looking at reducing contrail formation are highlighted along with the existing limitations. Humidity sensors on aircraft are then explored as a potential enabling lever to tackle some of the existing scientific uncertainty gaps.

2. CONTRAILS AND ISSR

2.1. Contrails explained

Condensation trails, or contrails, are white line-shaped ice clouds which form behind the aircraft at cruising altitudes under certain conditions. The creation of contrails is dependent on the ambient conditions (mainly temperature and humidity), the efficiency of the aircraft engines, the air properties, the water vapor content in the engine exhaust plume (water vapor emission index), and the specific energy content of the fuel. The fundamental theory which describes contrail formation has been studied for over 60 years (Schmidt-Appleman Criteria), and this determines whether a contrail will form or not but does not determine whether it will persist nor what the climate impact of that contrail might be.

Figure 1 Photograph of a non-persistent contrail

Most contrails disappear a few seconds after being formed, as the tiny ice crystals warm up and sublimate, leaving the background sky without any persistent visible mark. These are believed to have negligible impact on the climate (Figure 1).

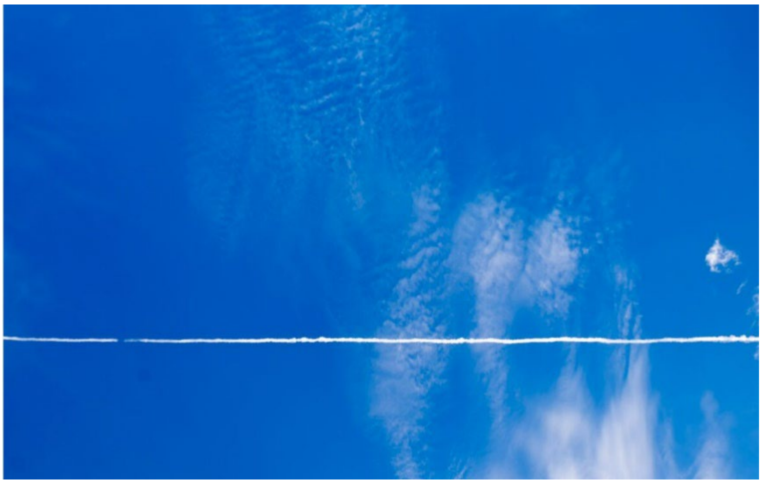


Figure 2 Photograph of a single persistent contrail

Sometimes, however, aircraft fly through regions which have enough water vapor in them to form ice clouds, but there are insufficient solid particles (ice nuclei) for the vapor to condense onto [1]. These regions are known as ice super-saturated regions (ISSR). As aircraft fly through these air masses, if the temperature is cold enough to form contrails, water vapor emitted from the aircraft's engines and water vapor present in the atmosphere condenses onto the unburned carbon particles that are left behind by the engine's exhaust, to form trillions of tiny ice crystals for every kilogram of jet fuel burned [2].

In these regions the ice crystals don't sublimate immediately but persist (Figure 2). A contrail will continue to exist as long as it remains within an ISSR; during this period, the ice crystals initially formed can absorb more atmospheric water vapor and grow laterally and horizontally. Studies estimate that a persistent contrail will have at least 10 times more water content coming from condensed atmospheric water vapor than from the water vapor exhausted from the aircraft's engines. A contrail can persist from several minutes up to several hours. Any contrail which remains for more than 10 minutes is classified as a "persistent contrail".

Persistent linear contrails can be spread by winds to form contrail-cirrus clouds. If the contrail-prone region is very large, it is possible that several flights will pass through it, and so a large portion of the sky can be covered by contrails (Figure 3). These clouds can grow to be a few kilometers in width and interact and merge with one another resulting in a large portion of the sky covered by high-altitude aircraft-induced cirrus clouds. One study estimates that about 0.06% of the sky area is covered by contrail cirrus globally, although in some high-traffic regions like the North Atlantic it could be up to 10% [3] [4].

Figure 3 Photograph of a large region of sky with multiple persistent contrails

2.2. The climate impact of contrails

Contrails have gained growing attention not only due to their visibility in the sky but also because of their climate impact. While climate modelling uncertainty remains very high, studies have estimated that, the overall averaged effect of these contrails causes a warming effect on the planet [5]. This is not to say that every single contrail is warming, nor that the effect is the same for every contrail. In fact, it is quite the opposite, and this is one of the reasons why tackling them is so complex.

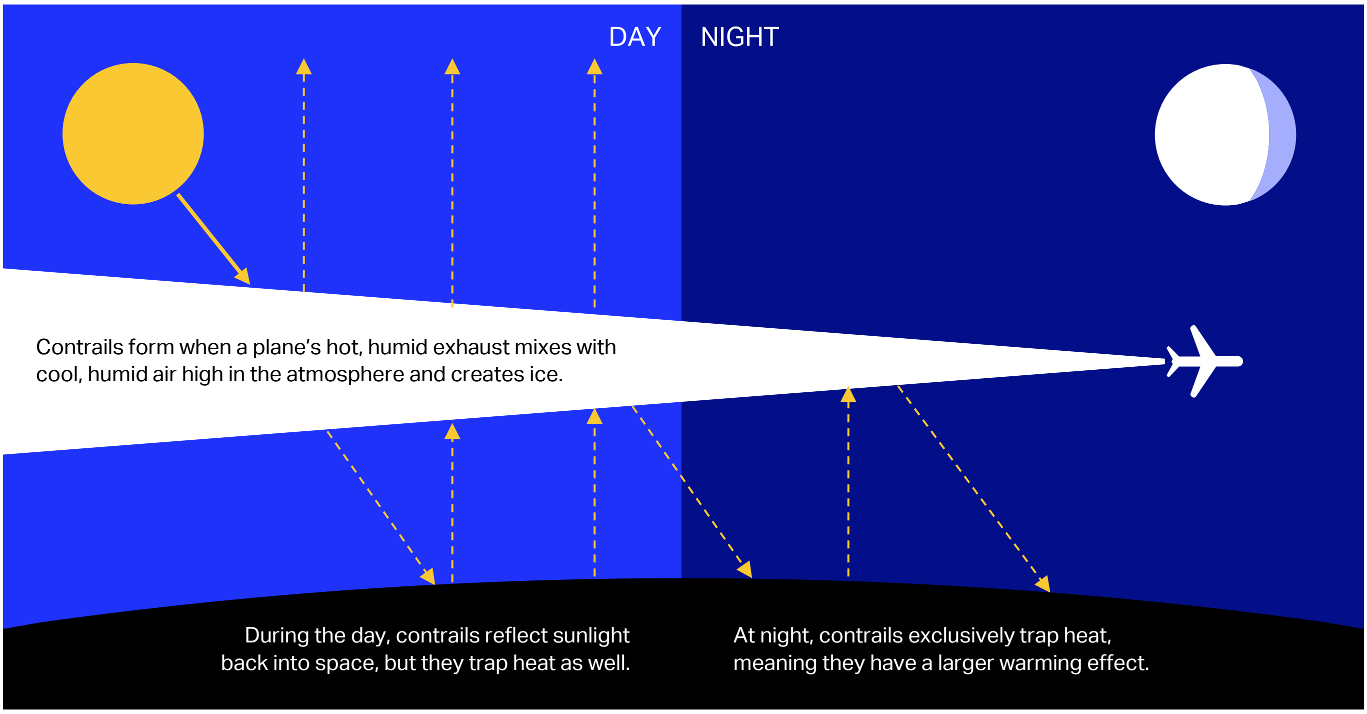


Figure 4 Illustration between day and night contrails. Courtesy of American Airlines

During the day, most contrails will have a dual effect: on one hand, they will reflect part of the incoming solar radiation back into space, thereby having a cooling effect but they can also trap thermal-infrared radiation that is leaving the ground and would otherwise travel upwards uninterruptedly. For most contrails, the warming effect predominates during daytime, except for optically very thick contrails which block most of the incoming sunlight. During the night, there is no solar radiation, so the cooling effect disappears, making night contrails on average more warming than day contrails (Figure 4).

The effect that a contrail (or indeed any other cloud) has on the climate depends on a multitude of factors, including the time of the day (or the angle of the incoming solar radiation) the optical thickness of the cloud, the surrounding clouds and surrounding atmosphere, whether the cloud is above the ground, or the sea, the time the cloud will last in the atmosphere, and the way it is advected by the wind or grown through windshear, amongst others. One of the consequences is that the same contrail can be warming during part of its life and cooling during another part; its total effect will depend on the importance of each of these opposite effects during its lifetime. Also, the net effect of the contrail on climate depends on understanding how the ice supersaturated layer would have evolved in the absence of aircraft.

The extent of contrail warming, even at an aggregated level, is still a subject to scientific debate and it is widely acknowledged that the uncertainty is significantly larger than that for CO_2 emissions. For example, a recent publication synthesized from several studies the effect of each aviation climate forcing term measured in Effective Radiative Forcing (ERF) [5]. In 2018, the best estimated value for past to present CO_2 emissions was 34.3 mW/m^2 with an uncertainty of ±17% which corresponds to minimum and maximum values of 28 and 40 mW/m^2 respectively. For the same year, the best estimated value for contrail-cirrus was 57.5 mW/m^2 with ±70% uncertainties (range of 17-98 mW/m^2) [5]. Recent publications, however, estimate values as low as 8 mW/m^2 showing the large variation in predictions [6].

Another yet unsolved complication arises from the fact that the climate impact of contrails may last for hours, while the climate impact of CO_2 will last for hundreds of years. This large discrepancy in the timescales of the climate effects of aircraft CO_2 emissions and contrails poses an unresolved challenge to the scientific community to find appropriate metrics to relate these two different climate impacts. Part of the difficulty in pinning down an ERF value has to do with the complexities explained above, and the limitations that global climate models have on solving the climate impact of isolated clouds or cloud clusters which are very small and short lived compared to the size of the planet. The poor quantification of contrails' climate impact is also a consequence of the very limited number of global climate models (only two reported in open literature) that can describe contrail formation and their climate impact.

2.2.1 Current approaches to mitigate the warming impact of contrails

The aviation community, formed by industry (airlines, manufacturers, air navigation providers), governments, universities, and research institutions are actively researching ways to minimize the warming impacts of contrails.

Some of the efforts focus on the use of **alternative fuels** with lower aromatic content. When burned, these fuels reduce the number of non-volatile particles emitted by the engines, which, in turn, can reduce nucleation sites for the formation of ice crystals that constitute a contrail. Though the final climate effect of this is not yet proven, simulations and experiments are increasing our knowledge on the effect of such low-aromatic fuels. Investigations are also being undertaken into the feasibility of introducing hydrogen fueled aircraft. Hydrogen is a fuel which contains no carbon and when used to power an aircraft would produce zero CO_2, sulfur oxides (SO_x) or carbon particles, thus eliminating these nucleation sites. Although this would not completely eliminate contrails it would change their characteristics.

New engine architectures which could capture part of the water vapor from the exhaust are also being explored, and existing lean combustors have shown to be capable of significantly lowering particulate emissions even more than what could be achieved by low or no-aromatic hydrocarbon fuels.

Airlines are also partnering with universities, research centers and private entities to identify the requirements and limitations of **navigational avoidance** of the areas where contrails are more likely to be formed. The sector continues to learn with these trials and some preliminary findings are sourced in this report. To be able to avoid the regions of the atmosphere where persistent warming contrails might form, it will be necessary to:

1. Accurately predict where these regions are.
2. Accurately predict what the warming impact of a single contrail forming on those regions would be.
3. Ensure that there is no extra climate impact because of the aircraft deviation.
4. Have the certainty that the aircraft is not being deviated to another region where a contrail will nevertheless form.
5. Understand the counterfactual scenario of what would have happened if the aircraft was not deviated.
6. Understand the impacts at a network level: Will all flights avoid that region? If so, what is the system-level climate impact of that? If not, what is the climate impact (if any) of one single avoidance if other flights don't avoid?).
7. Ensure that the deviation has no safety impact such as encountering elevated turbulence, convective weather, or aircraft separation concerns.
8. Validate the model used to predict the contrail and confirm that the deviation was successful.

Without properly addressing the points above, any contrail mitigating action could be incomplete and have potentially adverse climate effects. For example, aircraft could be diverted (at the cost of extra CO_2) to avoid a predicted ISSR that was not there in the first place (incorrectly predicted), or over a much greater area than was required. Aircraft could be deviated into an ISSR which was not previously detected, causing both, extra CO_2, and a contrail. Even in the case of a successful deviation, the climate benefit (extra CO_2, vs avoided contrail) would have to be evaluated and the exact climate impact of that potential contrail must be known. Significant research and information are thus required to minimize any climate risks.

This report provides more details on some of the enablers which can help as catalyzing tools to answer some of the questions above.

2.2.2 ISSR and persistent contrails characterization

For airlines to take preventive actions, which could potentially avoid the ISSR where persistent warming contrails form, there must be a deep understanding of what these regions are, where are they located, how large they are, and how accurately we can identify them today [7].

Location

- ISSRs are most frequently located in the upper troposphere and tropopause region at about 8-12 km altitude in the mid-latitudes, and about 12-18 km in the tropics [8] [9]. Some ISSRs have also been detected in the middle troposphere, although this is thought to be less common, and there are very rare occurrences of ISSR above the tropopause [10]. The altitude of the tropopause exhibits a strong zonal, seasonal and dynamical variability, and thus the occurrence of ISSRs varies greatly (Figure 5).
- Aircraft often cruise at a 9–12 km altitude, which is exactly where ISSR are at mid-latitudes. This is why contrail formation and ISSR occurrence is more common at mid-latitudes than near the tropics. Aircraft flying in the tropics or near the Equator, reach the upper troposphere/lower stratosphere (UTLS) much less frequently, as in those regions the UTLS is often above cruising altitudes [3].

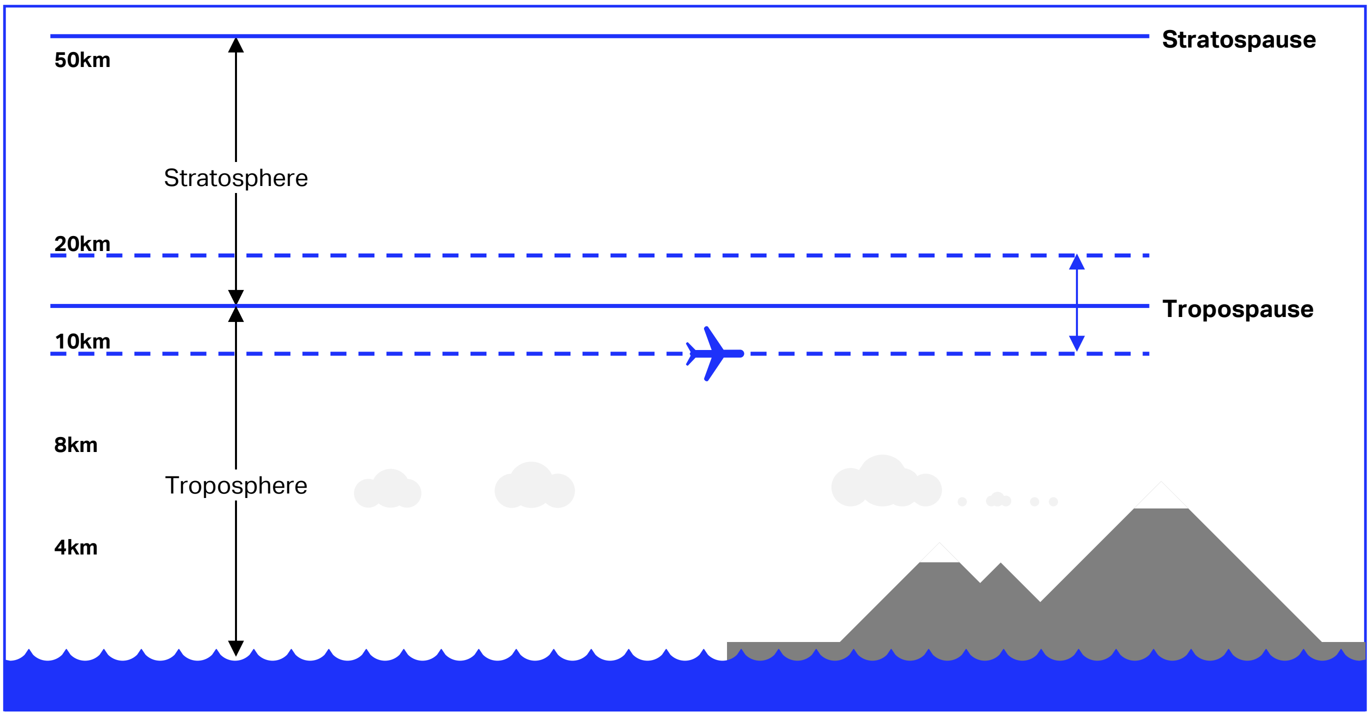


Figure 5 Illustration of the lower Earth's atmosphere layers

- The higher occurrence of contrails at mid-latitudes is also related to climatological conditions favorable for contrail formation, such as weather frontal systems and jet streams that bring varying temperature and humidity levels, creating suitable conditions for contrail formation.
- ISSR and thus contrail formation are more likely during the winter than during the summer, so there is not only a diurnal variation of contrail likelihood and effects but also a seasonal variation [3] [11].

Size

- Studies report that most ISSRs are in the range of 100-400 km in horizontal extension, with most being around 150 km [10] [12]. On average, an aircraft would take about 10 mins to fly through an averagely sized ISSR. This horizontal extension, however, can vary greatly. For example, a study using in-situ aircraft measurements estimated that about 90% of ISSRs had a horizontal extension smaller than 500 km, less than 1% reported to be larger than 1,000 km and less than 10% were reported to be smaller than 30 km [10].
- In-situ aircraft measurements have also reported that properties inside ISSR are quite heterogenous. In other words, these regions are patchy, with areas of higher and lower humidities and temperatures inside them. Sometimes this patchiness can be observed by the naked eye when a contrail is formed and the "contrail line" has one or several interruptions in its length.
- ISSR are estimated to be 600-800 m thick, with extreme values reported of 25-3000m [2].

Compared to the global scale, ISSRs are a very localized small-scale phenomenon, and this adds to the difficulty of detecting them. In situ aircraft-or balloon-borne measurements can detect ice supersaturated air masses with high spatial resolution but have limited coverage. The horizontal and vertical scales of ISSR thickness are typically near the edge of satellite resolution.

Lifetimes

- The lifetime of an ISSR has been estimated from observations to be of the order of hours. For example, the lifetime derived from the European Centre for Mid Weather Forecast (ECMWF) satellite trajectories was between 6 and 24 hours, with maximum duration of about 1 day [13]. Further research is required due to the limited reliability of trajectory calculations derived from satellite data with regards to ISSRs and the high relevance of atmospheric conditions to ISSR evolution, although recent research is showing promise with better resolution [14].

Humidity and temperature inside an ISSR

- The absolute humidity or water vapor concentration in the air can be measured in units of parts per million volume (ppmv). For example, at 25 C, with a relative humidity of 50%, the air would have a water vapor concentration of nearly 16,000 ppmv.
- At aircraft cruising altitudes in the upper troposphere, ambient temperatures can be -50°C or less, and the water vapor concentration as low as 5-7 ppmv - over 2,000 times lower than what it is at sea level [15]. For contrails to persist, the relative humidity over ice defined by the ambient pressure, the saturation pressure, and the air temperature must be above 100% [15]. In-situ observations of ice-supersaturated air masses measured onboard of passenger aircraft in the frame of the MOZAIC and IAGOS project[1] have reported water vapor concentrations above 25 ppmv, coinciding with the values of around 15, and 20 ppmv reported from research aircraft observations [7]. ISSRs are also associated with extremely low temperatures. Data from in-situ measurements showed that about 2% of the sampled air

[1] The IAGOS (In Service Aircraft for a Global Observing System) programme "is a European Research Infrastructure for global observations of atmospheric composition from commercial aircraft. IAGOS combines the expertise of scientific institutions with the infrastructure of civil aviation in order to provide essential data on climate change and air quality at a global scale". The equipment on-board aircraft include high-altitude humidity sensors.

indicated supersaturation but these results vary greatly depending on the variables explained above as well as instrument capabilities and accuracy [16].

Whichever means are used to detect the ISSRs must be able to measure accurately and precisely such low levels of temperatures and humidity. The location and time where they are formed and the wind field around them must also be known to understand how they evolve. The characteristics of ISSRs, thus set the high-level requirements for detection.

2.2.3 Contrails characterization

The aircraft-induced clouds formed inside ISSRs will have properties correlated to the ISSR in which they are formed. For example, mean contrail lengths have been reported of 150 ± 250 km, which is as long as the ISSR in which they form. However, as explained, these clouds can expand as they absorb more water vapor from the surrounding atmosphere and as they get sheared by winds [17]. A study which evaluated simulated contrail properties for the years 2019-2021 reported an average width of 9-10 km [3].

After formation, contrails experience a three-dimensional expansion. They grow longitudinally in the direction of travel of the aircraft as the plume is left behind, and laterally (growing in width). The downwash from the wing-tip vortices creates a vertical expansion too that directs the contrail downwards [18]. These create very complex 3-D structures that interact with the surrounding atmosphere and with each other. The contrail formed on the port engine will interact with the one on the starboard engine, and both with other contrails from other aircraft as well as with naturally formed clouds. This will influence the duration of the contrail, and its climate impact. Contrail lifetime can be highly variable with some disappearing immediately after formation and some reported to last for over 12 hours. However, publications based on observations and weather models seem to agree that most contrails will remain in the atmosphere for 1-3 hours [3].

2.2.4 Contrail avoidance: lessons learned from airline trials

Airlines are taking a lead with investigating non-CO_2 emissions through different means. United Airlines, for example, in partnership with Boeing ecoDemonstrator, NASA, GE Aerospace and DLR have conducted trials involving understanding the non-CO_2 effects of Sustainable Aviation Fuels (SAF) and lean combustors. Swiss International Air Lines has been working on increasing their understanding on Nitrogen Oxides emissions, and Virgin Atlantic Airways recently conducted a commercial transatlantic flight on 100% SAF which involved a thorough emission campaign prior to the actual flight where important data on engine emissions with 100% SAF were collected.

Some airlines have also conducted (or are preparing) trials to learn how feasible it would be to avoid ISSRs where contrails can persist. For example:

- American Airlines in partnership with Google and Breakthrough Energy
- Air France in partnership with Météo France
- Delta Air Lines in partnership with the MIT
- Etihad Airways in partnership with Satavia
- KLM Airlines in partnership with Satavia
- Lufthansa Airlines, DHL, Condor, TUI in partnership with DLR and DWD (in preparation at the time of writing)

The methodologies used for avoidance can be broadly grouped into two categories. One involves using weather data to estimate where ISSRs might be using a contrail formation numerical model, then review the filed flight plan to predict whether the contrail will be formed, and the potential estimated climate impact of that contrail. An alternative flight path is then filed which deviates the flight away from that region usually by vertical changes to the original route.

The second methodology involves using satellite imagery to observe a fraction of the sky. Through observations, some contrails might be detected, and their position reported. Following flights are diverted away from this region and the result is observed with satellite imagery.

A third "hybrid" approach is to use weather models to predict where a persistent contrail could be formed, then diverting (or not) an aircraft from that region and use satellite imagery to verify if the prediction was correct or not and if the contrail was avoided. These types of verifications have also been done with observations at ground-level and during flight, by asking volunteers to report contrails that have been spotted and verifying this with predictions.

These experiments have provided a valuable platform to evaluate the feasibility of such diversions, and the challenges that are still present. In this report, three challenges are highlighted.

Challenge 1: Accurately predicting the location of Ice Super Saturated Regions

The first challenge to avoid the formation of a persistent contrail, is to predict where the contrail will be formed and if it will persist. As mentioned in the introduction, contrail-prone areas are localized phenomena which are quite small, normally a few hundred kilometers in length. To predict these regions accurately, both the humidity and the temperature of the air in those regions must be known, and ideally also the wind velocity field so that the movement of this region can be estimated.

For years scientists have been using weather data (either forecasts, or reanalysis) which use satellite data as inputs, to predict ISSR and contrail formation. However, when the estimated humidity is compared to in-situ measurements, the result is poor. It is estimated that **the error in humidity (which is the key parameter to classify an ISSR) can be around 50% and as high as 80%** [8] [19]. Improvements are being made by modifying the algorithm that is used for humidity, or by feeding historical in-situ measurement data. For example, historical sensor-data can be used to correct for past humidity fields in localized regions where the data exists, to improve the contrail formation estimation of previous flights. Sensor data can also be used to 'train' the models for better prediction, but this is still a developing science. For accurate ISSR prediction of future flights, more data is required to be fed into the meteorological models as the starting points of the simulations needed for forecasting (data assimilation).

The vertical resolution of satellite-based humidity data is not granular enough to be able to accurately know the altitude at which the contrail was formed. Many contrails prediction tools use ECMWF satellite-based data for contrail creation forecast which provides a vertical resolution of 3,000 ft (914 m) at the altitudes where contrails form. In some regions, flights are separated by 1,000 ft (305 m) intervals, and hence it can be challenging to identify which exact flight crossed an ISSR with a coarser resolution than the flight separation. Likewise, most ISSR thickness are 1,000-2,500 ft (300-760 m), smaller than the resolution provided by the satellite data.

The high uncertainties associated with this first challenge will propagate and expand to the rest of the analysis, limiting the success of current avoidance methodologies. While a contrail prone region might be broadly identified today, its accurate location and its borders are much harder to predict. An analogy to this is weather forecasting or cloud formation. It is possible to predict roughly when it will rain but much harder to predict the formation of a specific cloud above a particular location. Airlines performing recent trials have reported on the difficulty to accurately identify and validate ISS regions.

Challenge 2: Accurately estimating the climate impact of single contrails

If an ISSR was identified and matched to an aircraft trajectory, the individual climate impact of the resulting persistent contrail must be evaluated to define whether it makes sense (climate-wise) to deviate that aircraft from that region. It must be highlighted that not every contrail is warming: a recent publication estimated that 14% of all flights, on average, form a contrail, and out of these, close to 30% could be net cooling [19] [3].

Diversions can result in additional fuel burn and CO_2 emissions, which have a long-lasting effect in the atmosphere. Accurately estimating the climate impact of a single contrail is very difficult with today's methods, models, and computational tools. This is equivalent to estimating the climate impact of a single cloud formed in any part of the world. While estimates can be made, these will have large uncertainty. Thus, accurately accounting for the climate benefit of an aircraft diversion continues to be a significant challenge. This is not only difficult to quantify but also very difficult to subsequently verify and validate.

Challenge 3: Verifying that the diversion has been successful

Provided that the ISSR has been accurately predicted, and the potential climate of the contrail has been evaluated, there must be a way to validate that the diversion has been successful. Furthermore, there must be a validation that the region avoided was indeed an ISSR. This remains one of the biggest challenges today.

The strategies that use satellite imagery or human observations provide an excellent first platform for visual verification but cannot detect ISSR in a clear sky. They also have other shortcomings, for example, the vertical resolution mentioned above also applies to satellite imagery. Satellites will only detect a contrail after its width has exceeded ~2 km, and this can take nearly one hour [17] [20]. By that time many flights are likely to have passed through that region, so matching and verifying a 1-hour old contrail to a specific flight remains challenging. More recent GOES satellites could help with this: When put in mesoscale mode with resolution down to 0.5 km, contrails are being observed within minutes of aircraft passage [14].

Another challenge is to distinguish between aircraft-borne contrails or naturally occurring cirrus clouds, particularly after the contrail has expanded [20]. Recent trials were successful in identifying the detected cloud as an aircraft-generated cloud 50% of the time when using an artificial intelligence (AI) algorithm, and 80% of the time when the matching was done or assisted by a person [17]. All these are areas of active research are likely to improve in the future but still present challenges for widespread implementation today.

In-flight rear-viewing cameras are also being used for verification (Figure 6). The FAAM Airborne Laboratory uses them to validate that the aircraft is indeed flying through an ISSR, but the limitation of this approach is that it's hard to evaluate persistence of contrails with this method.

Figure 6 Contrail photograph taken from rear-facing camera. Courtesy of FAAM Airbone Laboratory

There is broad scientific consensus that more humidity data is fundamental to tackle the three challenges mentioned above. Without more humidity data, it will be extremely hard to improve the current weather models which predict contrails, as well as to increase our understanding on their climate impacts. All studies in the open literature which deal with contrail formation or contrail climate impact acknowledge this limitation: Agarwal et al. estimated that "reanalyses [using satellite-data from ERA5 and MERRA-2] incorrectly identify individual regions that could form persistent contrails 87% and 52% of the time, respectively" [8]. Schumann, on the publication of one of the most widely used contrail prediction tools, CoCIP, states that "Presumably the most critical input from the NWP (Numerical Weather Prediction) model is the relative humidity over ice" [2],and Gierens et al. state that "unfortunately, the prediction of contrail persistence would be almost random [when using satellite-based data]" [19]. Airlines could be a strong contributor to help close this gap by providing more data to the scientific community for this purpose.

Operational considerations

While recent scientific publications show that only a small percentage of flights may create high-warming contrails, those flights are concentrated in specific regions and days. The limited experience has shown that adjustment of trajectories to avoid ISSRs has not always been possible due to capacity and traffic congestion, and this limitation is expected to continue.

Tactical adjustment of trajectories will be limited by fuel on-board and minimum fuel requirements for safety of operation. In a congested airspace, decisions and requests for tactical trajectory adjustment could have workload impacts on both air crew and Air Traffic Control (ATC). Operational opportunities and limitations for trajectory adjustments to avoid ISSRs will be tacked in a separate IATA publication.

3. Humidity sensors to increase the understanding of contrails

Civil aircraft today (with extremely few exceptions) do not have equipment on-board to measure outside air humidity, and the temperature readings available are often not accurate enough for the purpose of ISSR detection. All the information available to weather models for humidity at cruising altitudes comes from very scattered weather balloons (which have extremely limited coverage), satellite data, and an extremely small fleet of civil (about 10) and research aircraft.

At present, meteorological forecasts of ISSRs, based on satellite data assimilation have been proven to be inadequate for contrail formation forecasting [1] [8] [19]. Any ISSR forecast or reanalysis either to avoid the formation of a contrail or to estimate the non-CO_2 impacts of previous flights, as proposed by the European Union Monitoring Reporting and Verification (EUMRV) scheme, will have insufficient observational data for assimilation into models.

In the short-term, satellite predictions of ISSR could be validated by more in-situ measurements, should aircraft be equipped with the proper instrumentation (Challenges 1 & 2). In the medium term, more humidity readings could help fine-tune the meteorological models, and support scientists to understand the behavior and properties of ISSRs, thereby improving our understanding of cirrus cloud formation under those conditions.

Once these conditions are met, then the certainty of predicting contrail formation will be higher, and the need to operationally mitigate them (e.g. pre-departure flight planning) more credible. For this, a relatively small sub-set of aircraft will have to be equipped with humidity and temperature sensors on-board, provided that the data is quality controlled and assimilated into the appropriate numerical weather prediction models.

3.1. Aircraft as atmospheric research laboratories

The idea of using civil or research aircraft to collect atmospheric data is not new. Appendix 1 details past and ongoing initiatives which have used airliners to provide temperature, pressure, humidity, and atmospheric chemistry data to the local State meteorological provider and to the scientific community. Today 10 wide-body civil aircraft from 8 different airlines provide humidity data at cruising altitude through the IAGOS program[2] and

[2] Air Canada, Discover Airlines, China Airlines, Air France, Hawaiian Airlines, Cathay Pacific, Lufthansa Airlines, and Iberia. Aircraft installed: Airbus A340, Airbus A330, and there are plans to expand the program to Airbus A350.

about 140 narrow-body aircraft are equipped with humidity sensors which provide readings during climb and descent (AMDAR) [3]. There are also multiple research aircraft equipped with scientific instrumentation for atmospheric research, including humidity.

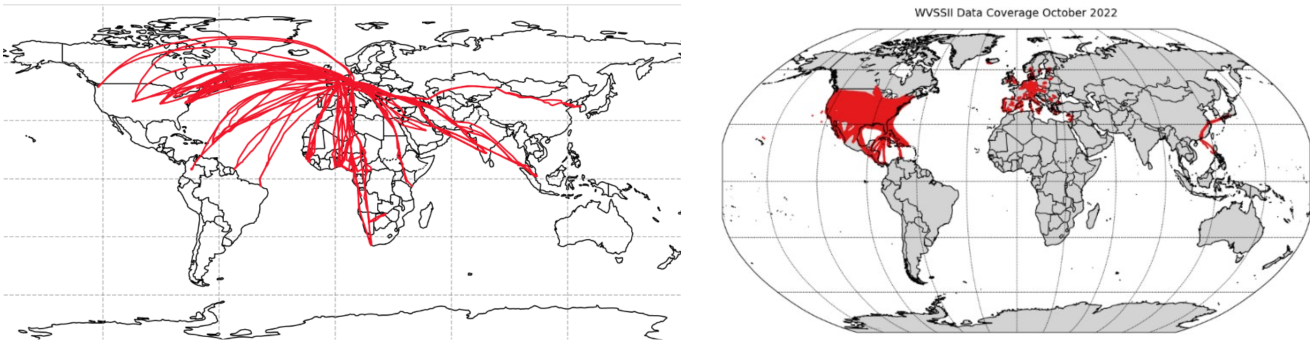


Figure 7 Left: IAGOS data coverage map. Right: WVSS II Data coverage map, WMO [21]

Some sensors like the commonly used WVSS-II have been deployed in commercial airliners but don't have the accuracy required for ISSR detection (Figure 7). Some others like the Chilled Mirror and the ICH sensors can measure very low levels of humidity but are slow to react at cruise speeds. Given that a flight could cross an ISSR in a few minutes (<10 mins, average), rapid response is needed from the sensors to be able to accurately detect them. Some other sensors were seen to be extremely accurate, even at low water vapor concentrations, but require constant calibration or maintenance.

	Low temps **-50 C** or less	Low H_2O concentration **~20 ppmv**	High H_2O concentration **~10,000 ppmv**	Fast reaction time **~30-60 s**	High resolution **~7-13 km**	**Low** maintenance	**Minimum** calibration	**Light** weight	**Easy** to install
'IDEAL' Sensor	Green	Green	Green	Green	Green	Green	Green	Green	Green
ICH	Yellow	Green	Green	Yellow	Yellow	Green	Green	Green	Green
WVSSII	Red	Red	Green	Green	Green	Green	Green	Green	Green
TAMDAR	Red	Red	Yellow	Yellow	Red	Yellow	Red	Green	Yellow
Chilled Mirror	Green	Green	Yellow	Red	Red	Red	Yellow	Green	Yellow
DLH	Yellow	Yellow	Green	Green	Green	Yellow	Yellow	Red	Red
FISH	Green	Green	Red	Green	Green	Red	Red	Red	Red
AIMS H20	Green	Green	Red	Green	Green	Yellow	Yellow	Red	Red
SHARC II	Yellow	Yellow	Green	Green	Green	Green	Green	Green	Yellow
HAI	Yellow	Yellow	Green	Green	Green	Yellow	Green	Red	Red

Blue = installed on commercial aircraft

Figure 8 Comparison humidity sensors. Blue text: sensors currently flying on commercial aircraft. Black text: Experimental sensors on research aircraft. Colour scale is a qualitative comparison against the ideal case.

[3] **UPS and Southwest Airlines mainly on 757 and 737, Lufthansa Airlines on A321.**

None of the nine sensors identified by IATA were deemed ready to be deployed immediately for the purpose of contrail climate impact mitigation (Figure 8). All sensors require the aircraft to get a Supplement Type Certificate (STC) for their installation, although for some, the STC already exists on some aircraft models.

Most of the sensors have been installed on research aircraft and are scientific instruments which are delicate and require constant maintenance and calibration. These sensors are very accurate but still unsuitable for airline operations (e.g., issues are still present with calibration, weight, maintenance, and accuracy). Some other more robust sensors have demonstrated to work on an airline environment but do not still have the resolution required at high altitude. A summary of all the findings can be found in Appendix 2.

New research is being funded in the US by the Department of Energy (DOE) ARPA-E PRE-TRAILS program to develop low cost, light weight humidity sensors for commercial aircraft. The CICONIA project in Europe is also investigating, amongst other things, improving the understanding of ISSR and contrail formation with new sensor technology. Research and development in this endeavor is expected to take a few years to be finalized.

3.2. Number of aircraft required

A remaining gap is the number of aircraft required to provide enough coverage for the purpose of non-CO_2 emissions. In other words what is the minimum number of aircraft required to maximize the coverage and weather data. As stated previously there are fewer than 10 commercial aircraft in the world operating with sensors capable of detecting ISSR, and this clearly is insufficient. However, it is widely recognized that not all aircraft need to be equipped by a sensor. This is still an open investigation question. An Observation System Simulation Experiment (OSSE) can be used to determine the required number of observations and thus the number of aircraft to be equipped with sensors. Based on a similar study using local models of the U.S., it can be assumed that this is in the order of magnitude of tens of aircraft (~10-100) per region, as opposed to thousands, however further scientific evidence is required for this.

3.3. Implications on aircraft performance

Gathering the data in Appendix 2, in terms of the weight of the sensors, the power required to operate them and the air inlet, IATA undertook a high-level evaluation of whether this would have any detrimental impact on aircraft performance or on CO_2 emissions.

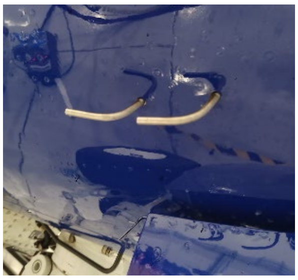
3.3.1 Performance penalties due to extra drag

As can be seen on the sensor summary information in Appendix 2, the air intake for the sensors protrudes from the aircraft fuselage. Many intakes can be used for humidity sensors. Four options are shown below in Figure 9, from left to right: the Rosemount inlet, flush mount, rearward-facing inlet, and fin type.

Rosemount inlet

Flush mount

Rearward-facing inlet



Fin type

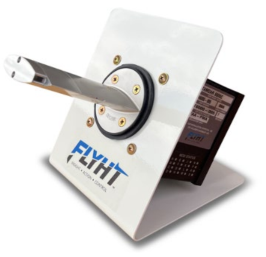


Figure 9 Sensor inlets from left to right: Rosemount, flushed mount, Chilled Mirror inlet, Flyht TAMDAR. Courtesy of FAAM Airborne Laboratory and FLYHT

The drag penalty of such inlets would mainly affect the profile drag of the aircraft, by creating a small interference of the air flow. However, compared to the size of the aircraft, and the size of other elements like pylons, engines, or even the other lifting surfaces, the extra drag of these small air inlets is in the order of tenths of a percentage and would have unnoticeable effects on performance, comparable to that of already existing equipment like pitot tubes or angle of attack probes. At a fleet level, however these marginal performance losses could add up, but more detailed analysis is required for further conclusions.

3.3.2 Performance implications due to the sensor's weight

The weight of humidity sensors varies from less than 1 kg to around 15 kg. Many of these sensors are scientific instruments designed for atmospheric research and thus have not yet been optimized for airline operations in terms of efficient packaging or weight. It is estimated that if this was done, the instruments could be considerably lighter. The extra weight is not considered impactful in terms of aircraft performance and emissions, having an effect in the order of extra grams of fuel per mission, which would be unnoticeable by operators and well within the rounding errors of simulations or even the metering precision of refueling equipment.

3.3.3 Power required by the sensors.

An indicative power requirement for the sensors from the review of specifications ranges from 100-300 Watts, which should be accommodated within the electrical power offering of the aircraft. The experience gained from operating sensors on airlines have proved the feasibility of this. However, this must be evaluated on a case-by-case basis and all the installation must be properly certified and in compliance with airworthiness requirements for the modification to be granted a STC. In comparison, the power produced by an aircraft's engine electrical generator, which is used by the avionics system, air conditioning, communications, entertainment system, lighting etc. can vary between around 100kW and up to 500 kW for narrow body and wide body aircraft, respectively, per engine. The power required by these sensors represents less than 0.1% of the available electrical power on-board.

4. Data transfer

Aircraft collect, receive, and transmit an incredible amount of data, from the constant monitoring of systems and technical parameters to voice transmissions, text messages, navigational information, and flight data. For this, aircraft are equipped with communication systems, some of which are already being used for meteorological data reporting. For example, the AMDAR program uses existing downlinks (VHF, HF or satellite) to relay meteorological data from aircraft to the National Meteorological Service using the Aircraft Communications, Addressing and Reporting System (ACARS) [22]. Some aircraft are already being delivered to airlines with standard software for monitoring some parameters like turbulence, wind, temperature, and icing.

For humidity, two approaches have been followed, one involves updating ACARS to transmit humidity too, once the sensor has been installed, and the other is to have an extra communications system which collects and transmits the data independent of the aircraft avionics using satcom. Newly delivered aircraft could be delivered with provisions to facilitate the integration of any humidity sensor in the future.

It is estimated that a frequency of 1 reading per minute, equivalent to approximately 13 km horizontal resolution could be appropriate for the purpose of ISSR detection, given their size reported in an earlier section. The data could then be transmitted live, merged with other data packages on ACARS and delivered to the local Meteorological Service for analysis. The data would then be used (as it is done today with other meteorological data) to be fed into the meteorological models to improve forecasts including ISSR formation and location.

Data transfer from emerging datalinks should also be considered in the future. For example, Automatic Dependent Surveillance – Broadcast (ADS-B) Minimum Operational Performance Standards (MOPS) contain the humidity parameter. Broadband systems continue to emerge which will allow for a more flexible protocol that aircraft can use to relay rich meteorological information. On-board internet connectivity could also be explored for this purpose.

5. Costs

The costs per aircraft for implementation include the capital cost of the sensors, maintenance costs, data transmission costs, and certification costs, and are approximated below based on the WVSS-II sensor, which is currently installed in over 140 narrow body aircraft[4] [21].

- **Cost of sensors:** highly variable depending on what the final sensor configuration could be but could oscillate between the 20,000 – 180,000 USD.
- **Certification costs:** the original Supplement type certificate for the first aircraft could be as high as 250,000 USD but would considerably drop for subsequent aircraft[5]. Traditionally, for the original STC most of the costs have been on the sensor supplier, rather than on the operator [23].
- **Installation costs:** could be done during routine maintenance, and for the WVSS-II are estimated to be 60-80 person-hours [23].
- **Observation costs:** estimated at about 1,000 USD per month per aircraft. According to the WMO-IATA AMDAR Programme (WICAP), the costs of delivering data from an aircraft to the National Meteorological Service varies greatly but falls in the range of 0.01 – 0.12 USD per observation (using VHF system), with a median value of 0.04 USD. Satellite transmissions are also possible but estimated to be 2 to 3 times more expensive than VHF [22]. It is not uncommon within the AMDAR program for these costs to be reimbursed to the airlines by the National Meteorological Service.
- **Maintenance costs** are very dependent on the sensor. The WVSS-II (not applicable for this purpose but used as an example) is designed for minimum maintenance, however inspections every 15,000 flight cycles are recommended. Confidence in the quality and calibrations of the data will be critical and may require more attention than in the past.

So far, the costs associated to implementing humidity sensors on commercial aircraft, as mentioned in Appendix 1, have been covered by government programs which look at improving the weather predicting capability. Both the IAGOS and the AMDAR programs are government funded and have proven to be extremely useful for the scientific community.

It is recommended that similar programs are established where governments can help airlines subsidize the high costs of the equipment and the installation, for airlines to be able to provide this much needed meteorological data. Research grants, government incentives, or technology funding could help mature these sensors and install them on part of the existing fleet.

[4] Information on costs courtesy of FLYHT, and references quoted on the body of the text
[5] More information on the process for obtaining an STC for water vapor sensors can be found in Ref: [**[23]**]

6. Benefits of water vapor measurements to airlines and to the scientific community

The benefits of aircraft-based weather observations have been extensively reported by the World Meteorological Organization (WMO) [21] [24]. A summary of aircraft-based humidity measurement benefits can also be found in the joint WMO-IATA initiative WICAP (WMO-IATA Collaborative AMDAR Program) [25] [26]. These are summarized here for brevity:

Benefits to airlines	Benefits to scientific and weather community

• Increased understanding of non-CO_2 emissions for their potential mitigation.
• Increased probability of contrail avoidance success.
• Reduces environmental risks of incomplete contrail avoidance strategies.
• More humidity readings can improve weather event forecasting at airports for better planning (i.e., fog, thunderstorms). (70% of all delays at high-capacity airports are weather related)
• Safer and more accurate route planning to avoid severe weather, as well as optimization of fuel planning and consumption.
• Customer perception improved due to taking a leading role in reducing environmental footprint as well as contributing to environmental and climate concerns.
	• Supplement existing radiosonde network to increase spatial and temporal resolution of upper-atmosphere -> better weather forecasting.
	• Increased understanding of contrail formation, persistence, and their climate effect.
	• Increased validation of current contrail prediction models, and models which predict ISSR location, lifetimes, and behaviour.
	• Improved warnings and forecasts on:
	  ◦ Precipitation type and intensity
	  ◦ Thunderstorms/heavy rain/ flooding events
	  ◦ Low-level wind shear/crosswinds
	  ◦ Low visibility conditions
	  ◦ Icing/frost/fog
	  ◦ Droughts/ wildfire weather

The AMDAR program is implemented in over 3,000 aircraft across more than 40 participating airlines (only about 140 of them equipped with WVSS-II humidity sensors on 3 airlines). The measurements include wind speed, pressure, temperature, and turbulence and they contribute to climate-related scientific studies and climate monitoring programs. The benefits have been quantified by the WMO and reported in *The Benefits of AMDAR Data to Meteorology and Aviation* [24].

7. Next Steps and Recommendations

Based on the findings of this research, it is clear there are many uncertainties regarding current feasibility to detect, quantify and ideally avoid non-CO_2 emissions from aircraft operations. To address this, it is important that the industry, together with governments, research institutions and academia, continues and expands trials to gather scientific data and support progressive solutions towards mitigation of non-CO_2.

In support of this, the following series of recommendations, which require active support from all stakeholders:

2024

- Continue trials for mitigation minimizing extra CO_2.
- Selected airlines to join aircraft-based observation trials (IAGOS-AMDAR).
- Improve humidity and weather models.
- Continue research and development of sensors for airlines operations applicable to ISSR detection.

2030

- Fit more sensors on civil aircraft with state support, for ISSR detection.
- Start transmitting data, improve models.
- Verify and validate avoidance trials.
- OEMs to consider provisions for water vapor sensors.
- OEMs to deliver aircraft with compatible software for MET data transmission.

2040

- Considerable worldwide fleet provides MET data.
- Contrail models are reliable with little error.
- Selected avoidance of contrails in some regions where feasible.
- Improved understanding on the climate impact of single contrails.
- NWP models have necessary horizontal and vertical resolution, and microphysics to achieve necessary humidity accuracy.

- Continue research to reduce uncertainties on climate impact.

Figure 10 Summary recommendations

Immediate term actions (2024-2030):

a. Priority number one must be to reduce the climate impact. Given the current uncertainty of contrail detection and climate impact, the priority must be on the reduction of CO_2 emissions and trials to gather scientific evidence for non-CO_2 at this stage should aim to avoid additional CO_2 emissions.
b. Increase airline participation on use of sensors. Airlines are encouraged to participate on programs which can equip aircraft with existing humidity sensors, such as IAGOS or AMDAR (see Appendix 1 for details).
c. Continue scientific research. Governments are encouraged to keep funding research activities in this area, particularly on model improvement for the climate evaluation of individual-flights contrails. Funding for the development of humidity sensors with the characteristics highlighted will also be required: Minimum water vapor concentration readability of 20 ppmv, measuring frequency of at least 1 reading per minute, with integrated temperature reading (accuracy needed +/- 0.5 C) capability, low weight, low or zero maintenance, and minimum calibration required. National technology and strategy programs for non-CO_2 research and technology development, like the UK ATI's non-CO_2 technology roadmap, are encouraged [27].
d. Improve humidity and climate models. The vertical and horizontal resolution of models with respect to humidity fields needs to improve. This will happen by improving the NWP models but also with State support for airlines and the State Meteorological Provider for the costs associated to retrofitting sensors into airlines for data assimilation and model validation.
e. Monitoring Reporting and Verification schemes. MRV must be built on technical, scientific, and economic feasibility studies which must prove the cost effectiveness of the measure in terms of mitigation of

climate impact. Furthermore, the results should be able to be validated and verified. Therefore, at this stage, MRV systems should only be developed to address gaps on research currently undertaken and be on voluntary basis for airlines and other participants.

Mid-term actions (2030-2040)

a. Establish standards for data transmission. Once more measuring infrastructure is established, a standard on readings and data transmission should be established and a scale-up of data assimilation incorporated into participating State Meteorological providers.
b. Continuous validation. More data will enable a more in-depth validation of the models so that they can become ever more reliable.
c. OEMs to include more provisions for meteorological observations. Aircraft manufacturers at this point should consider provisions for more software compatible with meteorological observations and data sharing, as well as additional measuring instruments.

Longer-term actions (2040-2050)

a. Increase of world-fleet providing data. An ever-increasing fleet of aircraft provide readings which help maintain and improve the level of accuracy of the numerical weather prediction models. This enables contrail creation to be forecasted accurately and enables selective contrail management.
b. Improved understanding on the climate impact of single contrails. The data collected over years of research now enables more accurate predictions of the individual climate impact of contrails considering most of the variables that could influence their formation and impact.
c. Non-CO_2 of alternative fuels better understood. The research on climate science, meteorology, and also engine emissions enable an increasing understanding on the non-CO_2 effects of alternative fuels like SAF or hydrogen, for integrated climate impact assessments.

APPENDIX 1 Using civil aircraft as airborne climate laboratories

Civil aircraft have been used as meteorological laboratories in the past. The European Union funded research project, MOZAIC (Measurement of Ozone and Water Vapour) equipped civilian aircraft with scientific instruments including water vapor sensors from 1993 to 2004 [28]. Since 2014, the IAGOS (In Service Aircraft for a Global Observing System) European Research infrastructure program has been using aircraft operated by airlines to take readings on atmospheric chemical composition including humidity. Through the past 30 years, MOZAIC and then IAGOS have provided invaluable data and information to improve weather models, compare and validate the humidity values taken from satellites, and fine tune numerical weather predictions, amongst other applications. A lot of what is known today about ISSR, has been directly or indirectly linked to such measurements.

To date, 8 airlines with 10 total active aircraft are committed to IAGOS[6]. While the humidity, temperature and atmospheric chemistry data have been extremely useful for climate research, this is not a scalable model for operationalizing contrail prediction tools. The instruments are part of a whole package of atmospheric research instruments, which are not suitable for installation on every aircraft. The data is handled by a small group of scientists which stores it and shares it open access after scientific qualification. The humidity sensor used is suitable for ISSR detection, however at low temperatures has reaction times which can reach 2 minutes (30-50 km of horizontal resolution) and so it may be of limited applicability with respect to the high resolution needed for this purpose.

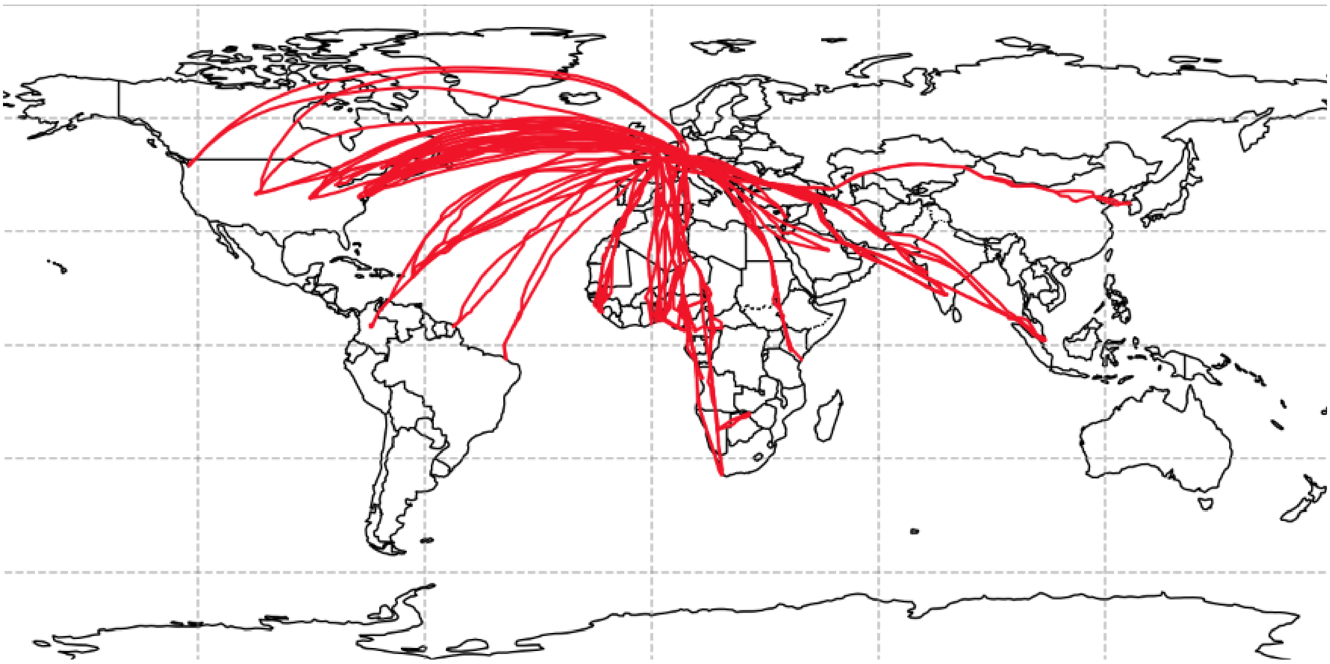


Figure 11 IAGOS data coverage map from: [21]

Another example is the AMDAR (Aircraft Meteorological Data Relay) program, which has been operating for over 30 years. AMDAR automatically transmits meteorological data from the aircraft to the ground to support improved weather forecasts and applications for aviation and the wider community [29]. Some AMDAR aircraft

[6] i) Air Canada, ii) Discover Airlines, iii) China Airlines, iv) Air France, v) Hawaiian Airlines, vi) Cathay Pacific, vii) Lufthansa Airlines, and viii) Iberia. Aircraft installed: 1 Airbus A340, 8 Airbus A330, and there are plans to expand the program to Airbus A350

are equipped with humidity sensors, however, in contrast to IAGOS, this program uses the data to do vertical profiling of humidity (mainly during ascent and descent) in complement to radiosondes. The data has been used to predict fog, thunderstorms, and to feed into weather stations for weather forecasting. The water vapour concentration resolution of the sensors (WVSS-II) used is in the range of 50-60,000 ppmv, and thereby not suitable for ISSR detection (where the lower range resolution needs to be about 20 ppmv). Project MEFKON, however, is currently testing, if the WVSS-II sensor would be capable to bring a benefit for ISSR detection. These sensors are the most common humidity sensors on aircraft and are operational mainly in the USA on board of over 140 aircraft[7].

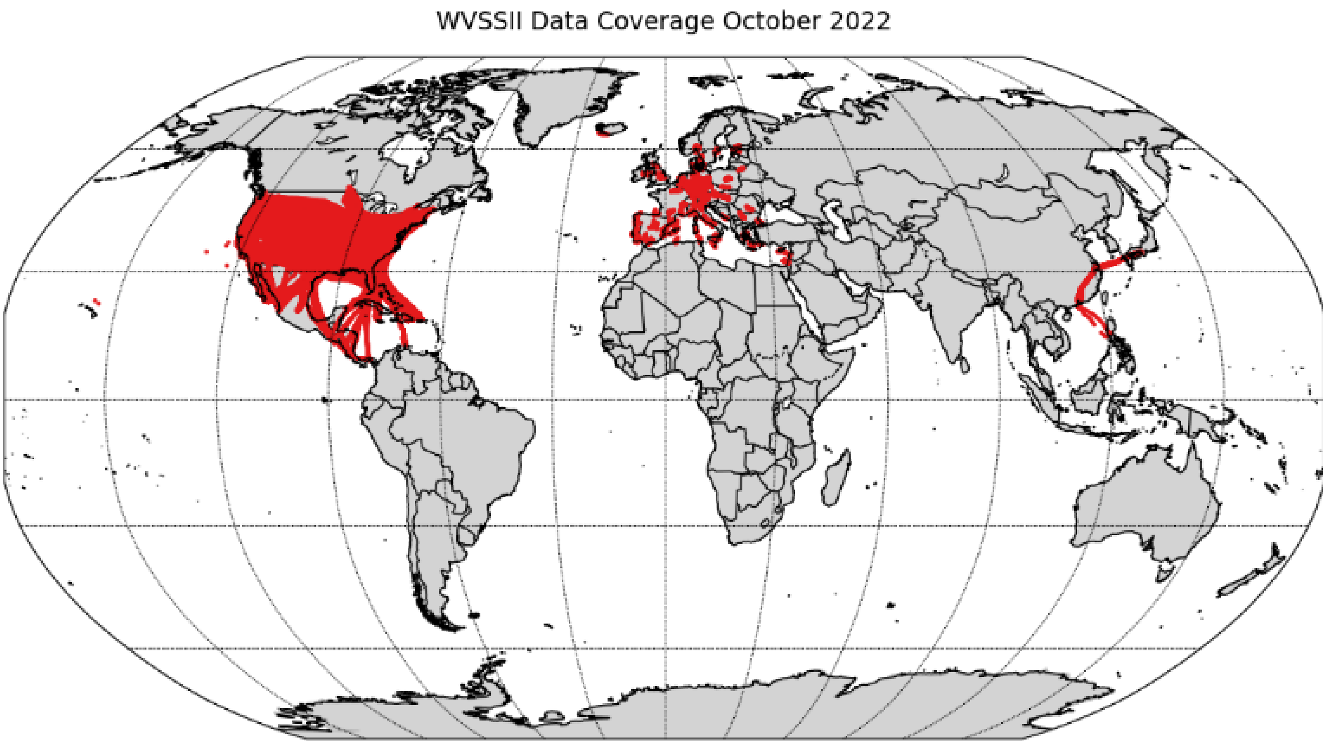


Figure 12 WVSS II Data coverage map, WMO [21]

Aircraft-based data collection is the most cost-effective solution for in-situ atmospheric weather data collection. For example, the humidity readings from the humidity sensors are estimated to cost only 12-20% of the costs of a radiosonde program and provide much larger coverage [24]. Beyond the humidity sensors, the World Meteorological Organization (WMO) states that around 3,500 aircraft are equipped with AMDAR reporting capability (which provide other meteorological data). Around 750,000 AMDAR observations are collected daily. The AMDAR observing system extended to six WMO world regions, including humidity observations over Europe and North America [30].

Other initiatives by research institutions like NASA, DLR or the FAAM Airborne Laboratory, amongst others, have equipped aircraft with scientific instruments for atmospheric research including humidity sensors. Aircraft like the BA146 (FAAM), the Gulfstream G550 (HALO aircraft, DLR), or a NASA fleet including a DC-8, a Falcon amongst others have tested scientific instruments for humidity at high altitudes with successful results. Japan Airlines and National Institute for Environmental Studies are conducting atmospheric observations in the frame of the CONTRAIL project since 2005 [31].

[7] A319, A320, and A321 Lufthansa, B757-200P, UPS and B737-300, -700, and -800 Southwest Airlines.

Lufthansa Airlines and Karlsruhe Institute of Technology will equip an Airbus A350 with the IAGOS-CARIBIC-System that is expected to enter service from 2025, replacing the first CARIBIC system that was installed on an A340 from 2004 to 2020 [32].

APPENDIX 2 List of humidity sensors and their characteristics

Tunable Diode Laser (TDL) absorption spectrometry

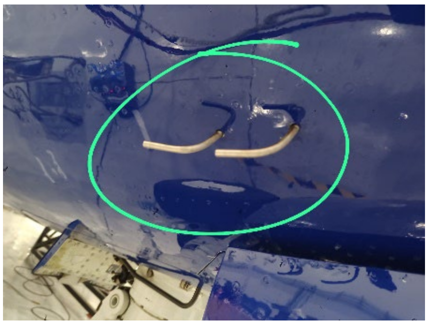
Sensor name	**WVSS-II**
Operation principle	Air is drawn into the sensor through an intake on the aircraft skin, the air is warmed and passed through a tube where a laser is passed through it. The receiver detects the laser and the water vapor content in the air is derived from changes in the laser beam. WVSS-II uses a special wavelength modulation technique lowering the detection limit, which allows designing a very compact instrument. Disadvantage is that the instrument needs a careful characterization depending on different parameters like pressure and temperature.
Minimum resolution	50-60 ppmv
Accuracy	High accuracy near ground-level but low accuracy at low humidity levels near the lowest range of detection. Unsuitable for ISSR detection.
Weight	~3 kg
Cost	~80,000 USD
Box size	25X13X8 cm (electronics box size)
Calibration	Designed for minimum maintenance and calibration – designed for airline operations
Aircraft in operation with these sensors	Through the E-AMDAR program: ~136 sensors on commercial aircraft mainly: B757-200P, B737-300/700/800, A319/20/21. Airlines operating them: UPS, Southwest, Lufthansa Airlines
STC	Existing STC for aircraft already in operation. Plans to extend to other aircraft. Historically the process for new aircraft type has lasted 9-24 months in the US.
Installation	Two inlet types: Rosemount air intake (left) and Flush mount, right. (Image credit: FAAM Airborne Laboratory.  While the flushed mount is closer to the aircraft skin and causes less drag, the Rosemount inlet receives air from outside the aircraft boundary layer, and so the readings are less affected by the interaction between the aircraft skin and the air. The Rosemount inlet, however, appears to be more susceptible to the effects of water ingestion, and there are indications that it slows the measurement response.
Suitability for airline operations:	Suitable and demonstrated. But probably not for ISSR detection, as the lower detection limit is higher than the water vapor concentration in the UTLS. These sensors, however, have proved to be highly effective for low altitude humidity profiling.
References	[33]

Sensor name	SHARC, (Sophisticated Hygrometer for Atmospheric Research)
Operation principle	Similar to the WVSS-II, the SHARC is also a TDL sensor: Air is drawn into the sensor through an intake on the aircraft skin, the air is warmed and passed through a tube where a laser is passed through it. The receiver detects the laser and the water vapor content in the air is derived from changes in the laser beam. The SHARC sensor uses direct absorption technique which in principle is calibration free. The SHARC sensor has longer absorption length than the WVSS-II above, and thus can provide readings at lower concentrations.
Minimum resolution	2-3 ppmv
Accuracy	Very high accuracy, +-1 ppm or 5%
Weight	~15 kg
Cost	~170,000 EUR
Size	42 x 38 x 18cm
Calibration	No calibration needed, but regular checks recommended every 1-5 years.
Aircraft operation with these sensors	DLR HALO research aircraft (Gulfstream G550)
STC	Inexistent basis for commercial aircraft.
Installation	Flush or Rosemount intakes
Suitability for airline operations:	Suitable. Commercially available (aerotrace GmbH) but currently only as 'scientific version'. For commercial use on airliners a more compact and robust version has to be developed.
References	[34]

Sensor name	DLH- Diode Laser Hygrometer
Operation principle	Same principle as SHARC and WVSS-II sensors
Minimum resolution	5 ppmv
Accuracy	5% or 0.5ppm
Weight	13 kg
Cost	
Size	43x33x23 cm
Calibration	
Aircraft operation with these sensors	NASA fleet: B200 - LARC, DC-8 - AFRC, Global Hawk - AFRC, P-3 Orion - WFF, WB-57 - JSC, Sherpa - WFF, HU25 Falcon - LaRC, Twin Otter - CIRPAS – NPS, FAAM Airborne Laboratory (planned)
STC	Only on research aircraft
Installation	Various installations have been tried, notably the DC-8 had a laser transceiver mounted to a window plate, emitting a laser beam to a reflective surface on the engine housing to complete an optical path.
Suitability for airline operations:	Potentially suitable but not available commercially

References	[35] [36] [37]

Chilled mirror

Operation principle	Air is drawn into the sensor and passed through a mirror which is temperature controlled. The temperature is regulated to the point where dew or frost is formed on the mirror surface. The dew/frost formation is detected by optical methods. The measured dew/frost point temperature is a direct measure of the humidity.
Minimum resolution	1-5 ppmv
Accuracy	Very high accuracy
Weight	Variable between manufacturers. Buck CR2 weighs ~3kg, Michell S8000RS weighs ~22kg. Both require external flow controller and pump in addition.
Cost	Over 30,000 EUR
Size	Buck CR2 is 10x10.5x3.5 inches, Michell S8000RS is 190 x 445 x 550mm
Calibration	Once a year, but could need regular cleaning of the mirror, particularly if the aircraft flew into dusty or very polluted conditions.
Aircraft operation with these sensors	Experimental and research aircraft, for example the FAAM Airborne laboratory, BAE 146
STC	Inexistent basis for commercial aircraft, just for research aircraft
Installation	The inlet is similar to a backward-facing pitot tube, the sensor is installed on the body of the aircraft if the instrument is designed for exposure to cold and low pressure. The FAAM BAE146 has the sensor box of a Buck CR2 in a bay near the nose landing gear. Similar instruments designed for laboratory use must be installed in the pressurized part of the aircraft. 
Suitability for airline operations:	**Not suitable.** Requires calibration and cleaning by specialist staff. Because the principle of measurement relies on the mirror to get condensation into it, the response time is slow. Since readings can take a few minutes to change, the aircraft could have flown into or out of an ISSR without it being detected, or a with a detection margin error of several kilometers.
References	[38] [39]

Lyman-alpha – Fast in Situ Stratospheric Hygrometer (FISH)

Operation principle	Outside air is drawn into the sensor by a forward-facing inlet. The instrument ionizes the water vapor molecules by using the Lyman-alpha radiation of a VUV lamp to dissociate water molecules into single hydrogen atoms and excited OH molecules. Fluorescence is produced as the OH molecules emit photons, and these photons are read by a receiver. These readings are then correlated to the air humidity.
Minimum resolution	1 ppmv

Accuracy	High accuracy, 0.4ppm or 6%. But low accuracy at high humidities (near ground level). Many sensors are calibrated to values against FISH sensors due to their high accuracy.
Weight	~45 kg
Cost	n/a
Size	42 x 50 x 32cm
Calibration	Needs to be calibrated periodically. The VUV lamp needs a Hydrogen-rare gas mixture from a bottle that must be refilled frequently.
Aircraft operation with these sensors	Experimental and research aircraft only. Flew in the DLR HALO aircraft, and on NASA research aircraft.
STC	Inexistent basis for commercial aircraft, just for research aircraft
Installation	
Suitability for airline operations:	**Not suitable.** Requires constant calibration, this is a robust research instrument, for atmospheric research purposes.
References	[40] [34] [41] [42]

Mass spectrometry – Atmospheric Ionization Spectrometer for Water Vapor (AIMS-H_2O)

Operation principle	Air draws in through an intake, the air gets ionized in an electrical discharge ion source. The ion clusters get measured with the mass spectrometer.
Minimum resolution	1 -500 ppmv
Accuracy	7-15%, low accuracy at low altitudes and high humidities (higher than 500 ppm). 50m horizontal resolution
Weight	~115 kg
Cost	n/a
Size	~ 43 x 50 x 130cm
Calibration	Can be calibrated in-flight by adding water vapor as a reference through it.
Aircraft operation with these sensors	Only research aircraft like DLR – HALO
STC	None for commercial aircraft
Installation	
Suitability for airline operations:	**No-** Requires calibration and maintenance, suitable for scientific purposes but unlikely to work on an airline environment.
References	[34]

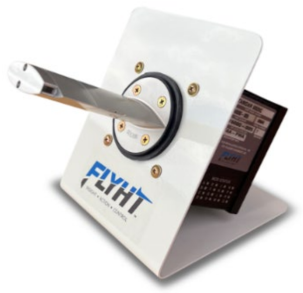
Capacitive Relative Humidity (ICH) (IAGOS sensor)

Operation principle	Humidity and temperature read based on the capacitance change of a hydroactive polymer film which absorbs H_2O molecules by the dielectric membrane on the sensor.
Minimum resolution	10 ppmv

Accuracy	High accuracy (~5-6% relative humidity with respect to water) at high altitudes, but slow response.
Weight	~2 kg (including transmission box)
Cost	25,000 Euros for the full system including sensor, housing, and transmission box. Installation costs can be 50-100,000 Euros
Size	Sensor box size: 14X12X7 cm
Calibration	Every 2-6 months between calibration, calibrated in climate chamber against chilled mirror frost point hygrometer. Could be extended to 6-12 months with in-flight calibration. Calibration run by the IAGOS program which exchanges the old sensor for calibration outside aircraft operation hours with a newly calibrated sensor.
Aircraft operation with these sensors	**Yes,** commercial airlines: Lufthansa Airlines, Air France, China Airlines, Cathay Pacific, Iberia, Hawaiian Airlines, Air Canada, Discover Airlines On A330 and A340
STC	Existing for A330, A340, and A350 is being explored
Installation	Rosemount inlet for the sensor. Electronics in a rack, along with other scientific instruments, located at the aircraft avionics bay.  Picture courtesy of Lufthansa
Suitability for airline operations:	The sensor response is slow due to the principle of measurement particularly at low temperatures (can be around 2 min response, corresponding to 30-50 km resolution). The sensor is operational in airliners but as part of a scientific program, which does not have the capacity to handle, calibrate, install and process the data from hundreds of aircraft.
References	[40] [43] [44] [45]

Capacitive Relative Humidity (TAMDAR)

Operation principle	Similar to ICH this sensor works on the principle of H_2O molecules absorption into a membrane which changes capacitance. Note: This sensor will be discontinued.
Minimum resolution	No data
Accuracy	Quite inaccurate at cruise levels. Very slow response, 1 reading every 7 minutes above 20,000 ft.
Weight	No data
Cost	No data
Size	No data
Calibration	No data

Aircraft operation with these sensors	124 sensors installed on AirAsia fleet mainly on regional aircraft, but the program is being phased out due to low accuracy.
STC	Required and existent for aircraft currently operating this sensor.
Installation	Self-contained in a fin-type inlet (photo) with GPS and transmitter all in one unit. 
Suitability for airline operations:	It has been tried on airline operations but proved to require constant maintenance and the readings were inaccurate
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