Project

Aircraft Contrails – Observation and Prediction

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Abstract

Purpose – In this project contrails in the sky are observed. Their existence and persistence is compared with calculations.
Methodology – Photos are taken of aircraft and of their contrails passing by in cruise. The contrails are categorized according to their lifespan. The website flightradar24.com is used to obtain flight data (altitude and temperature). Also, satellite images and contrail recordings were collected from other publicly available websites. The Schmidt-Appleman diagram and the Schmidt-Appleman criterion were used for predicting contrail existence and persistence. Input data is altitude, temperature, and relative humidity. Relative humidity was obtained via the website windy.com from the European Centre for Medium-Range Weather Forecasts (ECMWF).
Findings – Contrails can be predicted with the method. For contrail lifespan three categories were defined: no contrails, transient contrails (lifespan of a few seconds up to five minutes), and persistent contrails. The lifespan of contrails was correctly categorized.
Research Limitations – The observation took place with the naked eye and a smartphone camera. Accordingly, no observations could be made during the night. In addition, only a limited number of aircraft were observed. The resolution of the relative humidity is limited with respect to altitude and time.
Practical Implications – A hands-on approach is presented, ready for everyone to apply.
Social Implications – Contrails can be seen by everyone. Systematic contrail observations readily expose the aviation industry as fostering or boycotting avoidance of warming contrails.
Originality – The well-known idea of contrail observation and prediction from the ground may have been deemed too simple and unworthy of science so far to be applied in a project.

HAW HAMBURG

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

Aircraft Contrails – Observation and Prediction

Task for a *Project*

Background

Aviation-induced cloudiness (due to contrails, persistent contrails, and contrail cirrus) is globally responsible for about half of the warming effect of aviation (depending on the metric). Locally, contrails can be warming or cooling. Avoiding many single warming contrails can help to reduce the global warming effect of aviation. It is a two-step process; first it needs to be predicted if an aircraft leaves a contrail behind or not. This is done with the Schmidt-Appleman Diagram. Input values are altitude, temperature, and relative humidity. If it is determined that a contrail is formed, it is investigated in a second step if the contrail stays in the sky for a short or for a long time. This depends again on temperature and especially on relative humidity. Contrails are persistent at higher relative humidity. Otherwise, they dry (sublimate; the direct transformation of ice into water vapor). Only contrails that are sufficiently persistent to form cirrus clouds are relevant for the energy balance of the atmosphere. A comparison can be made between observed contrails in the sky and their calculated possibility of existence and estimated persistence. If calculations and observations show good agreement in a trial, contrail prediction with the aim to avoid warming contrails becomes feasible.

Task

Task of this project is to observe contrails in the sky and to compare their existence and persistence with calculations. These steps need to be worked on:

- Summarize contrail fundamentals (formation, duration, impact, avoidance).
- Explain prediction of contrails and estimation of their span of life.
- List elements of contrail observation and documentation.
- Observe aircraft passing by in cruise, classify their contrails, compare with results from their contrail prediction, and discuss the achievable accuracy of the prediction also in view of required expenses for necessary tools.

The report has to be written in English based on German or international standards on report writing.

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List of Abbreviations

ADSBE	ADS-B Exchange
AROME	Application of Research to Operations at Mesoscale
BE	Breakthrough Energy
CD	Cambridge Dictionary
CED	Collins English Dictionary
CoCiP	Contrail Cirrus Prediction Model
CW	Collins Wörterbuch
DOC	Direct Operating Costs
DWD	Deutscher Wetterdienst
ECMWF	European Centre for Medium-Range Weather Forecasts
EFR	Effective Radiative Forcing
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FL	Flight Level
GFS	Global Forecast System
GWP100	Global Warming Potential for one hundred years
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
LFKB	Lärmschutzgemeinschaft Flughafen Köln/Bonn e.V.
NEMS	NOAA Environmental Modeling System
NOAA	National Oceanic and Atmospheric Administration
SAC	Schmidt-Appleman Criterion
SAF	Sustainable Aviation Fuel
UKV	United Kingdom Variable-resolution weather forecasting system

List of Symbols

RH	relative humidityof ambient air
RHmin	relative humidity for saturation with respect to ice (the theoretical relative humidity for a persistent contrail)
R	persistence factor

List of Definitions

Cloud
"A grey or white mass in the sky, made up of very small floating drops of water."
(Cambridge University Press & Assessment 2023b)

Contrail
"A visible condensation of water droplets or ice crystals from the atmosphere, occurring in the wake of an aircraft, rocket, or missile under certain conditions."
(Collins 2023a)

DOC
"Airline costs may be divided into Direct Operating Costs (DOC) and Indirect Operating Costs (IOC). DOC are costs that can be allocated to the aircraft whereas IOC are more generally caused by running the airline's business. DOC are made up of depreciation, fuel costs, maintenance costs and other costs and other cost elements depending on DOC definition."
(Scholz 2004)

Flight level
"A specified height at which an aircraft is allowed to fly."
(Collins 2024)

SAF
"Sustainable aviation fuel (SAF) is the main term used by the aviation industry to describe a nonconventional (fossil derived) aviation fuel. SAF is the preferred IATA term for this type of fuel although when other terms such as sustainable alternative fuel, sustainable alternative jet fuel, renewable jet fuel or biojet fuel are used, in general, the same intent is meant."
(IATA 2023)

There are many ways to get a Fuel "sustainable." The author limits himself to using the term only if the fuel was really produced in a climate-neutral way and renewable energies or waste products were used. A fuel that is described as climate-neutral through supposed offsetting projects or certificate trading is not to be regarded as "sustainable" in this project.

1 Introduction

1.1 Motivation

Aviation-induced cloudiness (due to contrails, persistent contrails, and contrail cirrus) is responsible for huge amounts of the warming effect of aviation. This warming effect can be eliminated tomorrow and for almost no money. This project will explain how this can be done. In contrast to other pollutants, contrails can be observed by everyone. How they are evaluated will also be explained here. Everyone can see if aviation will continue to change cloudiness to the detriment of our climate or if aviation will change for the better.

1.2 Title Terminology

Aircraft
“Any vehicle, with or without an engine, that can fly, such as a plane or helicopter.”
(Cambridge University Press & Assessment 2023a)

Contrail
“A visible condensation of water droplets or ice crystals from the atmosphere, occurring in the wake of an aircraft, rocket, or missile under certain conditions.”
(Collins 2023a)

As part of this project, only contrails that arise from aircraft’s exhausts are considered. Contrails that appear on the flaps during landing approaches, for example, are not considered.

Observation
“Is the action or process of carefully watching someone or something.”
(Collins 2023b)

Prediction
“If you make a prediction about something, you say what you think will happen.”
(Collins 2023c)

1.3 Objectives

The aim of this work is to use simple tools which everybody could use to predict contrail formation. Another aim is to clarify whether it is necessary to create complex numerical models, or whether simple tools are sufficient to make a fairly accurate prediction which could be useful for reducing the climate impact of contrails. To do this, observations should be made. Some calculations are therefore needed. Possibly, a strategy to avoid them could be developed with the help of these simple tools.

1.4 Literature Review

In the course of this project, some scientific articles were read, and their results were incorporated into this project. In the following, the author presents a selection of some which either have been particularly helpful or could be of interest to the reader in the opinion of the author.

Schumann (1996) explains in a very comprehensible way what research has already been done in the past on contrails. He refers to all kinds of papers by previous authors. The bibliography listed there therefore contains a great deal of knowledge about contrails. Schumann also explains how exactly contrails are formed. It also provides a large part of the formulas that seem to have been incorporated into Professor Dieter Scholz's Excel table. Furthermore, the so-called Schmidt-Appleman diagram can also be found there, which plays a key role in the verification of the observations.

At http://environment.aerolectures.de there are many lectures regarding the topic environment. The lectures take place regularly. By clicking at the link, you can also view slides of lectures that have already been held. Some of them have already been viewed by the author and have certainly contributed to the interest in the topic dealt with here. Some selected contributions are listed below and can also be found in the List of References. (Burkhardt 2021, Scholz 2022, Jurkat-Witschas 2022, Leemüller 2022, Voigt 2022)

Google also cites studies as part of its project (more on this in Chapter 2.5). The studies are listed in the reference section under: McCloskey 2021, McCloskey 2023a, McCloskey 2023b, Geraedts 2023. Last but not least, some other publications that might be interesting to read: Kaiser 2012, Castino 2023, Lee 2021.

1.5 Structure of the Work

First of all, the basics of contrails will be presented. Chapter 2, which is the first main chapter, therefore deals with how contrails form in the first place and what the causes are. Then the differences between the contrails are discussed and for the observation different categories for contrails must be defined. In the third Chapter Schmidt-Appleman Criterion gets explained and the tools for the observation are shown. In the fourth Chapter the observation itself is carried out and the results of the observation itself are presented.

Chapter 2 deals with the fundamentals of contrails and categorizes them.
Chapter 3 explains Schmidt-Appleman criterion and the diagram and deals with the tools of the observation.
Chapter 4 shows the observation, its results, and its discussion.

2 Fundamentals of Contrails

2.1 What Are Contrails and How Do They Form?

Almost all aircraft nowadays fly with kerosene. The combustion of kerosene mainly produces carbon dioxide and water vapor. This produces approximately 3.16 kg of CO2 and 1.23 kg of water vapor per kilogram of fuel. In addition, small amounts of nitrogen oxides and other greenhouse gases, as well as soot and free dust, are emitted (LFKB 2021, ICAO 2018). Airplanes fly most of the time at altitudes where the outside temperature is less than -40 °C. When the hot exhaust gas comes out of the engines and cools down quickly, the air may reach the so-called liquid saturation point. The point at which droplets of water may start to condense. Small water droplets can condense particularly well on small particles, such as soot particles, which may speed up the process. These droplets freeze into smaller ice crystals due to the cold temperatures and condensation nuclei from the surrounding atmosphere or exhaust gases.

There is most likely a gap between the aircraft and the start of the contrail. That is because there must be sufficient mixing by the hot gases with the ambient air so that the saturation point is reached, and furthermore only above a certain size do these ice crystals scatter enough light to be visible to the naked eye.

2.2 What are the Conditions for Contrail Formation?

Contrails usually need certain conditions to start formation this is usually at altitudes greater than 26000 ft, where the temperature is mostly below -36.5 °C, but more likely at temperatures below -40 °C (Wikipedia 2023b). Contrails will almost under all conditions form when the ambient temperature is below -51 °C. More details about their formation can be found in Schumann (1996). There are some other factors than the temperature alone. For example, there propulsive efficiency and the pressure. Which will not be discussed in depth in this work. More details can be found in papers by other authors such as from Schumann (1996) and in the there referred sources.

Sometimes small contrails can be detected in the wake vortices behind airplanes or the propeller blades. These are caused by the pressure drop and thermodynamic effects associated with condensation of the moist. However, this phenomenon will not be examined further in the context of this project.

2.3 What is Their Size and Duration?

The size and lifespan of the contrails depend heavily on conditions in the atmosphere. If the air is rather dry, i.e. has a relative humidity of a few percent, the contrails have a short lifespan of a few seconds to a minute – if they form at all. After this time, the contrails will dissolve again. This is because the relative humidity of the air fell below the ice saturation (because of mixing with surrounding air or subsidence or radiation heating). In general, the contrails with a short lifetime extend only a few hundred meters in length and in the low three-digit range in width. Vertically, depending on the type of aircraft, between 300 and 500 meters are typical. (Wikipedia 2023b)

Contrails can survive for several hours under suitable atmospheric conditions. These contrails can then extend over several hundred meters in width and over many kilometers in length. A short contrail can be seen in Figure 2.1. An example of a longer contrail is shown in Figure 2.2.

Figure 2.1: Example of a short contrail created by an aircraft.

If contrails persist for several hours, they are exposed to natural winds. As a result, the contrails lose their density over time and become more and more wide. At some point, these contrails may have become natural cloud-like formations. These structures can take on almost all kinds of shapes. Often there are cirrus clouds. This can be seen in Figure 2.2 as well as in Figure 2.3 in the background, behind and around the contrails.

Figure 2.2: Very long contrail and (most likely) Contrail-Cirrus Clouds in the background.

Figure 2.3: Picture of several aircraft contrails at sunrise. Source: Dieter Scholz.

2.4 What is Their Impact?

The average contrail itself has very little impact on the climate. Although the contrails have a fairly high density after release and are therefore not penetrable for parts of the solar radiation, they then extend over a very small area and, as already described, the lifetime is most of the time also rather short. That is why the direct influence, after release, of average contrails is negligible.

However, some of the contrails may spread out and form clouds which have been shown to have a greater effect on the climate. The resulting cirrus clouds are less radiation-permeable to long-wave thermal radiation, but the short wave length radiation can pass through them (Gerhard 2019). During some time of the day, the reduction in radiation may act like a solar shield that scatters and reflects parts of the sun's radiation back into space. At night, on the other hand, clouds created by contrails can act kind of as a blanket and thus intensify the greenhouse effect.

There are already studies that deal with the consequences for the climate of these clouds. The study by Lee (2021), which dealt with the question how much the air traffic between 2008 and 2018 contributes to climate change comes to the conclusion that the sector's contrail-related warming impact contributes significantly more to the climate change than CO_2 emissions.

The global effective radiative forcing (EFR) from aviation in 2018 was about 100 mW/m^2 which was 3.5% of the total EFR. About two-thirds of this share come from non-CO_2 effects. Where contrail cirrus have the largest contribution with about 57% (Jurkat-Witschas 2022). When looking at another measure of the influence of contrails on the climate, the Global Warming Potential for 100 years (GWP100), it becomes clear that the effect is anything but negligible. The estimated percentage of Contrail Cirrus is at 35% while CO_2 and NOx are at 56% and 9% respectively. (Leemüller 2022)

The "Umweltbundesamt", which is the Federal Environment Agency of Germany, has also dealt with the topic. It also concludes that the climate effect of contrails is not negligible. (Bopst 2019, Matthes 2023a, Matthes 2023b)

2.5 What Is Currently Being Done to Avoid Contrails?

It has become clear to companies that they must position themselves in an environmentally friendly manner in the future. Many companies around the world are already investing in projects that aim to do something about climate change. There are also projects that specifically want to tackle the problem of contrails. The following is a selection of projects and companies that could potentially be of interest to the reader and are intended to provide a picture of the current situation surrounding the reduction of the climate effects of contrails.

2.5.1 Smaller Players

There are many smaller companies and start-ups that are committed to reducing contrails that have a negative impact on the climate. Most of them aim, to reduce the climate impact by using alternative fuels. An example of such a company would be Synhelion. The company wants to use solar energy to produce synthetic fuels. These fuels should then have a lower climate impact because, on the one hand, they are CO2 neutral and on the other hand, they are expected to release fewer soot particles into the atmosphere, which in turn would mean fewer potential condensation nuclei. This is intended to reduce the climate impact of contrails. SkyNRG follows a similar approach but with different ways to generate the SAF. (Synhelion 2023, SkyRNG 2023)

2.5.2 Bigger Players

But there are bigger players around. Google is one of them. Google and its research team have decided to develop a model based on artificial intelligence. Unlike other models, it does not rely solely on weather data, but uses AI to look for contrails in satellite images. Google is currently using just one satellite but is planning to spread out to the Meteosat network of geostationary satellites. Regarding Google, it is possible to predict contrails with their systems. Google also partnered with American Airlines, one of the biggest airlines in the world, to test contrail avoidance in the real world and evaluate their results. According to Google only a slight change in flight altitude is necessary to avoid the very humid areas and prevent the formation of persistent contrails. These slight changes in flight altitudes itself are not a problem for the airlines, as it is already common practice to avoid turbulence, for example. Unfortunately, the author was not able to find a way to use Googles model. It seems that it is not publicly available. In consequence it can't be used for the observation and prediction in this project. (Google 2023)

American Airlines is not the only big airline company teaming up with companies, who claim to have strategies to avoid contrails and to show that they seem to be doing something against climate change. For example, there is Etihad. Etihad is cooperating with SATAVIA which claims that their vision is to make aviation greener (Etihad 2023). SATAVIA says:

"SATAVIA's vision is to make aviation greener, implementing contrail management with leading operators like Etihad to cut per-flight climate impact." (SATAVIA 2023b)

SATAVIA is a company which is specialized for developing software for the aviation industry. The company offers a wide range of services, including aircraft monitoring, weather prediction, and flight route optimization. SATAVIA's technology uses data analysis and machine learning to help airlines reduce their operating costs while increasing the safety and efficiency of their flights and now has developed software that should help in contrail avoidance. (For more information for min. DOC take a look at Caers 2019.) SATAVIA itself has several big players as partners or stakeholders including AWS, Microsoft, and the University of Cambridge's Aviation Impact Accelerator. (SATAVIA 2023a, SATAVIA 2023b)

It seems like that big companies are more and more getting interested in reducing the climate impact of their doing but none of them has gone beyond some testing. As far as the author knows there is no company actively trying to avoid warming contrails at the time.

Social media wise there is not much to find but it seems like the topic is getting more interest at the time of writing this publication. For example, there is a Youtuber called "Mentour Pilot" with a current subscriber base of over 360000 people at the Mentour Now channel at which he recently talked about this topic. The recent video can be found under Hörnfeldt 2023. Hörnfeldt has currently 1.9 million subscribers at his main channel Mentour Pilot, which covers many different topics regarding aviation.

2.6 What are the Different Contrail Categories within This Project?

As part of this project, the various contrails were divided into categories to allow better comparison in between. In the following a short explanation of these categories is presented. There may be times where no contrail can be seen. Then its category name is "**No contrail at all**." The persistence factor (Chapter 3.2) is expected to be less than one.

There may be some times, where a contrail of short lifespan can be observed. A semi-persistent or **transient contrail** is one that has a lifetime, once formed behind the aircraft, of a few seconds to five minutes. The end of its lifespan is reached when the contrail is no longer visible to the naked eye. The persistence factor (Chapter 3.2) is expected to be less than one, but close to one.

Finally, a **persistent contrail** is one that has a lifetime, once formed behind the aircraft, of longer than five minutes. The end of its life is reached when the contrail is no longer visible to the naked eye. Typically, it diffuses so that it is not distinguishable from the surrounding clouds after some time. Here the persistence factor (Chapter 3.2) is expected to be greater than one.

Why this kind of definition? Why is the time for a transient contrail chosen for a few seconds to five minutes? Why not longer than that? First of all, the lifetime of contrails is not clearly defined. Everyone has their own definition of lifespan. Consider the spread of contrails and their seamless transition to cirrus clouds. This means that one person could claim that the observed cloud is still a cloud caused by contrails and therefore, in a more distant sense, a contrail, while another person no longer believes that it is a cloud caused by a contrail. The transparency of the contrail is also disputed. Is the supposed contrail still a contrail? Or is it just some haze that is still in the atmosphere? Furthermore, contrails cannot always be observed over their entire lifetime. It is sometimes the case that winds carry them away and they are therefore out of reach of the observer. All this led the author to opt for such a short period of time as the basis for the definition.

3 Prediction of Contrails

3.1 Fundamentals of the Schmidt-Appleman Criterion

Schmidt and Appleman have conducted many studies on contrails over the past century and are trying to better understand their formation. In his article, Schuhmann uses the knowledge of various authors to explain the formation of contrails. A very detailed explanation and his assumptions should be omitted here. (Schumann 1996)

When the exhaust gas leaves the engine, a mixing process begins. The hot exhaust gas mixes with the cold ambient air. The Schmidt-Appleman diagram is based on idealized cooling. It is assumed that the mixture comes to rest and completely releases its kinetic energy. The two curves in the diagram out of Gierens (2008) which can be seen in Figure 3.1, represent the saturation pressure curves. The upper one is for water, the lower one for ice. The cooling then follows from the top right from the top right, out of scale area, to the bottom left into the visible area of Figure 3.1 until complete mixing is achieved. The phase progression of the mixture describes a straight line that runs along the arrow and the dashed line in Figure 3.1. Depending on where this cooling ends, different events can occur. This means that no contrails could appear at all. This would be the case if the cooling ends to the right of the tangent (the right dotted line). Also, short-duration contrails could occur (transient contrails, shown in light gray in the diagram). Or persistent contrails could arise. (Shown as a dark gray area in the diagram.) In reality, the transitions between the areas are fluid and not sharply defined as shown here. The tangent of the cooling shown in the diagram (shown here with dashed lines) can be calculated. For more information on the calculation, Schumann (1996) or Scholz (2023b) (partly in German) is recommended. The trajectory tangent to the water saturation curve (dotted) marks the warmest temperatures for which contrail formation is possible. Contrails are persistent and can spread out into contrail cirrus when the trajectory ends in an ice supersaturated state. Otherwise, the contrail will be short with a lifetime of up to a few minutes.

In the third chapter of the article, Schuhmann cites a so-called Schmidt-Appleman diagram (Figure 3.2). The Schmidt Appleman diagram shows the so-threshold temperature T_{LC} over the altitude (or pressure) for various relative humidities of the ambient air. From the Schmidt-Appleman criterion follows that contrails are to be expected if the temperature falls below the threshold Temperature. As can be seen from the diagram, the threshold temperature depends on the relative humidity of the ambient air. If the temperature falls below this limit value (i.e., it can be found to the left of the relative humidity curve), a contrail is formed. If, on the other hand, the temperature is too high (i.e., to the right of the curve), no contrail will form. In this diagram, the minimum height for contrails at a relative humidity of 100% is about 8.4 km. Here, the ISA temperature line intersects with the function of relative humidity. At a humidity of 0%, it is also recognizable that there is a second intersection point at about 14 km. This is where the maximum height for this humidity for formation of a contrail regarding ISA-Temperature is reached. According to the diagram, there are no contrails above 14 km. With further calculations the persistence of contrails can be predicted. Therefore, take a look at: Scholz (2023a), Scholz (2023b). A detailed explanation should be omitted here.

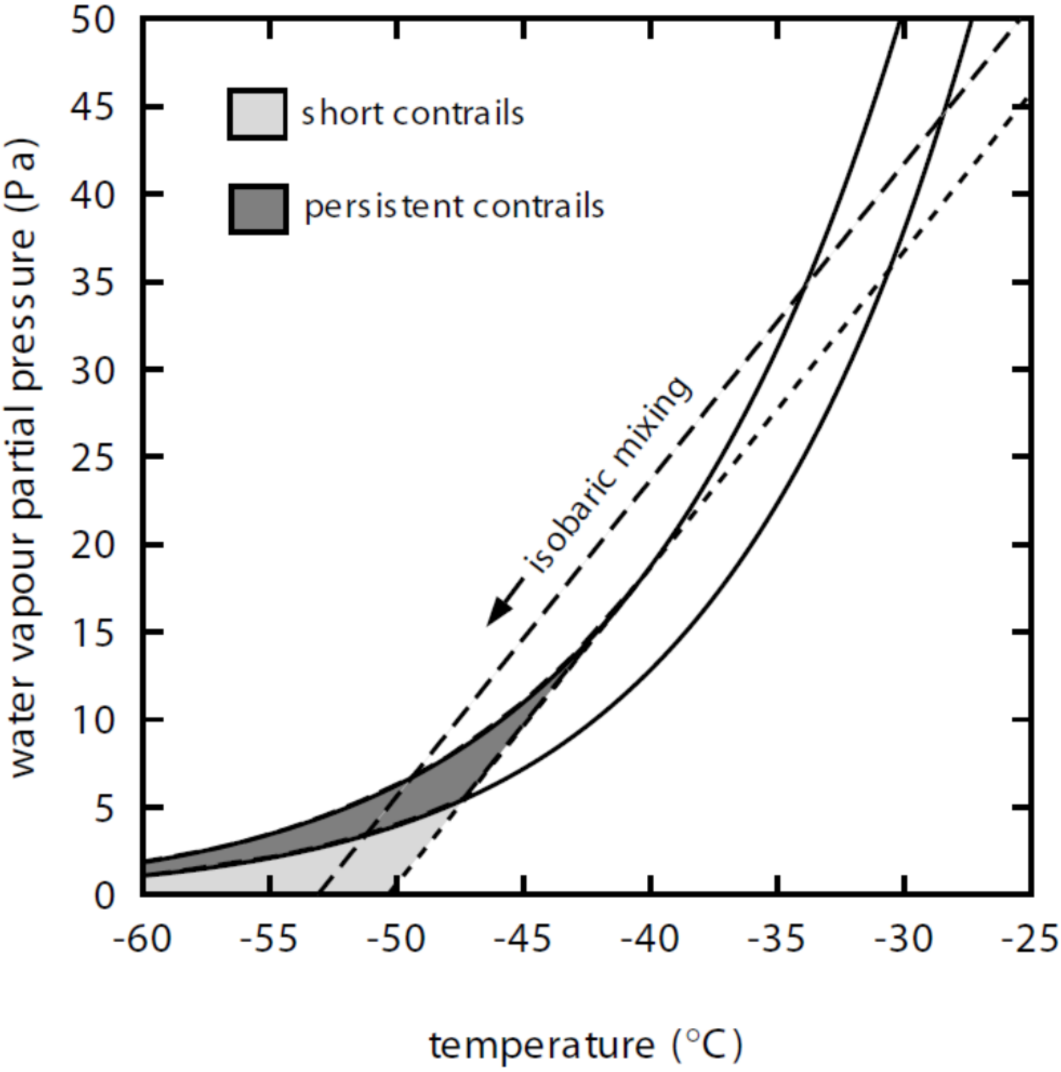


Figure 3.1: Schmidt Appleman Criterion Sketch: The two solid curves represent saturation with respect to liquid water (upper curve) and with respect to ice (lower curve). The phase trajectory of the mixture of exhaust gases and the ambient air is a straight line (from upper right to lower left) in the e-T diagram (dashed). The trajectory tangent to the water saturation curve (dotted) marks the warmest temperatures for which contrail formation is possible. Source: Gierens (2008)

a)

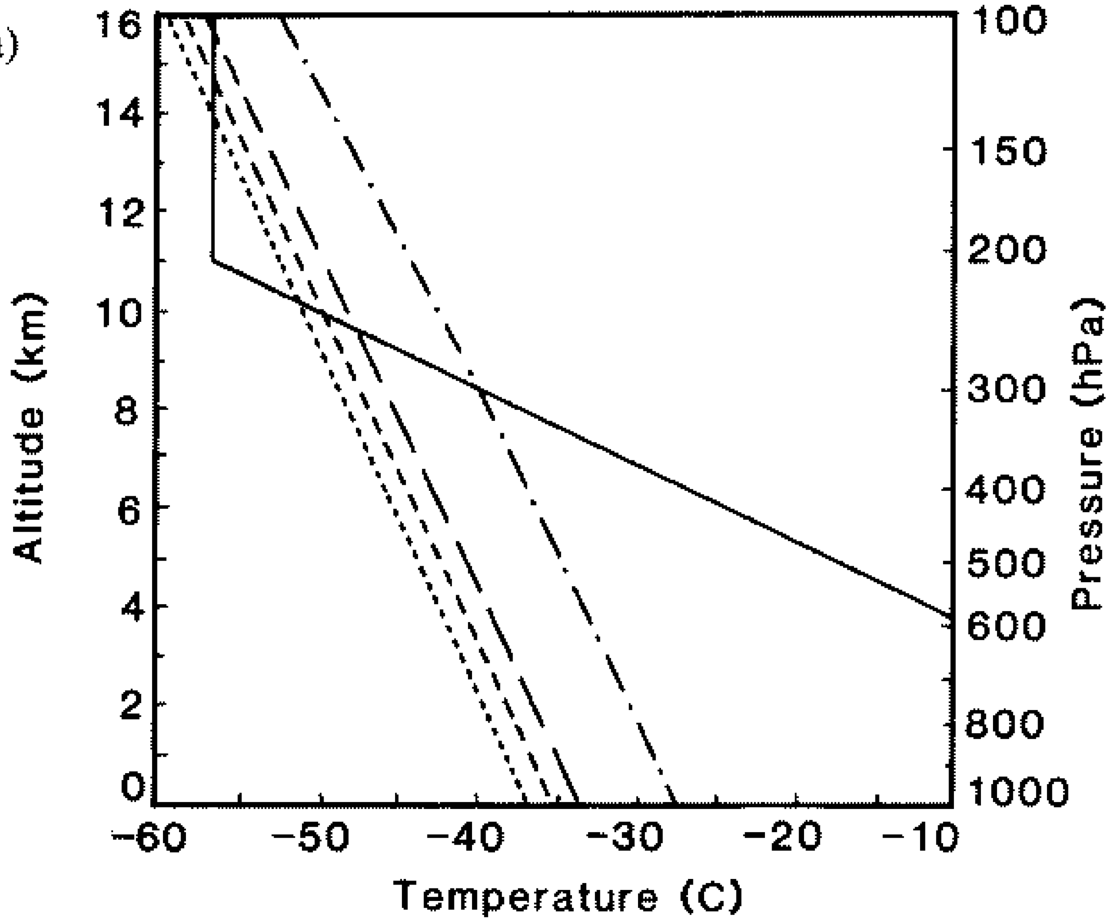


Figure 3.2: Schmidt-Appleman diagram with threshold temperature T_{LC} versus altitude for relative humidity of 0 (short-dashed curve), 30% (medium-dashed), 60% (long-dashed) and 100% (dash-dotted line), and the temperature profile of the ISA (full), for kerosene and overall propulsive efficiency of 0.3. Source: Schumann (1996)

3.2 Persistence Factor R

This project defines a factor that can be used to see whether a contrail is persistent or not. This factor is called the **persistence factor**.

$$R = \frac{\text{relative humidity of ambient air}}{\text{relative humidity for saturation with respect to ice}} = \frac{RH}{RHmin} \tag{3.1}$$

The relative humidity of the ambient air is divided by the relative humidity for saturation with respect to ice (the theoretical relative humidity for a persistent contrail). However, it is unlikely that R = 1 is sufficient for a persistent contrail in reality. A somewhat higher factor is probably necessary.

This project starts with this hypothesis:

- $R < 0.5$ no contrail,
- $R = 0.5 \ldots 1.3$ transient contrail,
- $R > 1.3$ persistent contrail.

3.3 Data for the Schmidt-Appleman Criterion

In the context of this project, the Schmidt-Appleman diagram in Figure 3.2 is used. The required relative humidity data can be obtained from Windy.com. It should be noted, however, that as described in Chapter 3.6, calculated data are only available for some heights. It may therefore be that an assumption must be done. In addition, the Excel table by Dieter Scholz is used to predict persistence of the observed contrails.

The data of the aircraft itself, such as the altitude, can be found quickly and easily from the GPS altitude of Flightradar24. The GPS altitude was used for the observation.

3.4 Flightradar24

To observe what is happening in the sky, it is necessary to collect data on the aircraft as well as on the contrails and their properties. Immediately afterwards, the flight data must be recorded. There are many websites on the Internet where you can track the current air traffic. They collect the transponder data with receivers and process them and show them on a map. This allows the exact position of the aircraft as well as other data such as altitude and speed to be displayed. One of the biggest websites is Flightradar24. Already the free version can deliver a lot of data. Not all data that is important for observation is available as freeware. Therefore, if the reader wants to recreate the observation himself, a gold subscription is required. An example of the data which can be expected is shown in Figure 3.3.

Data that are important for the observation:

- GPS altitude in feet
- Barometric flight altitude in feet
- Vertical speed in feet per minute
- Outside temperature
- Information about the aircraft type
- The current GPS position indicated in altitude and latitude.
- Direction of flight in degrees

Some other information which may be useful:

- Speed over ground.
- True speed
- Displayed speed.
- Mach number
- Wind direction and speed.

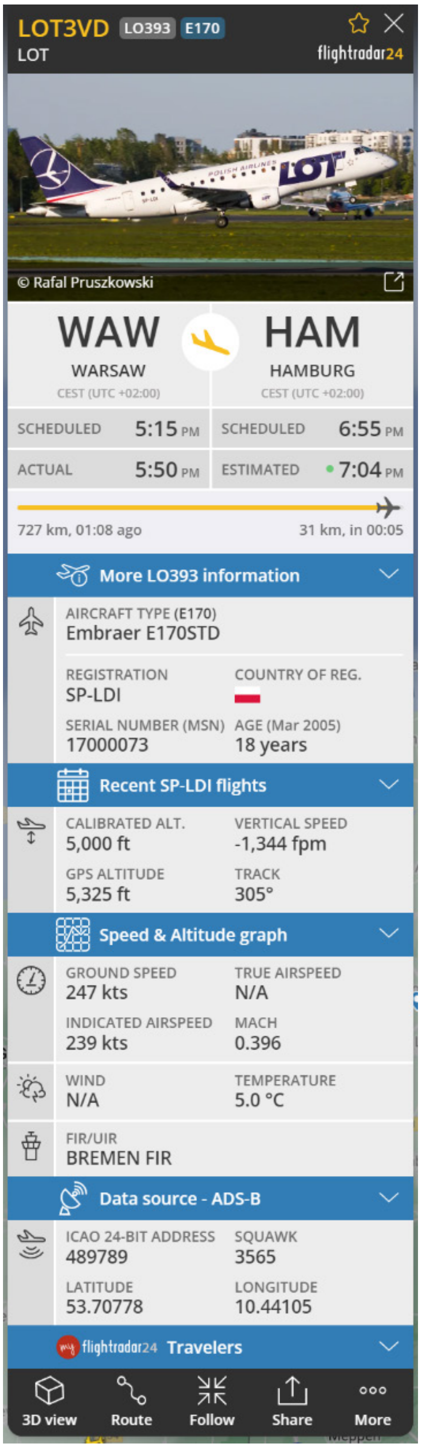


Figure 3.3: Flight-Data like speed, altitude and outside temperature taken from Flightradar24 for the Embraer with the registration SP-LDI. Source: Flightradar24 (2023)

3.5 Camera

A photo is needed to store data about the contrail, such as size and lifespan. A Samsung Galaxy S23 Ultra was chosen as it has many rear cameras with different focal lengths and can run the Flightradar24 App, as well as the Windy App (Chapter 3.7) and has access to the Internet via a web browser. These four different cameras with different focal lengths allow you to take photos of the contrails at many different zoom levels. The zoom levels are 0.6x, 1x, 3x and 10x optical. Digital zooming takes place between the optical zoom levels. A maximum zoom of 100x magnification is possible, but not very useful. The images are recorded in a sufficiently large resolution so that you can still zoom in afterwards. Their different maximum resolutions can be seen in a press picture of Samsung Electronics America in Figure 3.4.

Figure 3.4: Press Picture: The different cameras of the Samsung Galaxy S23 Ultra (Samsung Electronics America 2023)

3.6 Satellite Images

3.6.1 Used Satellites

The satellites of the Meteosat satellite network were primarily used for this project. The satellites of the Meteosat network are operated by **EUMETSAT**. "The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) is an intergovernmental organization created through an international convention agreed by a current total of 30 European Member States." It is not an organization of the European Union, even if the majority of the members come from the European Union.

The Meteosat satellites are in **geosynchronous orbit**. A geosynchronous orbit means that a satellite orbits the earth exactly once during one earth day. The earth orbital period around its own axis and the orbital period of the satellite around the earth are therefore synchronous. However, the satellites do not have to move in a perfect circle around the equator and so it can happen that they move a little relative to a viewer on earth (i.e. not geostationary). Usually, this movement has a shape about an eight. However, these satellites are quite far away from Earth. The **advantage** of this is that a large area can be covered and thus it is possible to observe and photograph almost half the globe. In addition, unlike lower-flying satellites, which can only take pictures of an interesting place every few hours, because this kind of satellite is very low and therefore has a slightly inclined orbit, the higher one can still take pictures of the entire world. With higher-flying satellites, it is possible to take pictures regularly and in short periods of time. Images are available that are updated every 15 minutes, some websites offer even 5-minute intervals. A **disadvantage** of this is the comparatively low resolution of often only 1 km by 1 km, which means that larger clouds can be seen, but no fine contrails. So is in the pictures used in this project. (Wikipedia 2023a, EUMETSAT 2023, Lea 2015)

Satellites nowadays have several instruments on board with which photos can be taken. Which then have different channels. They not only record images within the visible range, but also in different spectral ranges. Some combinations are relevant for this project. These are briefly outlined below.

3.6.2 The Different Image Types

The visual image is an image that approximately represents what the human eye would see. The visual image is shown in Figure 3.5. It has the advantage of showing very well how the clouds obscure the sky from the viewer's view. A downside is that not much can be seen at night. Therefore, other image types must be used at night. Sometimes some channels of the infrared spectrum are combined to get use of the additional information and thus lead to RGB pictures (Not shown here). RGB pictures allow to get an estimation about the height of the clouds.

The infrared image (Figure 3.6) shows the level of infrared radiation emanating from the ground and clouds. The radiation depends on the temperature. The warmer an object is, the darker it appears in the image. As a result, high clouds tend to appear brighter than low ones. The infrared image can also be used at night.

To fulfill special purposes, different satellite channels can also be combined. Various variations are possible. In Figure 3.7 is one possible channel combination shown which may be suitable for identifying ice clouds. The DWD writes the following on its website (translated by the author):

> *A combination for highlighting ice clouds is the color composite image (NIR016/VIS008/VIS006). Cloud-free areas appear in greenish colors, but water clouds are not yellow, but reddish-gray, and ice clouds are cyan. This combination takes advantage of the near infrared property that ice particles only weakly reflect sunlight.*
>
> *In this combination, ice particles in clouds and on the ground in the form of snow-covered areas cannot be distinguished. However, this distinction is very easy to make with animated images, and differences in the structure of clouds and ground can also be seen.*
> (DWD 2023a)

It almost looks like there is no limit to the combination of channels. Another example image is shown in Figure 3.8. On websites like the one from EUMETSAT you can put together images of the various satellites and their channels. The DWD shows a powerful but complicated combination on its website (DWD 2023a). The DWD writes about this (translated into English by the author):

> *An extremely complex product is available with the air mass combination. Due to the great potential, it is worth working with this combination. The color composite includes the water vapor channels and two additional infrared channels. The red color channel is formed by the difference in the brightness temperatures of the water vapor channels (WV062-WV073). This difference depends directly on the temperature and humidity distribution in the troposphere. The difference between the brightness temperatures of the ozone and window channels (IR097-IR108) is shown in the green. This allows the ozone content and thus the height of the tropopause to be determined. Finally, the WV062 also occupies the blue color channel, which shows the humidity of the upper troposphere. Effects such as "dry intrusions", folding zones and "jet streaks" become clear here. The composite shows thick clouds ranging from ocher (mid-level clouds) to white (high-level clouds). The color of low clouds and cloud-free areas depends on the humidity of the environment. Warm areas with high tropopause appear dark green (when humidity is low in the upper troposphere the green appears somewhat "dirty"), cold areas with low tropopause are blue. Areas where cold tropospheric air sinks are particularly interesting. These are often coupled with jets and a high isentropic potential vorticity (IPV) and are clearly shown in reddish tones. In particular, the statements about the differences in brightness temperatures are only of limited use at high satellite zenith angles. From a viewing angle of 80 degrees, so-called "limb cooling" occurs, which manifests itself in the product turning blue.*
> (DWD 2023a)

Depending on the situation, it could be that a source does not provide meaningful results. The author has therefore always chosen the source that makes most sense to him.

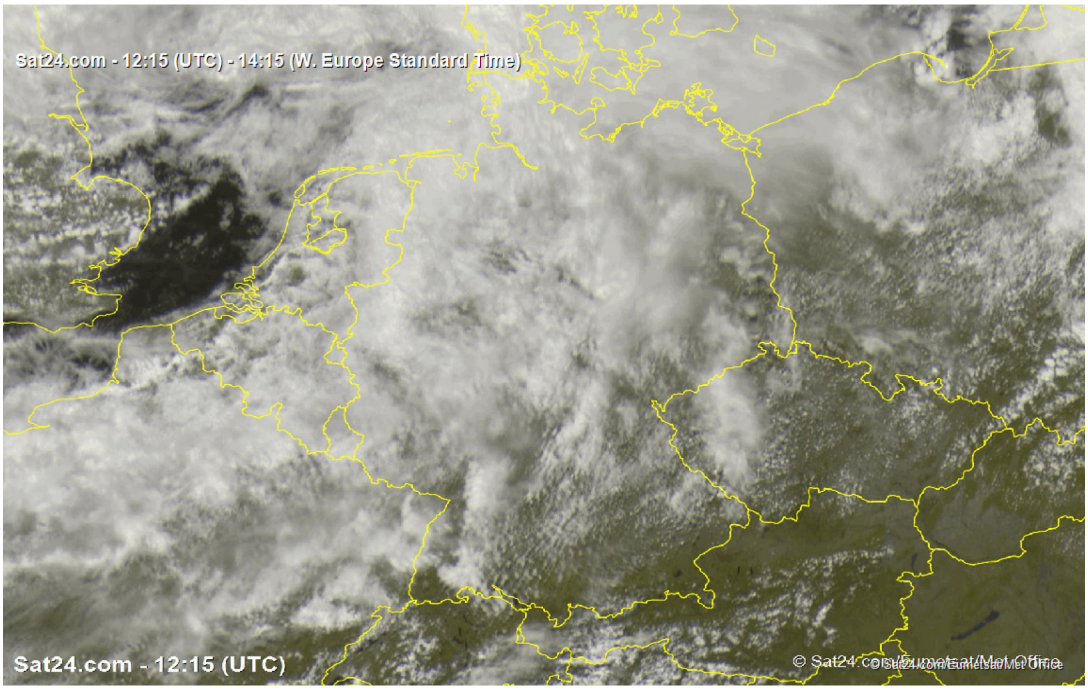


Figure 3.5: Example of a visual image, screenshot taken at 7/23/2023 3:07 PM. A cloud layer over Germany is visible. (Sat24, 17 Jul. 2023)

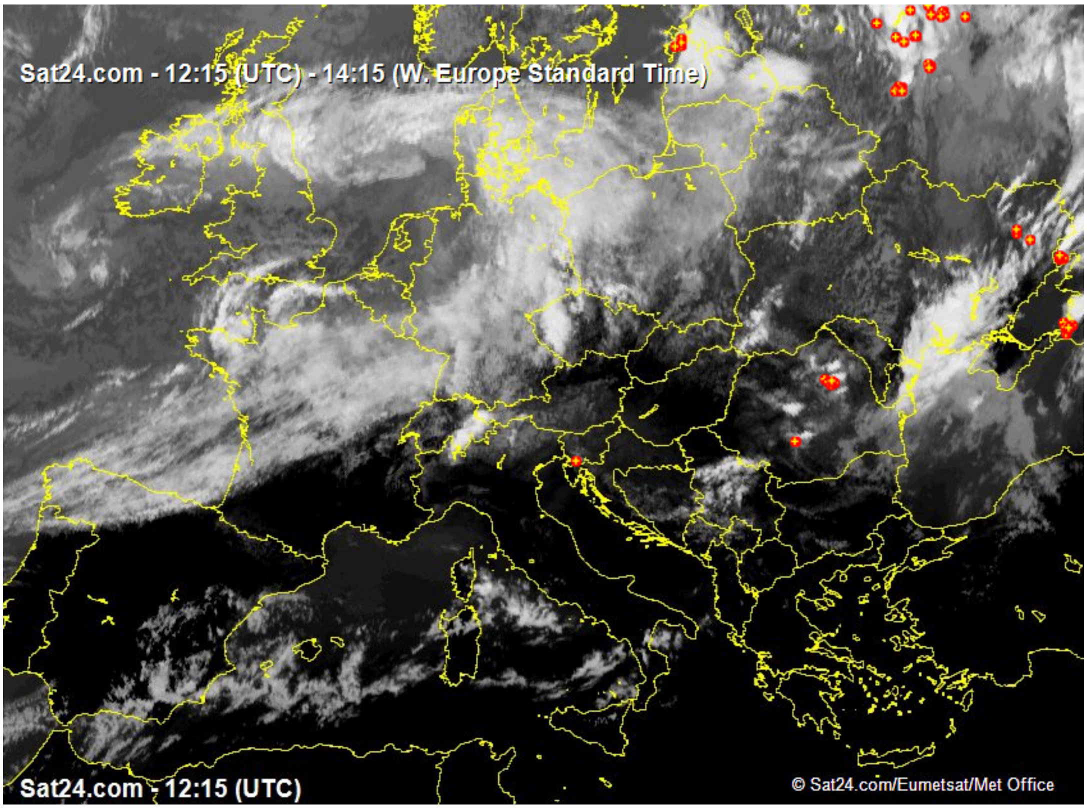


Figure 3.6: Example of an infrared image, screenshot taken at 7/23/2023 3:07 PM. A cloud layer over Germany is visible. (Sat24, 17 Jul. 2023)

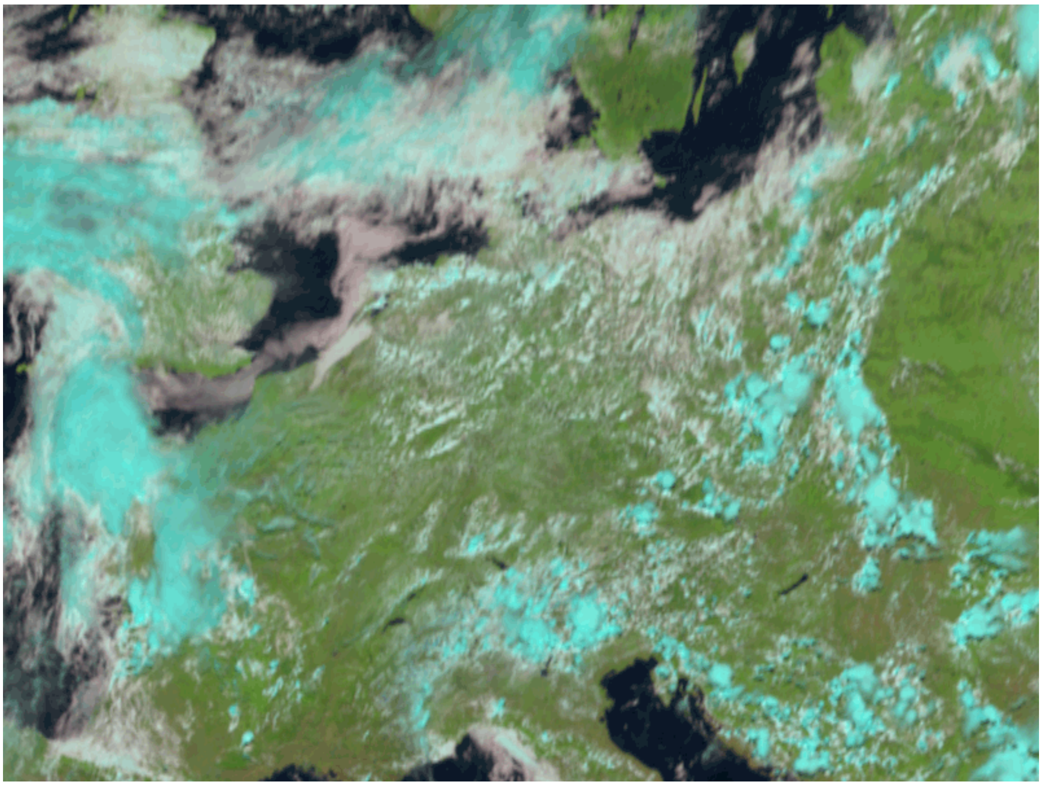


Figure 3.7: Example image from the DWD of ice clouds (Channels NIR016 / VIS008 / VIS006 in combination). Cyan clouds are most likely ice clouds. Source: DWD (2023a)

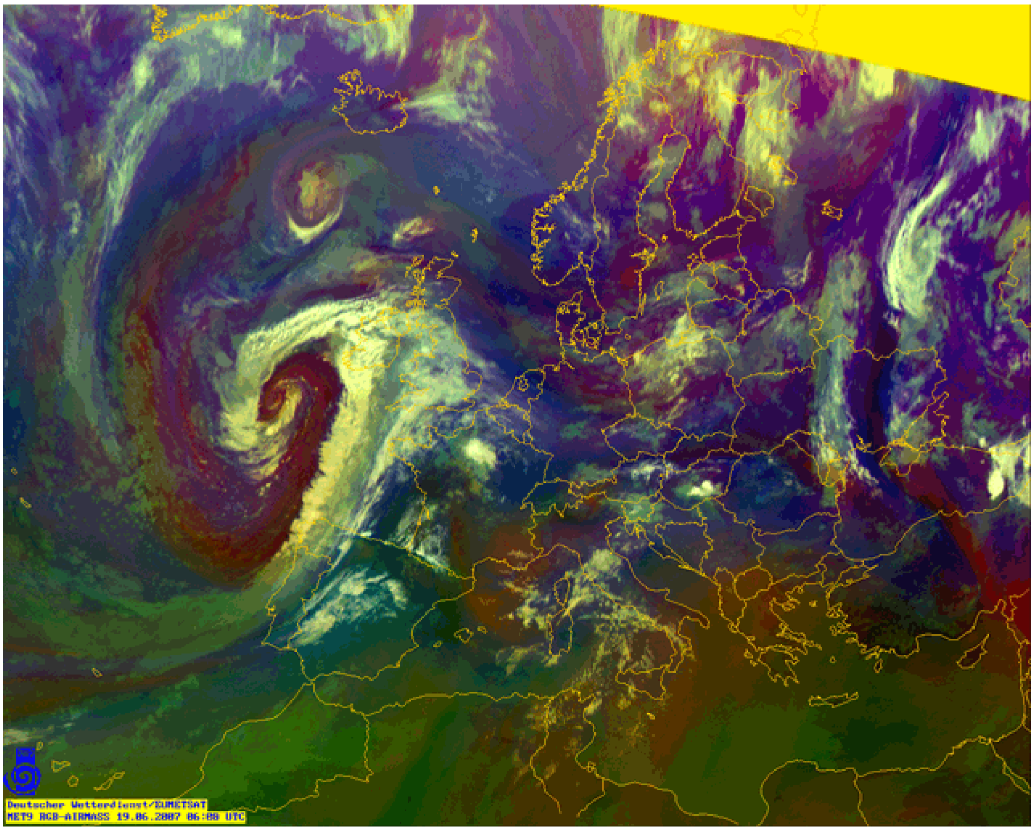


Figure 3.8: Combination of several Channels (*WV062-WV073/IR097-IR108/WV062)* Source: DWD (2023a)

3.7 Meteorological Data

Nowadays there are many websites that could be used as sources. Websites that are primarily used to predict the weather most of the time also provide radar maps or satellite images. An example of such a website would be AccuWeather. Then there are websites that are specifically designed only for satellite images. Sat24, Eumetview and astrofan80.de (the last one is in the reference section referenced as Schnabel 2023.) would be some examples and can also be found in the references. So, there is a large selection that needs to be narrowed down in order to create comparability with one another. Therefore, the author has created a table and compared these different criteria. The results can be found in Table 3.1. A "+" means that the website meets this criterion well, an empty cell means that it is neither good nor bad, and cells that have a "-" fulfill this criterion rather poorly in comparison to each other.

As can be seen in the table, the different websites all have their advantages and disadvantages. Since Windy.com has a map that can be freely selected in both zoom level and map section and some other meteorological data are also available on this website, the author has chosen this website as the primary source.

Table 3.1: Comparison between the different Websites for Satellite Data

	Criterion				
Website	Easy to use	Number of Data	Freely selectable Section	Resolution	Different image types available
Windy.com	+		+	+	
Eumetview	-	+			+
Astrofan80.de	+		-	-	
Sat24.com	+	+	-		

3.7.1 Website Windy.com

The Website Windy.com (Windy 2023) was chosen for most meteorological Data. The website provides access to all kinds of data. For example, current cloud cover, divided into low, medium, and high clouds, as well as temperature, dew point, wind, humidity and many more. The prediction is usually divided into different layers. The resolution in the higher layers depends on the weather model used. For most prediction categories, the following heights can be selected:

Table 3.2: Available layers at Windy.com

Pressure hPa	Approximate Height ft	Flight level FL
	0	000
950	2 000	020
925	2 500	025
900	3 000	030
850	5 000	050
800	6 400	064
700	10 000	100
600	14 000	140
500	18 000	180
400	24 000	240
300	30 000	300
250	34 000	340
200	39 000	390
150	45 000	450

The weather models do not provide live data, as the calculations are to complex. The models are updated in intervals, depending on the chosen weather model. As the author owns a premium subscription most data are available in one-hour steps and the model gets updated several times a day.

The premium subscription (at the time 20.99 €/year) has some advantages over the free accessible version of Windy.com. The main benefits are:

- Higher resolution at the map
- Updates up to four times daily (instead of two)
- Up to ten days prediction
- Satellite data of the past + archive
- Functions for convenience (example: setup of standard settings for startup)
- One hour forecast interval (instead of three)

Windy offers many different weather models. Over northern Germany, the following are applicable:

- ECMWF
- UKV
- GFS
- ICON-D2
- ICON-EU
- ICON
- NEMS
- AROME

3.7.2 ICON Weather Model

The ICON-D2 model is the weather model of the “Deutscher Wetterdienst” (short DWD), which is the German organization for weather services. The D2 Model is based on the ICON weather model and builds on various previous models. The D2 weather model is a regional weather model and therefore cannot cover the entire globe. The general ICON weather model, on the other hand, is globally valid. The ICON-D2 is limited to one area that covers Germany, Switzerland, the Netherlands, Belgium and Austria. Some neighboring countries are also partially covered. Figure 3.9 shows where the model is valid.

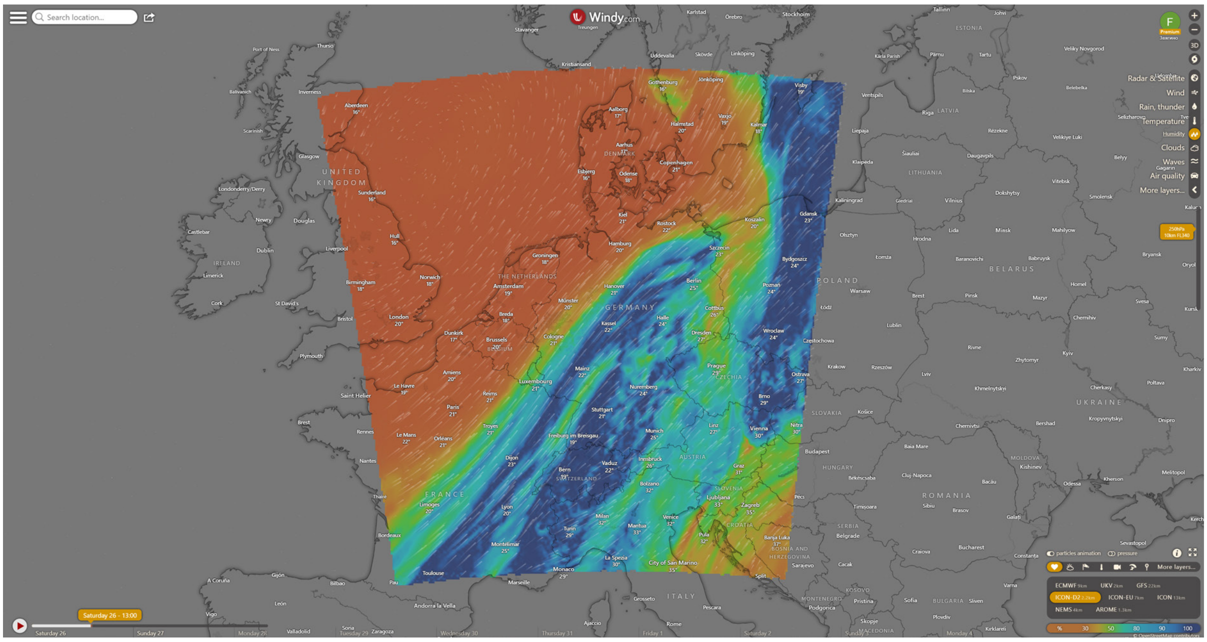


Figure 3.9: Area where the ICON-D2 Model is valid, Screenshot taken at August 26, 2023 (Windy 2023)

The D2 variant of the ICON model offers the advantage of the very high horizontal resolution of 2.2 km compared to the other weather models and should therefore be used primarily. The ICON-D2 weather model – like all other weather models – is a numerical model. Accordingly, the area in which the weather model applies is discretized. The model under consideration uses a triangular grid of 542 040 grid points horizontally and 60 layers vertically. Thus, a total of about 35 million lattice points are used at which model equations are solved. However, the model is not accurate enough to calculate very local phenomena. For example, atmospheric convection. Convection is generally understood to mean the rise of an air parcel that is warmer than the environment. If this air parcel contains sufficient water vapor, it rises into cooler air layers and water vapor can condense. Smaller cloud droplets may form. In the process, energy is released, which further drives this convection. This process takes place in different forms in the atmosphere. In stronger forms, this leads to the classic thunderstorm cells, which are known to have only a few kilometers in extent. The ICON-D2 weather model is at least approximately able to calculate such effects and does not have to resort to overly crude simplifications such as the global ICON model. (Wikipedia 2022, DWD 2023b)

The smaller the atmospheric structures captured by the model, the shorter their lifetime and thus the more limited their predictability. Large high- and low-pressure systems have typical lifetimes of several days and therefore the global model ICON can make meaningful predictions of several days for them. Whereas the lifespan of thunderstorm cells is only about one hour. Due to the small model area, only short prediction times are useful with this model. The model is therefore updated at regular intervals of three hours and gives a 27-hour weather forecast. The update of the day starts at 0 o'clock UTC. It should be mentioned that the data for the weather model does not all come from the DWD but is partly fed in by other services. More detailed information can be found on the website of the DWD (DWD 2023b).

3.7.3 ECMWF Weather Model

The ECMWF weather model is calculated by the European Centre for Medium-Range Weather Forecasts which is booth a research institute and a 24/7 operational service, which produces numerical weather predictions and other data for their member- and cooperating states. The ECMWF is an independent intergovernmental organization supported by 35 states. The ECMWF claims that the Centre has one of the largest supercomputer facilities and meteorological data archives in the world. The organization was established in 1975 and now employs around 450 staff from more than 35 countries. (ECMWF 2023)

The weather model gets updated four times a day and is available worldwide. The horizontal accuracy listed at windy.com is nine kilometers. More information about how the model works and where the ECMWF gets its data from can be found at their website.

As already mentioned, Windy can not only display the current weather situation, but can also predict the weather for a few days, depending on the weather model. For example, a forecast of two days can be made with the ICON-D2 weather model. The ECMWF weather model allows a forecast of up to nine days. These forecasts can be used, for example, to predict situations in which contrails could develop or simply where the ICON-D2 weather model is not available.

3.8 Contrails Map

The website called “Contrails Map” is a website which provides a map showing contrail formation and is created by Breakthrough Energy (short “BE”), a company which was founded by Bill Gates, with some other heavy investors like Jeff Bezos, Mark Zuckerberg, Jack Ma, Mukesh Ambani, Michael Bloomberg and Richard Branson (Koh 2022). There is a collaboration with many organizations like the Transport & Environment Laboratory at Imperial College. BE is a global initiative that aims to develop and deploy clean technologies to reduce greenhouse gas emissions to net zero by 2050. Therefore, it runs various programs, such as Breakthrough Energy Ventures, Breakthrough Energy Catalyst, Breakthrough Energy Europe, and Breakthrough Energy Policy. Breakthrough Energy works with partners from the public and private sectors to promote research and innovation in areas such as green hydrogen, industrial decarbonization, long-term energy storage and other new technologies. BE also supports policy initiatives that facilitate market access and cost reduction for clean solutions. (Breakthrough Energy 2023a)

The Contrails Map is based on the model from DLR Institute of Atmospheric Physics to predict contrail formation and the code is open source and therefore available to the public at GitHub (Dean 2023). The meteorological data used are taken from the European Center on Medium Range Weather Forecasting (ECMWF) HRES Forecast (Breakthrough Energy 2023b). The Map can be used to look on the Map to see if there are any contrails in the area to be expected, created by past flights and if so if they are to have a warming effect or a cooling effect, according to the DLR model. It’s model only gets updated in several intervals. It may be that the data for yesterday may not be available, but they certainly will in the next days.

But who is the DLR Institute of Atmospheric Physics? On the DLR's website the following is stated:

> *The Institute of Atmospheric Physics (in German: Institut für Physik der Atmosphäre - IPA) is located on the DLR Campus Oberpfaffenhofen.*
>
> *It focuses on the research of the physical and chemical processes of the atmosphere.*
>
> *About 140 people work in the institute. It is structured in six departments.*
>
> *The Institute of Atmospheric Physics investigates the physics and chemistry of the global atmosphere from the Earth's surface up to the upper boundary of the middle atmosphere at about 120 km height. As an institute of the German Aerospace Center (DLR) we answer questions associated with atmospheric processes and with relevance to the research programs "Aeronautics, Space, and Transportation" and "Energy" of the Helmholtz Association (HGF). The institute covers a full variety of methods comprising the development of sensors, observations on different spatial scales (local to global), analysis, theory construction, and numerical modelling including predictability. With these competences the institute works both on fundamental and application-oriented problems, where long-term basic research in the forerun of applications is emphasized. The institute offers its competence to the society and the politics in relation to all problems of atmospheric relevance.*
> (Rapp 2023)

As already stated above, the institutes model is used to predict contrail formation and is used at the Contrails Map. The model which is most likely being used is the Contrail Cirrus Prediction Model (CoCiP). The DLR Institute itself says about CoCiP at its website:

> *The method describes the life cycle of each contrail individually using a Lagrangian Gaussian plume model with simple bulk contrail ice properties, without feedback to meteorology. Contrails are initiated when the Schmidt-Appleman criterion is satisfied and when the ambient atmosphere is humid enough to allow for contrail persistence. The initial plume properties reflect properties of the originating aircraft. The evolution of individual contrails of cruising aircraft is computed using wind, temperature, humidity, and ice water content from numerical weather prediction (NWP) output. The plume trajectory follows horizontal and vertical wind. The model simulates shear and turbulence driven plume spreading, ice water content as a function of ambient ice supersaturation assuming ice saturation inside the contrail, and some ice particle loss processes (turbulent mixing, aggregation and sedimentation). Radiative cloud forcing is estimated from the contrail properties using the radiative fluxes without contrails from NWP output.*
>
> *The tool allows for efficient contrail simulations even globally. The method has been tested for some case studies with comparisons to observations. The most critical input parameter is the NWP humidity field. The results compare favourably with observations and support interpretations of insitu, satellite and lidar observed aviation impact on cirrus clouds. CoCiP can be used to predict and minimize the climate impact of contrails.*
> (Schumann 2023)

By looking at Figure 3.10 it should be clear that not every flight (in this case over Germany) is shown. By hovering above the flight, some basic information like destination and departure airport are shown. By clicking at the plane, more contrail related information is shown. Figure 3.11 shows the detailed information in the lower left corner. There is a rating of the contrail which probably got formed of how much impact it might have for the environment. In this particular example it states, “low warning”. An altitude profile over time is shown. In this graph the potential regions of contrail formation are marked. As shown in the left upper corner, the blue marks show potential for cooling contrails and the orange warming ones.

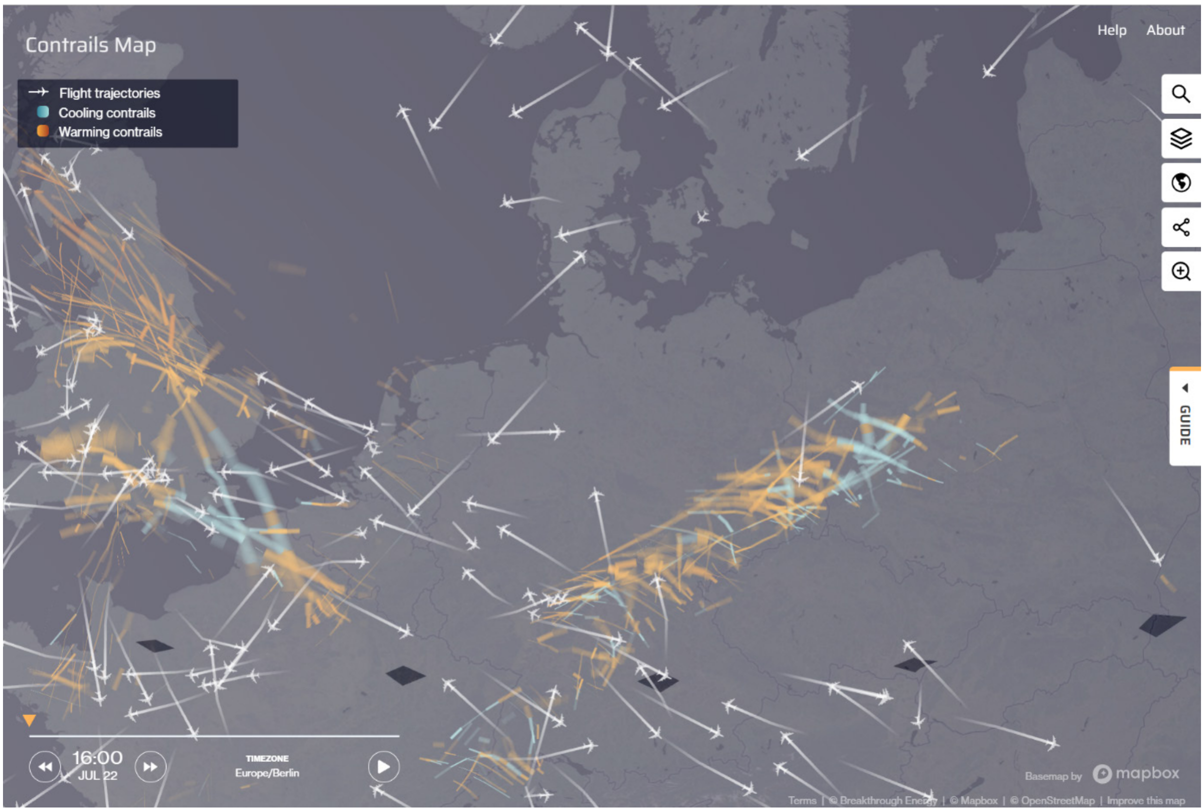


Figure 3.10: General look of the Contrails Map over center Europe, on July 22, 2023. The aircraft’s contrails can be seen in orange to blue colors. On the bottom left there is a timeline. Source: Breakthrough Energy (2023b)

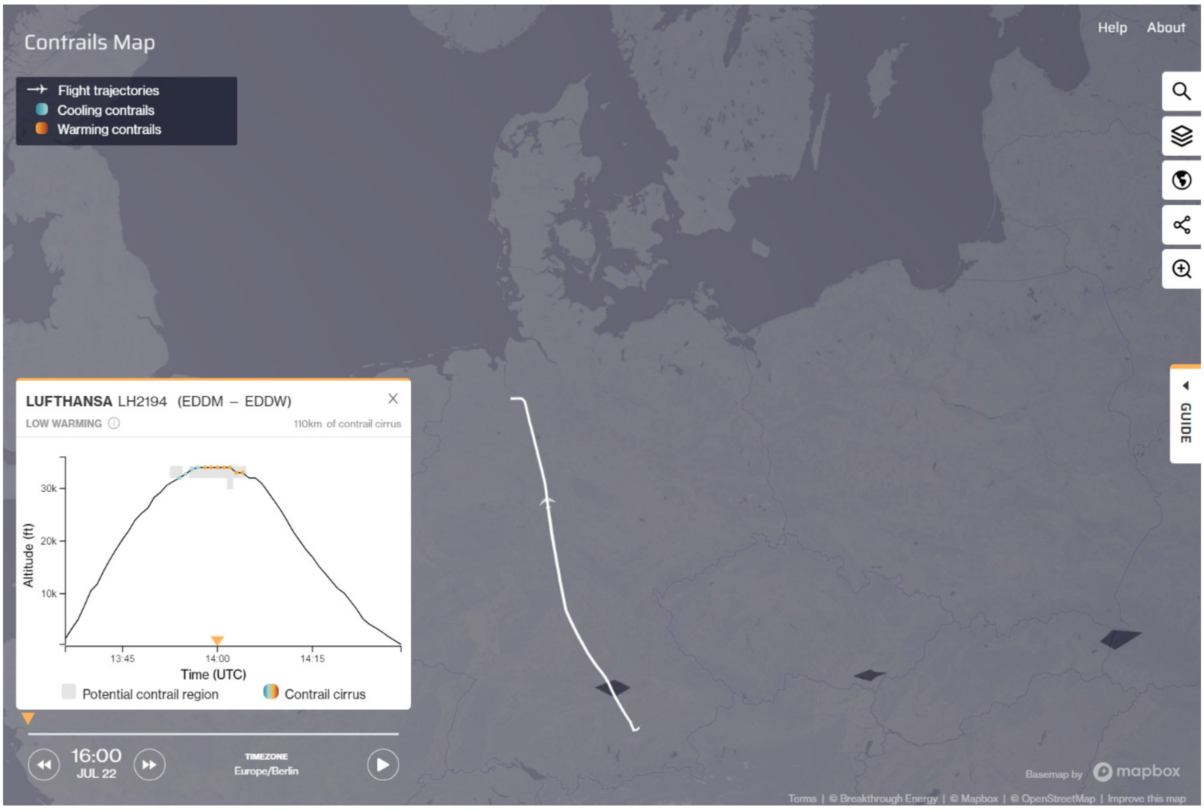


Figure 3.11: Detailed information regarding contrail formation by clicking at the flight route. The aircrafts route can be seen in white color. On the bottom left there is a diagram showing time vs altitude of the tracked aircraft. Source: Breakthrough Energy (2023b)

The search (for example for flight numbers) can be accessed by clicking at the magnifying glass at the right top corner of the website. By searching for a flight number, past and completed flights which potentially formed contrails can be tracked.

It's also possible to just look at the map for the contrails which are shown in their specific colors and click on them to see which aircraft may have caused them, how old they approximately are and how strong their environmental effect might be. Take a look at Figure 3.11, Figure 3.12 and Figure 3.13.

There is also an option to show regions in which contrails are likely to form. It is deactivated by default but can be turned on by clicking on the icon for layers on the right side.
Furthermore, it is possible to simply click on the date in the left lower corner and change it to any date of the past year. So, it is possible to track flights well in the past.

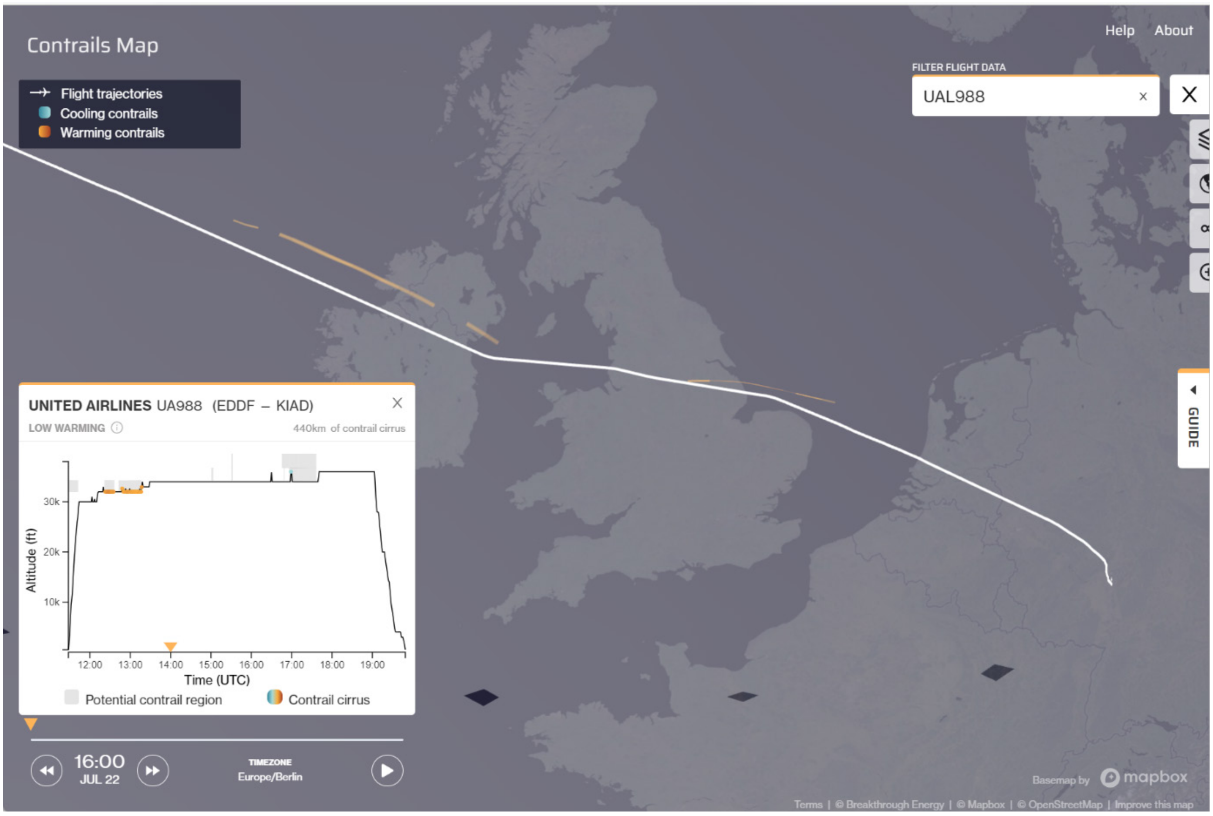


Figure 3.12: Clicking on a contrail the aircrafts track is shown in white color. Near the track some contrails can be seen colored orange. Source: Breakthrough Energy (2023b)

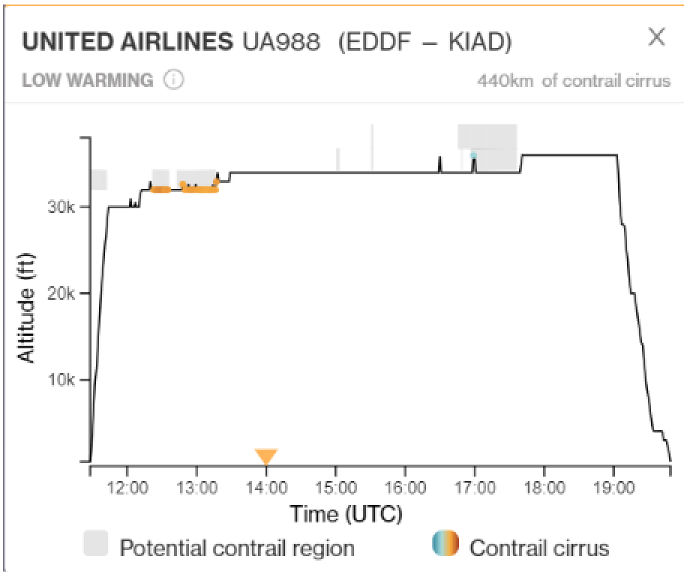


Figure 3.13: Bigger view of the graph of the bottom left corner of Figure 3.12. A time vs altitude diagram of the flight. The times and altitudes where contrails are expected are marked in orange color. Source: Breakthrough Energy (2023b)

3.9 Schmidt-Appleman-Criterion Excel Table

Another tool for the Schmidt-Appleman Criterion is the Excel tool created by Professor Dieter Scholz. With this Excel tool you can enter the height data from Flightradar24 into the table. The Excel tool then creates some graphs. With the help of these graphs, it is then possible to use the Schmidt-Appleman criterion to assess when a contrail is likely to be persistent. Contrails are persistent when the final state of cooling of the exhaust gases ends in an ice-supersaturated region (ISSR). Scholz defines that this is the case if the relative humidity in Figure 3.16 is above the blue line.

The table has two sheets. The first one named "SAC" is for calculations regarding the Schmidt-Appleman-Criterion. In the following the Excel sheet may be called "SAC-Excel-Sheet" by the author. For some screenshots, see Figure 3.14, Figure 3.15 and in Figure 3.16. as well as the Windy App (Chapter 3.7) and has access to the Internet.

The second sheet named "SAD" is for calculating the Schmidt-Appleman-Diagram. A further description how this is being done can be found in the Excel table itself or in the PDF, which is partly in German (Scholz 2023a). Screenshots can be seen in Figure 3.17 and Figure 3.18. Scholz (2023b) offers the Excel table. The most recent version of the table is always available from https://purl.org/aero/SAC.

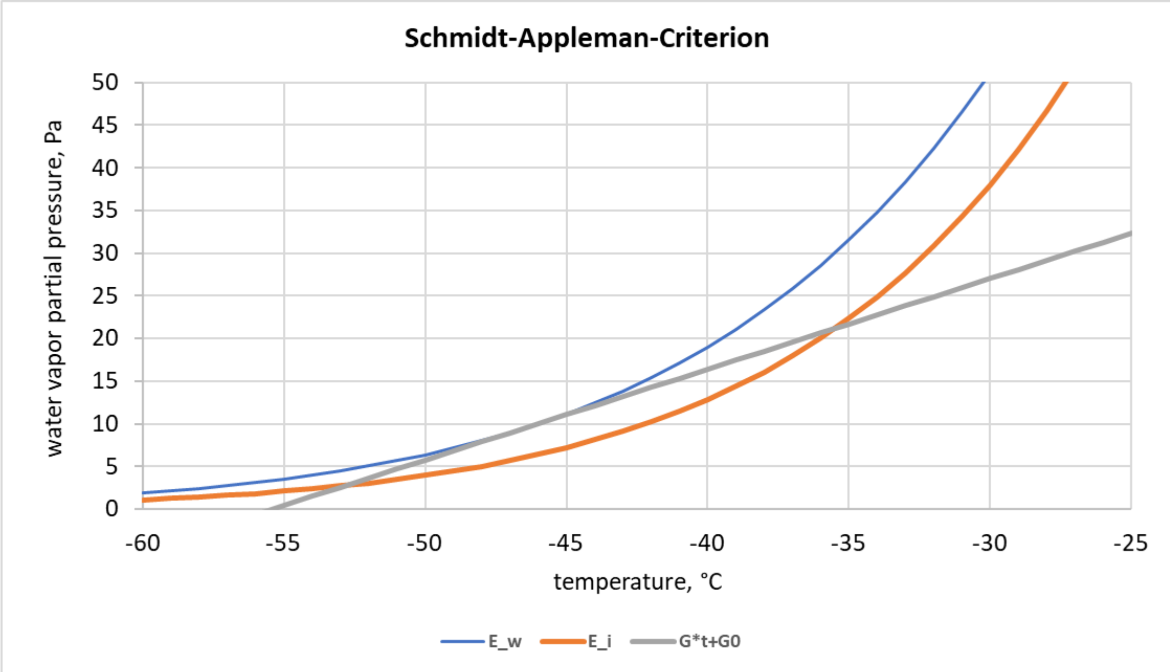


Figure 3.14: Example diagram of the SAC sheet for 45000 ft. Source: Scholz (2023b)

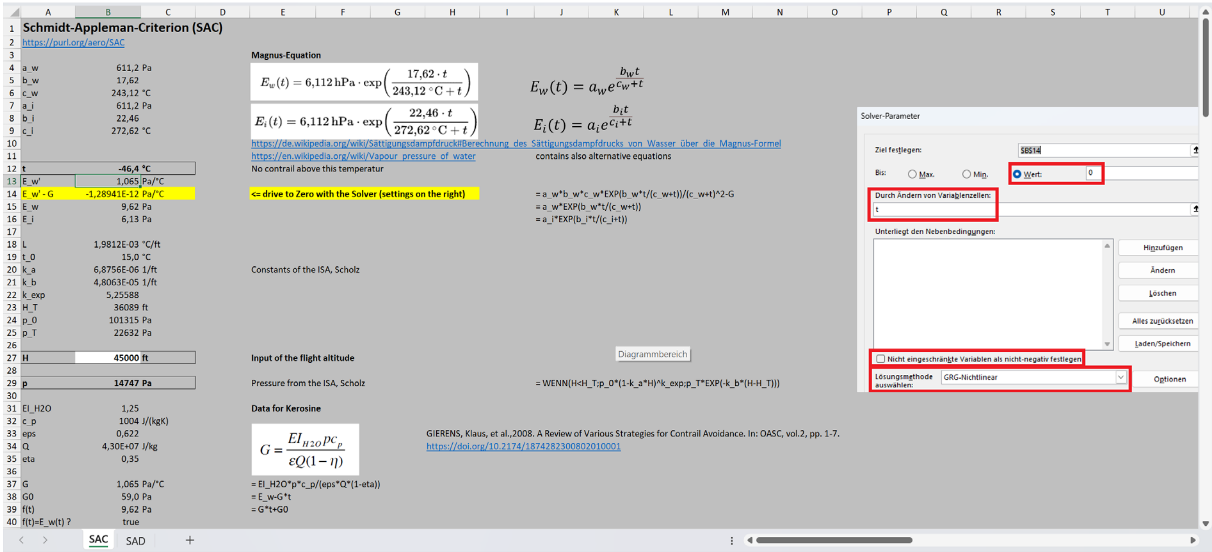


Figure 3.15: Extraction of the Calculation Part of the Excel Table's SAC sheet. (for 45000 ft). Source: Scholz (2023b)

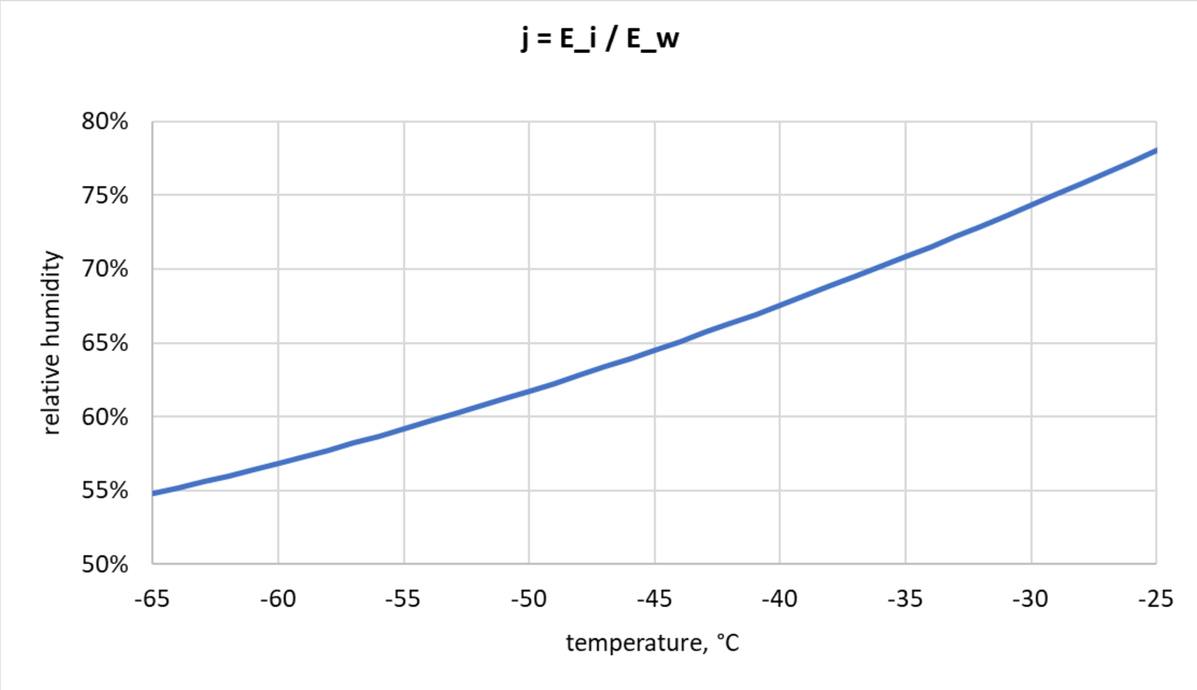


Figure 3.16: The graph shows the relative humidity (blue line) as function of temperature, above which persistent contrails are expected to occur. Source: Scholz (2023b)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**Constructing the Schmidt-Appleman-Diagram**															
2																
3	1.) Enter altitude, H in tab "SAC" and operate Solver (e.g. for a calculation of a new altitude)															
4	2.) Copy new colum "C" into the column to the right to safe for later															
5																
6	G	Pa/°C	1,065	3,361	1,065	2,172	1,721	1,634	1,354	1,065	0,837	0,658	0,518	0,407	0,320	
7	G0	Pa	59,0	149,1	126,3	106,4	87,7	84,0	72,5	59,0	48,4	39,3	31,9	25,9	21,0	
8	H	ft	45000	20000	25000	30000	35000	36089	40000	45000	50000	55000	60000	65000	70000	
9	H	m	13716	6096	7620	9144	10668	11000	12192	13716	15240	16764	18288	19812	21336	
10	p	Pa	14747	46559	14747	30087	23840	22632	18754	14747	11597	9120	7172	5640	4435	
11	t_SAC,100	°C	-46,4	-34,2	-36,6	-39,0	-41,5	-42,0	-43,9	-46,4	-48,7	-51,0	-53,3	-55,5	-57,6	
12	t_SAC,0	°C	-55,4	-44,4	-46,5	-49,0	-50,9	-51,4	-53,2	-55,4	-57,9	-59,6	-61,7	-63,7	-65,6	
13	Δt,tot	°C	9,0	10,2	10,0	10,0	9,5	9,4	9,3	9,0	9,1	8,6	8,4	8,2	8,0	
14																
15	t	E_w	phi	phi	phi	phi	phi	phi	phi	phi	phi	phi	phi	**Diagram for typical kerosine aircra**		
16	-60	1,901	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0,4584			
17	-59	2,158	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0,1943	0,6436	EI_H2O		1,25
18	-58	2,447	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0,4404	0,7792	c_p		1004 J/(kgK)
19	-57	2,771	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0,1638	0,6265	0,8749	eps		0,622
20	-56	3,134	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0,4120	0,7641	0,9388	Q		4,30E+07 J/kg
21	-55	3,539	0,1192	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0,1192	0,6013	0,8625	0,9775	eta		0,35
22	-54	3,992	0,3724	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0,3724	0,7428	0,9296	0,9963			
23	-53	4,497	0,5673	n.a.	n.a.	n.a.	n.a.	n.a.	0,0595	0,5673	0,8455	0,9716	n.a.	EI_H2O and Q for Kerosine		
24	-52	5,060	0,7146	n.a.	n.a.	n.a.	n.a.	n.a.	0,3204	0,7146	0,9169	0,9936	n.a.			
25	-51	5,686	0,8231	n.a.	n.a.	n.a.	n.a.	0,1264	0,5232	0,8231	0,9632	n.a.	n.a.			
26	-50	6,382	0,9002	n.a.	n.a.	n.a.	0,2555	0,3686	0,6783	0,9002	0,9894	n.a.	n.a.			
27	-49	7,155	0,9518	n.a.	n.a.	n.a.	0,4684	0,5571	0,7943	0,9518	0,9995	n.a.	n.a.			
28	-48	8,011	0,9829	n.a.	n.a.	0,1928	0,6332	0,7015	0,8783	0,9829	n.a.	n.a.	n.a.			
29	-47	8,960	0,9976	n.a.	n.a.	0,4147	0,7582	0,8095	0,9364	0,9976	n.a.	n.a.	n.a.			
30	-46	10,010	n.a.	n.a.	0,1403	0,5882	0,8506	0,8878	0,9734	n.a.	n.a.	n.a.	n.a.			
31	-45	11,171	n.a.	n.a.	0,3687	0,7215	0,9163	0,9418	0,9935	n.a.	n.a.	n.a.	n.a.			
32	-44	12,452	n.a.	0,0981	0,5487	0,8217	0,9602	0,9761	1,0000	n.a.	n.a.	n.a.	n.a.			

SAC SAD

Bereit Barrierefreiheit: Untersuchen Anzeigeeinstellungen 108 %

Figure 3.17: The table shows the Schmidt-Appelman Diagram in form of numbers from relative humidity 0% (green) to 100% (red). It is taken from the SAD-sheet. Source: Scholz (2023b)

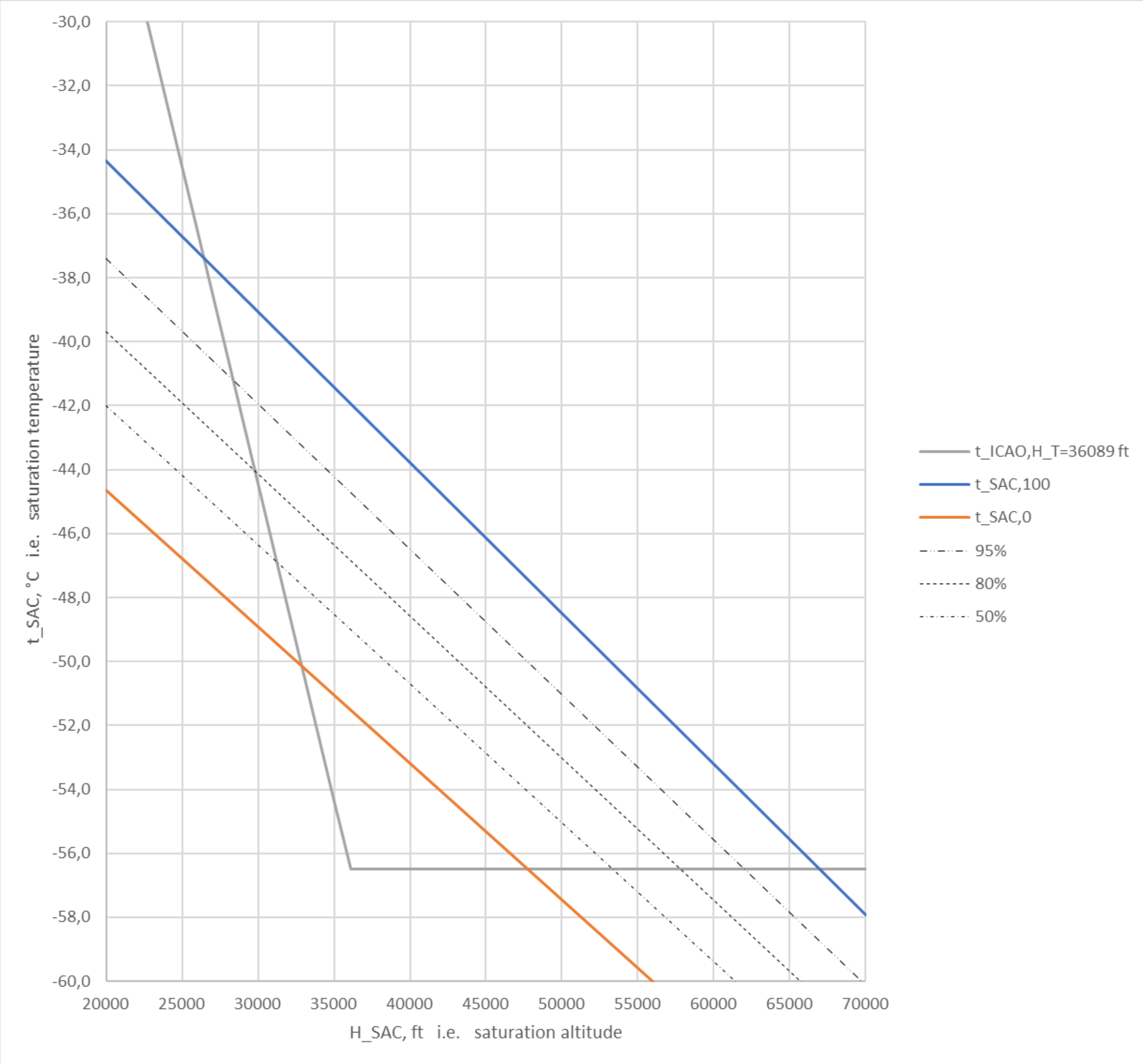


Figure 3.18: Screenshot of the Schmidt-Appleman-Diagram result from the Excel-sheet. The orange represents the line of 0% relative humidity, the blue line 100%. In between there are lines of 50%, 80% and 95%. The full grey lines represent the ISA-Temperature at 36089 ft. If pressure and temperature conditions exist to the left of a moisture line, a contrail will form. To the right, there is no contrail expected to form. Source: Scholz (2023b)

3.10 Data Storage

3.10.1 ZIP Archive

In the main folder there are some files. This contains the images in uncompressed form and is thus intended to enable high-quality prints. It is recommended to use the standard PDF file that are also located in the root directory, which should have a better resolution regarding pictures than the PDF/A one. The PDF/A is much smaller, and its quality should be sufficient for most prints, but not for a very detailed look. The Excel spreadsheet described in Chapter 3.10.2 can also be found there. The main folder's structure with the raw data is shown in Figure 3.19.

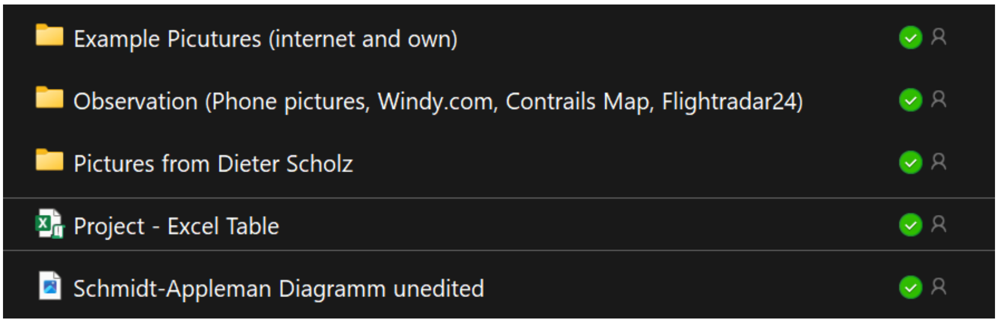


Figure 3.19: Main folder and its structure.

In the folder called "Observation [...]" are the data of the contrails stored, which include several subfolders which are divided into the different categories. Therefore, take a look at Chapter 3 and Figure 3.20.

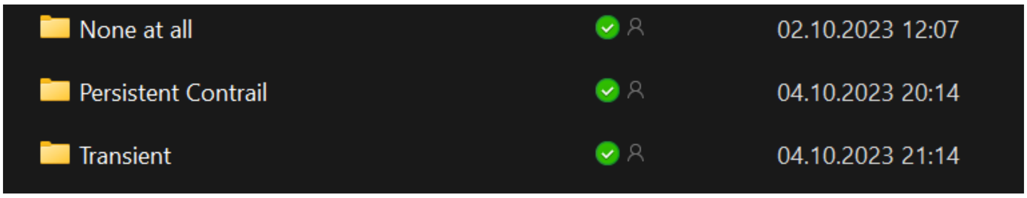


Figure 3.20: The folders inside of "Observation".

Within these folders there are other folders named after the different registrations of the aircraft (Figure 3.21). This also makes it possible to track aircraft that have already changed hands at the time of reading this project paper. In most cases, the registration remains the same after an ownership change.

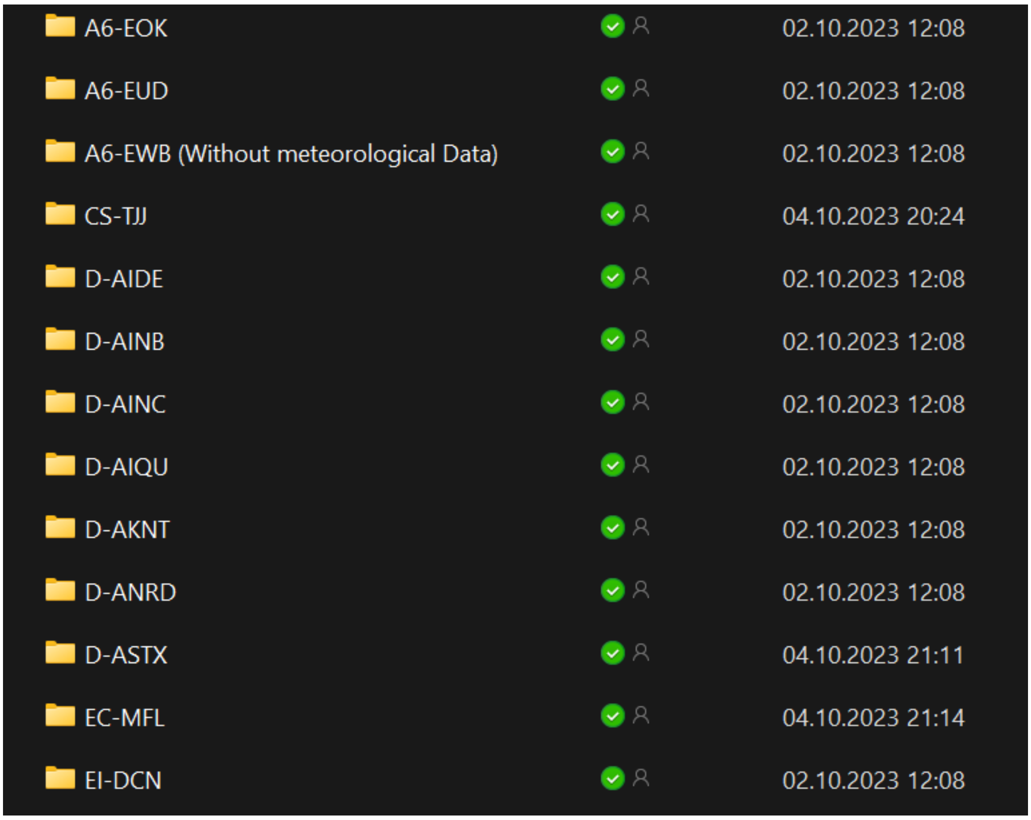


Figure 3.21: Subfolders of a category with the different aircraft registrations.

Within these folders, there are data that have been collected. They usually include a complete data set being such as listed in Chapter 3, such as the data from Flightradar24.com, the meteorological data, the images taken with a camera and the data from the Contrails Map website.

The "Pictures by Dieter Scholz" folder contains pictures by Dieter Scholz. The author has added some data that could be obtained afterwards. However, the data usually does not contain a complete data set regarding all the possible sources given under previous Chapter's. Normally Flightradar24 screenshots, satellite images and the actual photos of the contrails can be found here. The pictures are usually taken a few kilometers south of Hamburg.

In Figure 3.22, the subfolders can be seen. The first folder contains images for which the place of origin is not known. There is no Flightradar24 data on this either. In addition, there is a folder where only images of contrails that were observed south of Hamburg can be found and for which Flightradar24 data are available and the author has added further data if possible. Finally, there is a folder which contains pictures but without any Flightradar24 data. A link to all the folder and all "raw data" can be found in "Appendix A: Raw Data collected for this project."

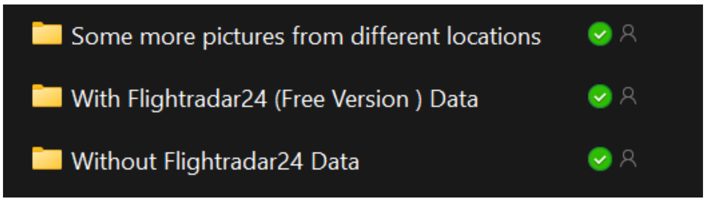


Figure 3.22: Inside the folder „Pictures from Dieter Scholz “, there are three more subfolders. To some of the pictures Flightradar24-Data have been found and added.

3.10.2 Excel Table

There is an Excel table called “Project - Excel Table.” It contains several sheets. They are shown in Figure 3.23. The first three sheets are named by the different contrail categories as defined in Chapter 2.6. There is a sheet for “Persistent Contrail,” for “Transient Contrail” and for “None at all” and “Data by Dieter Scholz.” These sheets contain data such as flight data from Flightradar24 and some calculated quantities like the Mach number. Figure 3.24 and Figure 3.25 show an example what data are contained inside read from left to right. First, there is the flight data in the form that can be found in Flightradar24. This is followed by some conversions of this data into the metric system in light orange font, so that readers who are more familiar with the metric system can get a feel for the data. ΔT is then calculated to calculate the pressure. Then there is another sheet for every category in which some average values can be seen. Furthermore, average values were calculated to see whether a difference between them can be spotted. These average values can be seen in Figure 3.27, Figure 3.28 and Figure 3.29 and are located in dedicated sheets. The average temperature for the category “none at all” is as expected the warmest category by average temperature, with the least average flight altitude. The category “persistent contrails” has the lowest average temperature and the highest flight altitude. The average true airspeed is nearly the same across the categories as almost all aircraft have been jet powered aircraft.

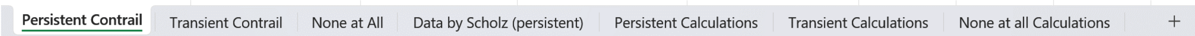
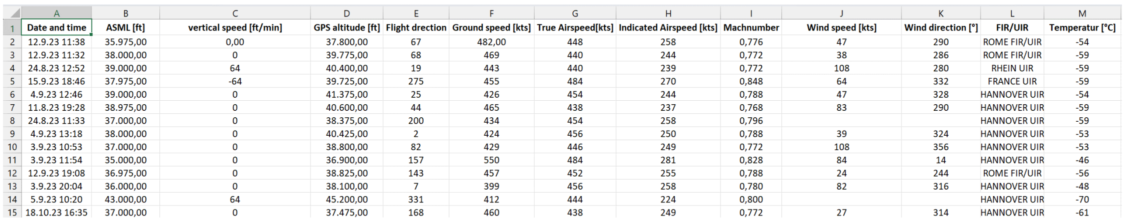


Figure 3.23: The different sheets inside the Excel table.



	Date and time	ASML [ft]	vertical speed [ft/min]	GPS altitude [ft]	Flight drection	Ground speed [kts]	True Airspeed[kts]	Indicated Airspeed [kts]	Machnumber	Wind speed [kts]	Wind direction [°]	FIR/UIR	Temperatur [°C]
2	12.9.23 11:38	35.975,00	0,00	37.800,00	67	482,00	448	258	0,776	47	290	ROME FIR/UIR	-54
3	12.9.23 11:32	38.000,00	0	39.775,00	68	469	440	244	0,772	38	286	ROME FIR/UIR	-59
4	24.8.23 12:52	39.000,00	64	40.400,00	19	443	440	239	0,772	108	280	RHEIN UIR	-59
5	15.9.23 18:46	37.975,00	-64	39.725,00	275	455	484	270	0,848	64	332	FRANCE UIR	-59
6	4.9.23 12:46	39.000,00	0	41.375,00	25	426	454	244	0,788	47	328	HANNOVER UIR	-54
7	11.8.23 19:28	38.975,00	0	40.600,00	44	465	438	237	0,768	83	290	HANNOVER UIR	-59
8	24.8.23 11:33	37.000,00	0	38.375,00	200	434	454	258	0,796			HANNOVER UIR	-59
9	4.9.23 13:18	38.000,00	0	40.425,00	2	424	456	250	0,788	39	324	HANNOVER UIR	-53
10	3.9.23 10:53	37.000,00	0	38.800,00	82	429	446	249	0,772	108	356	HANNOVER UIR	-53
11	3.9.23 11:54	35.000,00	0	36.900,00	157	550	484	281	0,828	84	14	HANNOVER UIR	-46
12	12.9.23 19:08	36.975,00	0	38.825,00	143	457	452	255	0,788	24	244	ROME FIR/UIR	-56
13	3.9.23 20:04	36.000,00	0	38.100,00	7	399	456	258	0,780	82	316	HANNOVER UIR	-48
14	5.9.23 10:20	43.000,00	64	45.200,00	331	412	444	224	0,800			HANNOVER UIR	-70
15	18.10.23 16:35	37.000,00	0	37.475,00	168	460	438	249	0,772	27	314	HANNOVER UIR	-61

Figure 3.24: Excerpt from the left part of the sheet “Persistent Contrail” with data like time, speed, altitude etc.

T	U	V	W	X	Y	Z
ASML [m]	vertical speed [m/min]	GPS height [m]	Ground speed [m/s]	True Airspeed [m/s]	Indicated Airspeed [m/s]	Wind speed [m/s]
10.965,18	0,00	11521,44	247,9622222	230,4711111	132,7266667	24,17888889
11.582,40	0,00	12123,42	241,2744444	226,3555556	125,5244444	19,54888889
11.887,20	19,51	12313,92	227,8988889	226,3555556	122,9522222	55,56
11.574,78	-19,51	12108,18	234,0722222	248,9911111	138,9	32,92444444
11.887,20	0,00	12611,1	219,1533333	233,5577778	125,5244444	24,17888889
11.879,58	0,00	12374,88	239,2166667	225,3266667	121,9233333	42,69888889
11.277,60	0,00	11696,7	223,2688889	233,5577778	132,7266667	0
11.582,40	0,00	12321,54	218,1244444	234,5866667	128,6111111	20,06333333
11.277,60	0,00	11826,24	220,6966667	229,4422222	128,0966667	55,56
10.668,00	0,00	11247,12	282,9444444	248,9911111	144,5588889	43,21333333
11.269,98	0,00	11833,86	235,1011111	232,5288889	131,1833333	12,34666667
10.972,80	0,00	11612,88	205,2633333	234,5866667	132,7266667	42,18444444
13.106,40	19,51	13776,96	211,9511111	228,4133333	115,2355556	0
11277,6	0	11422,38	236,6444444	225,3266667	128,0966667	13,89

Figure 3.26: Conversions in the middle of “Persistent Contrails” to the metric system.

AA	AB	AC	AD	AE
p_{ISA} [Pa]	T [ISA]	ΔT=T[ISA]-T[ADS-B]	$p_{ISA+\Delta T}$ [Pa]	Δp=p[ISA]- p[ISA+ΔT]
20845,54	216,65	2,50	20845,54	0,00
18957,79	216,65	-2,50	18957,79	0,00
18396,78	216,65	-2,50	18396,78	0,00
19003,40	216,65	-2,50	19003,40	0,00
17554,56	216,65	2,50	17554,56	0,00
18220,78	216,65	-2,50	18220,78	0,00
20277,33	216,65	-2,50	20277,33	0,00
18374,68	216,65	3,50	18374,68	0,00
19867,33	216,65	3,50	19867,33	0,00
21767,04	216,65	10,50	21767,04	0,00
19843,47	216,65	0,50	19843,47	0,00
20547,12	216,65	8,50	20547,12	0,00
14606,57	216,65	-13,50	14606,57	0,00
21173,72	216,65	-4,5	21173,72	0,00

Figure 3.25: Calculation of Δp in Persistent Contrails

Avg. Temperature [°C]	Avg. GPS Height [ft]	Avg. True Airspeed [kt]	Avg. ΔT [K]
-56,43	39555,36	452,43	0,07

Figure 3.27: Average Values for “Persistent Contrails”

Avg. Temperature [°C]	Avg. GPS Height [ft]	Avg. True Airspeed [kt]	Avg. ΔT [K]
-53,97	38786,43	452,34	2,32

Figure 3.28: Average Values for “Transient Contrails”

Avg. Temperature [°C]	Avg. GPS Height [ft]	Avg. True Airspeed [kt]	Avg. ΔT [K]
-46,15	36344,23	454,77	8,73

Figure 3.29: Average Values for “None at All”

4 Observation, Classification, and Prediction of Contrails

In the following the results of the observation shall be presented. In order not to have to constantly jump, a subdivision into the categories listed in Chapter 2.6 was made. Listing every observed aircraft in the results would not make sense, so we will limit ourselves to a selection. Further data can be viewed at any time via the link to the raw data. In the following aircraft are often named by their registration as it normally does not change over their lifetime, and it therefore will be easier to lookup data even after an ownership change.

4.1 No Contrail at All

On September 5th, 2023, an Boeing 737 MAX8 flew over at 2:54 PM. The observer was near Glinde, east of Hamburg. The aircraft was at a GPS altitude of 39250 ft. According to the transponder, the ambient air temperature was -51 °C. The aircraft position can be found in Figure 4.1 which shows the map of Flightradar24 for the observed aircraft. In Figure 4.2 flight data like the temperature and height can be seen. A photo of the aircraft can be seen in Figure 4.3.

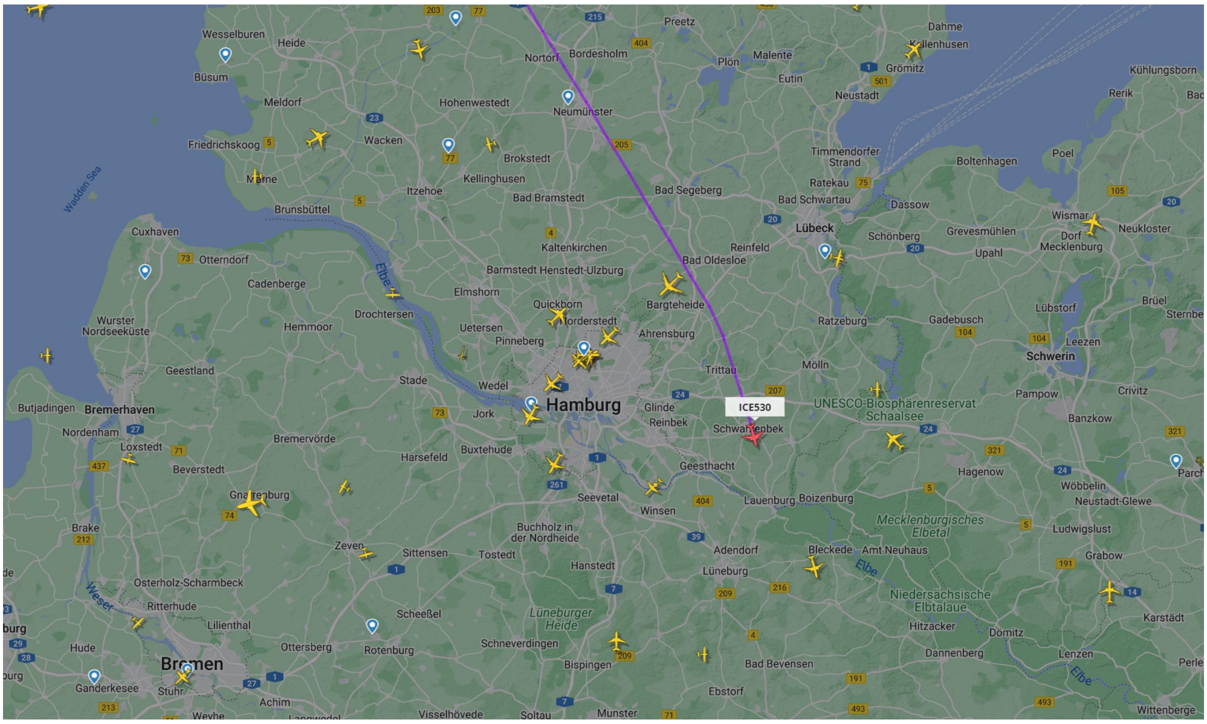


Figure 4.1: Map out of Flightradar24 for TF-ICH. The aircraft is to the east of Hamburg. Several other aircrafts can be seen at the map. Source: Flightradar24 (2023)

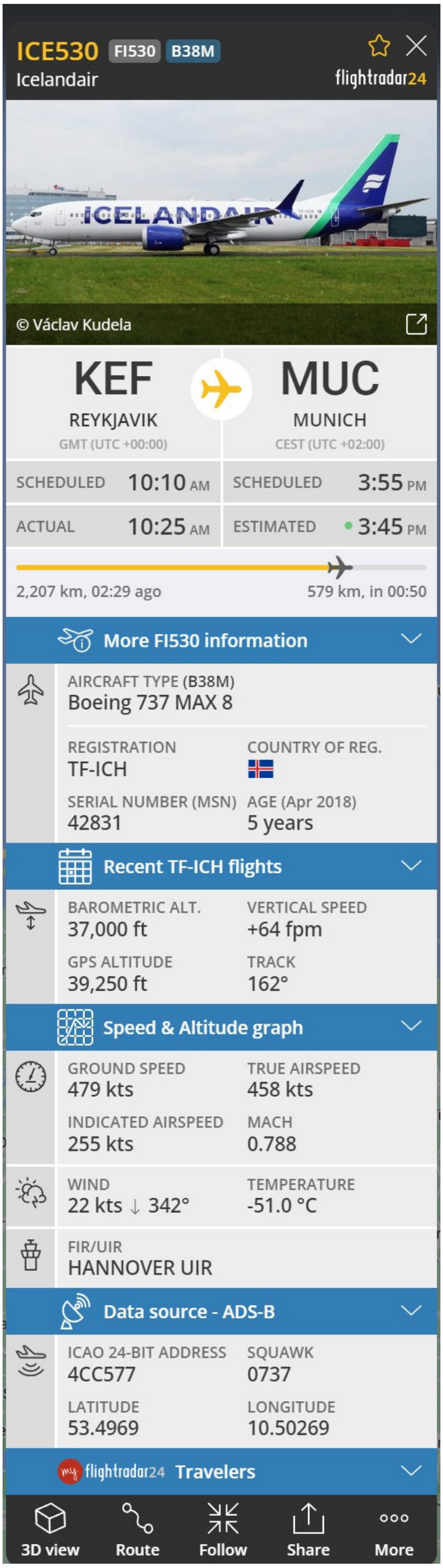


Figure 4.2: Flightradar24-Data for the 737 MAX with registration TF-ICH. Data like altitude, speed Source: Flightradar24 (2023) and temperature can be seen. Source: Flightradar24 (2023)

Figure 4.3: Photo of TF-ICH. A Boeing 737 MAX in the blue sky.

The satellite images taken at the time of the observation do not show any contrails in the region. In addition, as can be expected from the picture, the sky is quite clear. However, some smaller clouds can be seen. Take a look at Figure 4.4.

Figure 4.4: Satellite image for TF-ICH at time of observation. Some clouds can be seen in the northeast of Germany. Source: Windy (2023)

Even a while later, the picture does not change much. Compare Figure 4.4 and Figure 4.5. The white cloud over the North Sea, in Figure 4.4 not far from the border of the Netherlands, barely moved. In Figure 4.5 the cloud just reached Bremerhaven area.

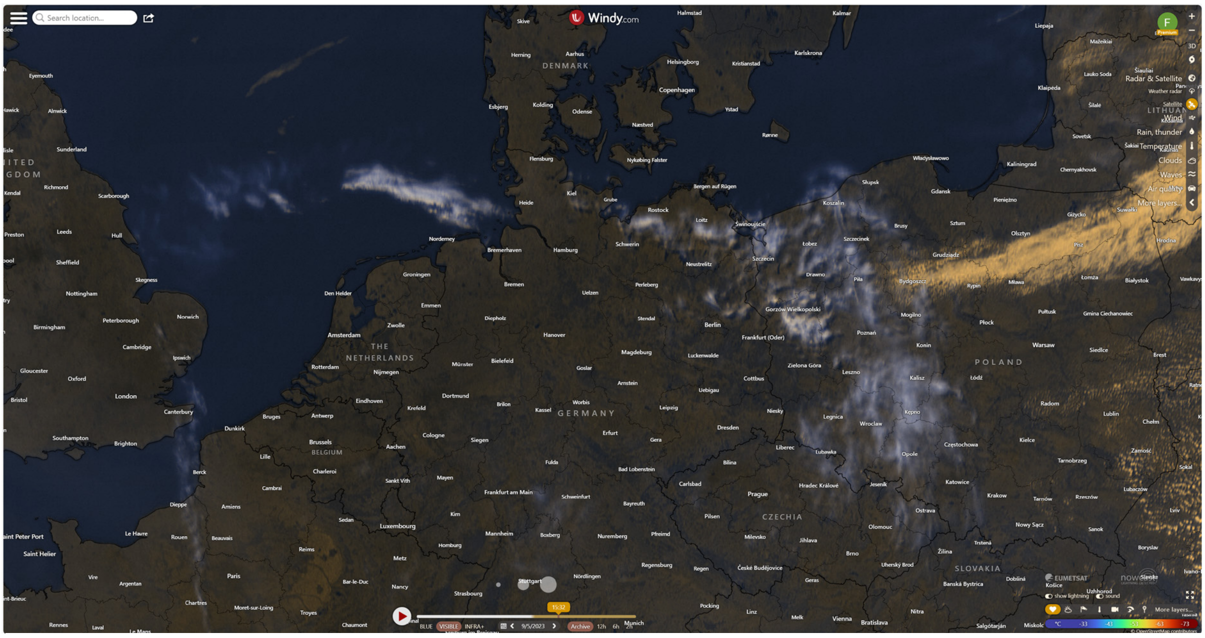


Figure 4.5: Satellite image from TF-ICH about 40 minutes after the observation. The clouds moved a little to the east. Source: Windy (2023)

As already mentioned, the meteorological data can only be recorded for FL390 and FL450. In addition, as already mentioned, data is only available on the hour. At the time of observation, the ICON-D2 weather model was not used. The ECMWF model was used instead. In order to determine the existing relative humidity as accurately as possible, all four screenshots must be taken into account. The images are shown below. Take a look at Figure 4.6, Figure 4.7, Figure 4.9 and Figure 4.8.

The data between 2 PM and 3 PM hardly differ, and the observation took place almost at 3 PM. Therefore, the author decided to use the data from 3 PM. The aircraft's GPS altitude only deviates 250 ft from FL390, so the author decided to use the Figure 4.9 data without making any further interpolations. The author therefore assumes a relative humidity of 27%.

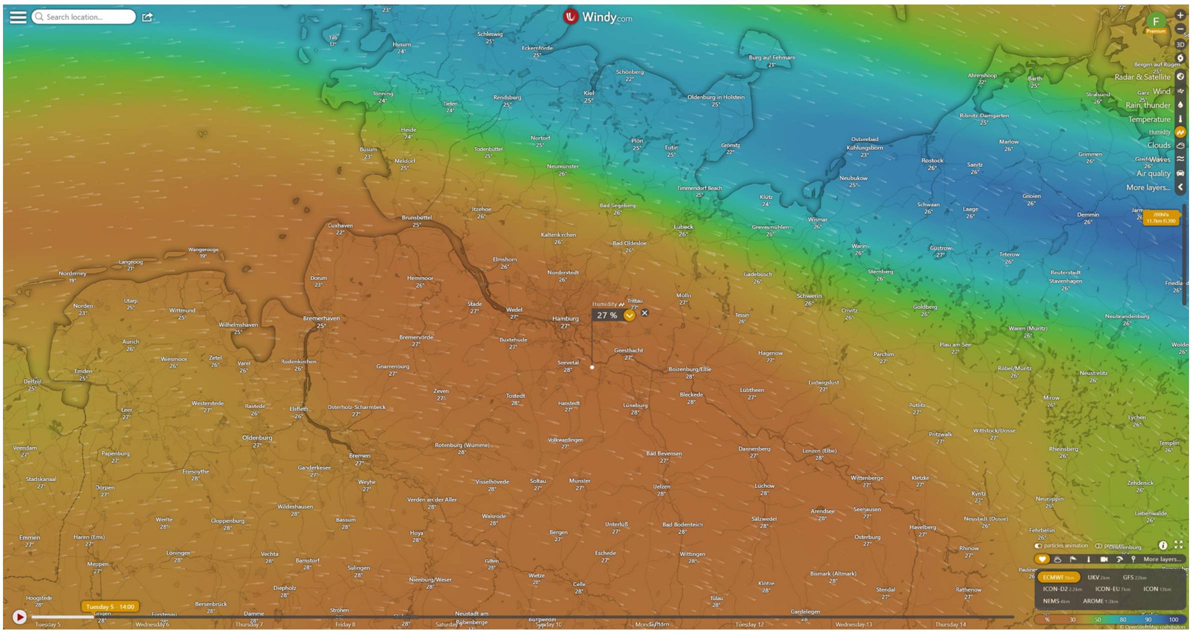


Figure 4.6: FL390 at 2 PM. for TF-ICH. Red areas show a relatively low relative humidity and blue areas a high relative humidity. The “comets” are an indication for the wind direction and speed. Source: Windy (2023)

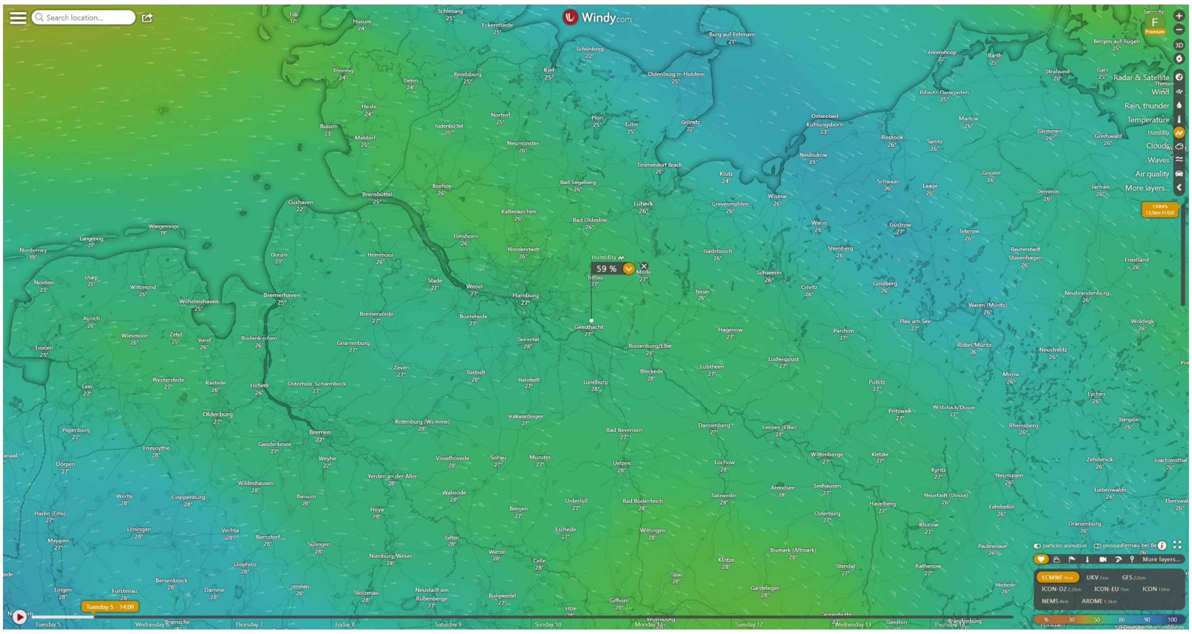


Figure 4.7: FL450 at 2 PM for TF-ICH. The explanation for the color scale can be found in the bottom right corner of the Figure. The “comets” are an indication for the wind direction and speed. Source: Windy (2023)

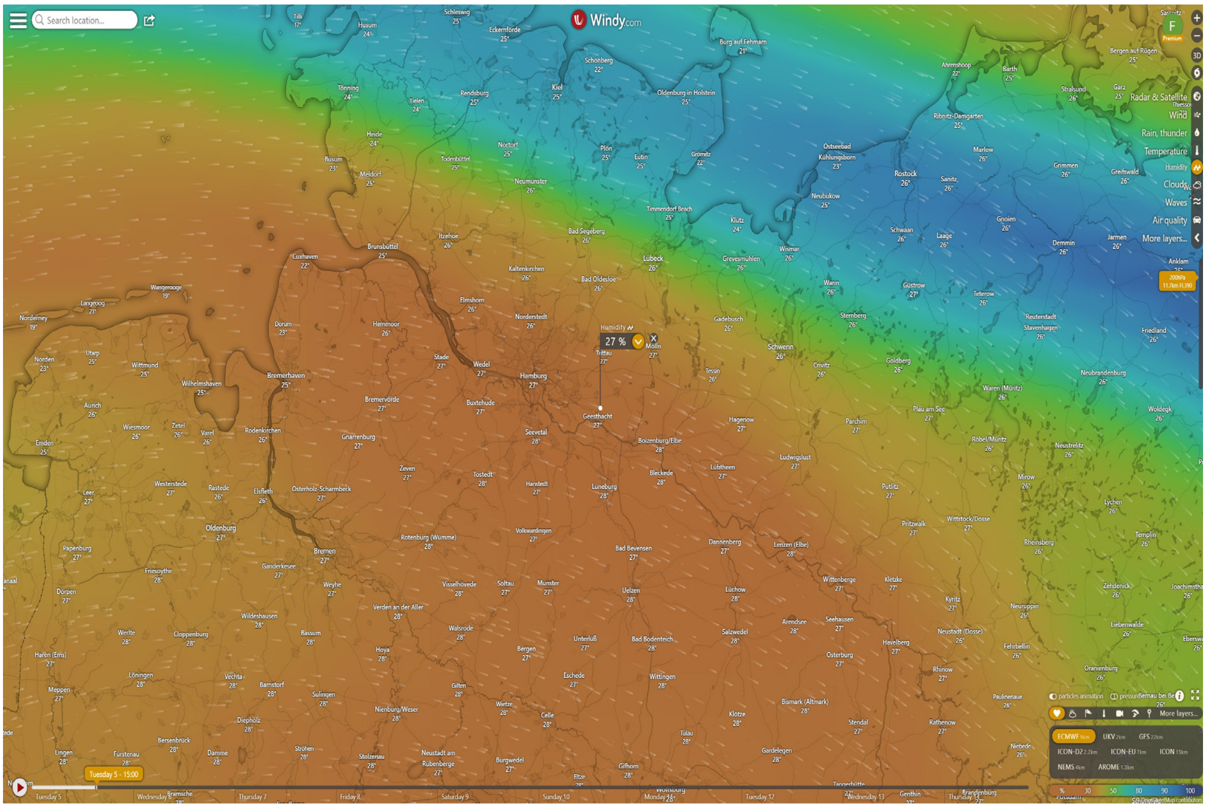


Figure 4.9: FL390 at 3 PM for TF-ICH. In the red areas there is a relatively low relative humidity. In the blue regions a relatively high relative humidity. The color scale is shown in the bottom right corner. “Comets” show the wind direction and speed. Source: Windy (2023)

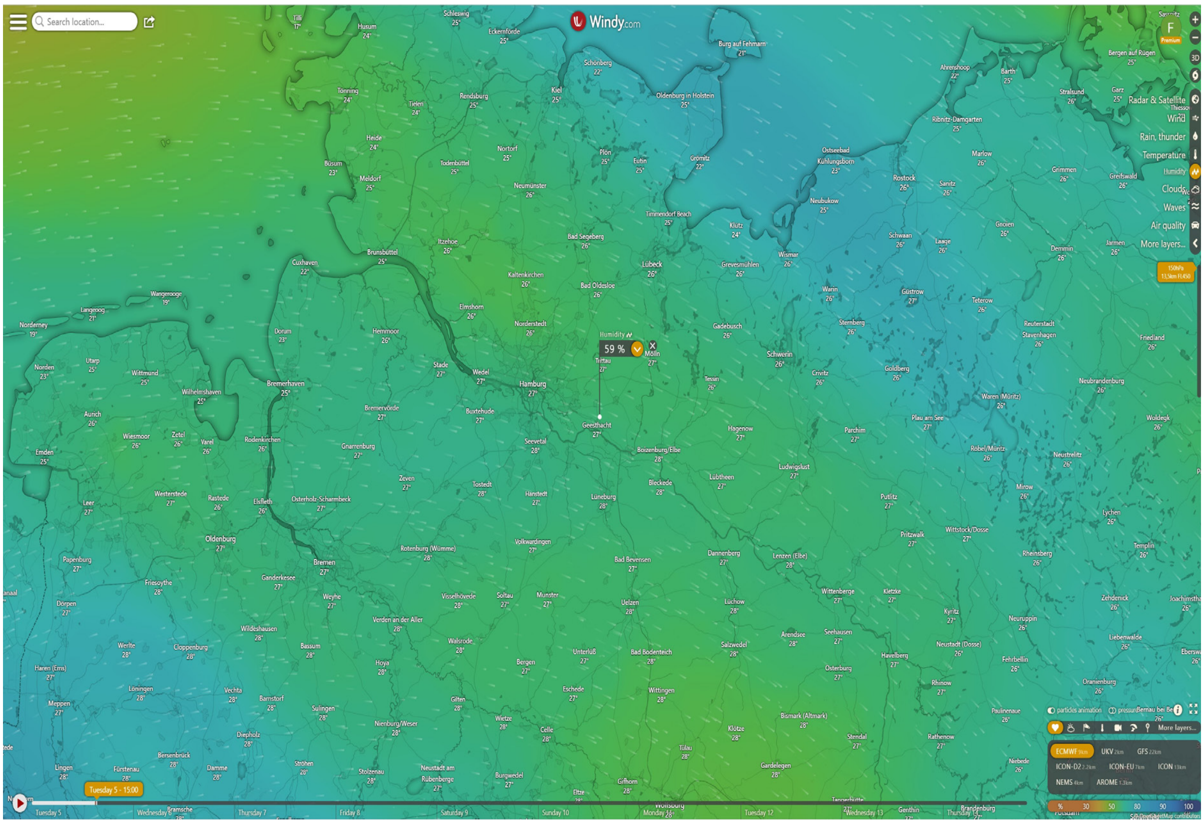


Figure 4.8: FL450 at 3 PM for TF-ICH. The color scale ranges in the 50-80% region. The “comets” show the wind direction and speed. Source: Windy (2023)

A look at the Contrails Map shows that no contrails are predicted by the DLR model over northern Germany about an hour after the observation (Figure 4.10) and for some time later (Figure 4.11) after the observation. However, a few potentially warming contrails can be seen in the south of Germany. Even using the search function does not return any results. Therefore, take a look at Figure 4.12.

Figure 4.10: Contrails Map at 3:50 PM Several blue contrails can be seen in the east and south of Germany. Some orange contrails in the northeast of Germany, near Russia. Source: Breakthrough Energy (2023b)

Figure 4.11: Contrails Map at 4:30 PM. Several contrails can be seen in the top right as well as over Germany. Source: Breakthrough Energy (2023b)

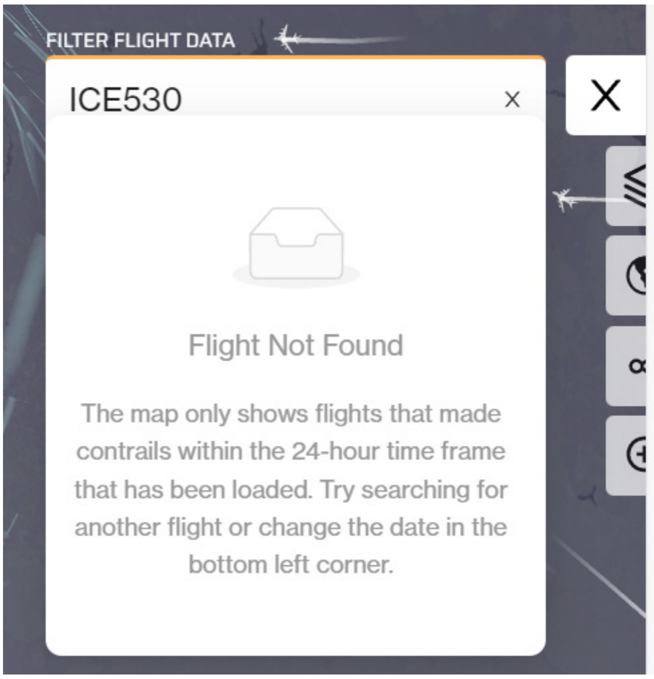


Figure 4.12: Use of the search function of the Contrails Map. Source: Breakthrough Energy (2023b)

The Schmidt-Appleman diagram was evaluated for the prediction. It is shown in Figure 4.13. The red cross is indeed to the right of the light blue line, so the Schmidt-Appleman diagram predicts that no contrail will form. According to the SAC sheet, a minimum relative humidity of 61.2% is needed to form persistent contrails. With Equation 3.1 $R = \frac{27\%}{61.2\%} = 0.44$ which is smaller than 0.5. The calculated criterion for no contrail is fulfilled. The diagram of minimum relative humidity needed for persistent contrails is shown in Figure 4.14.

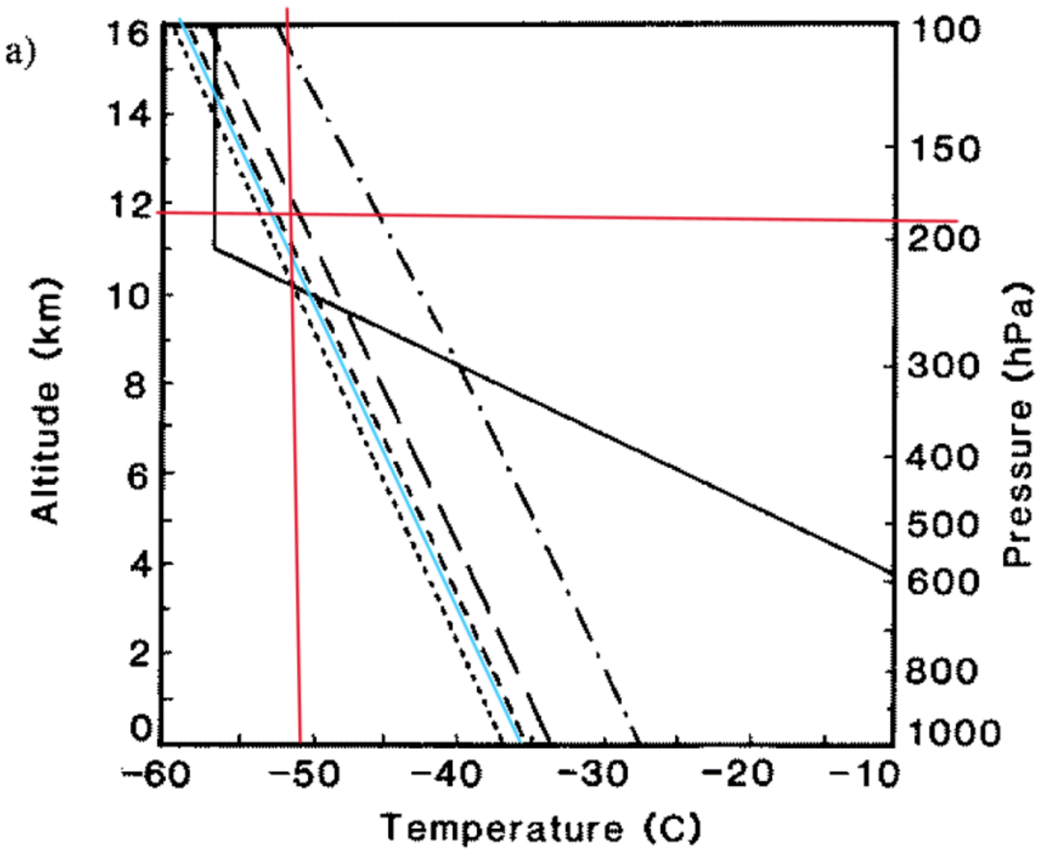


Figure 4.14: Schmidt-Appleman diagram with threshold temperature T_{LC} versus altitude for relative humidity of 0 (short-dashed curve), 30% (medium-dashed), 60% (long-dashed) and 100% (dash-dotted line), and the temperature profile of the ISA (full), for kerosene and a propulsive efficiency of 0.3. Red lines: Temperature and Altitude; Blue line: approximate relative humidity. Source: Schumann (1996)

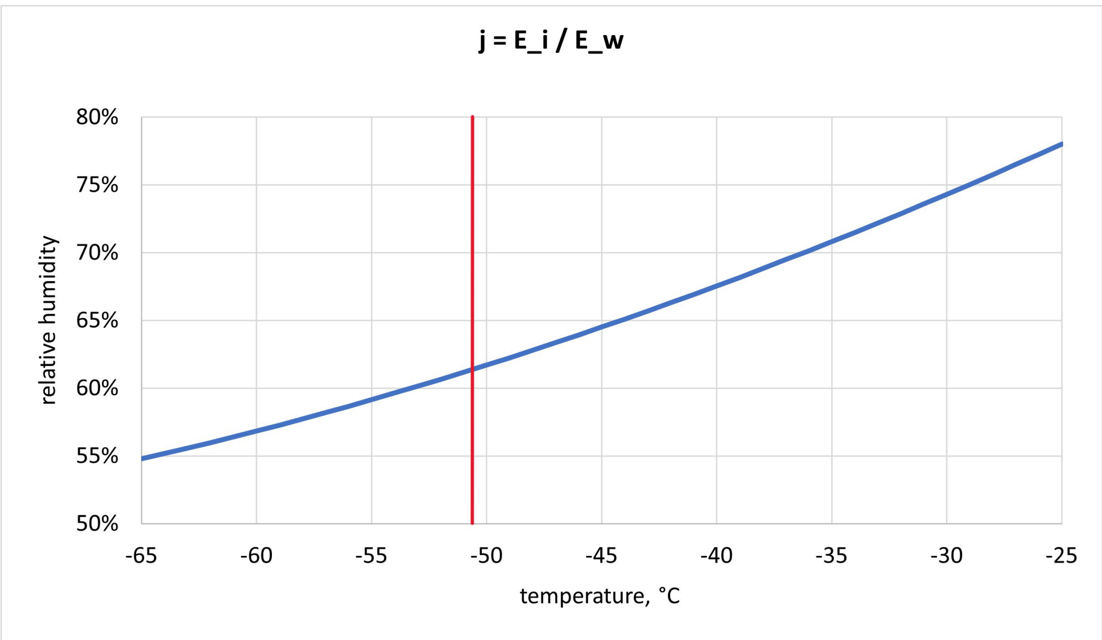


Figure 4.13: Minimum relative humidity for given temperature for persistent contrails. Source: Scholz (2023b)

A second example can be found in the following. At 1:07 PM on August 21, a United Airlines 767-424(ER) flew by. The aircraft has the registration N76062. It was flying at 31450 ft by GPS altitude. The outside temperature was -35 °C. Further details can be found in Figure 4.15. The observer was positioned near Glinde. The aircraft position shortly after flyby can be seen in Figure 4.16. A picture of the aircraft can be seen in Figure 4.17.

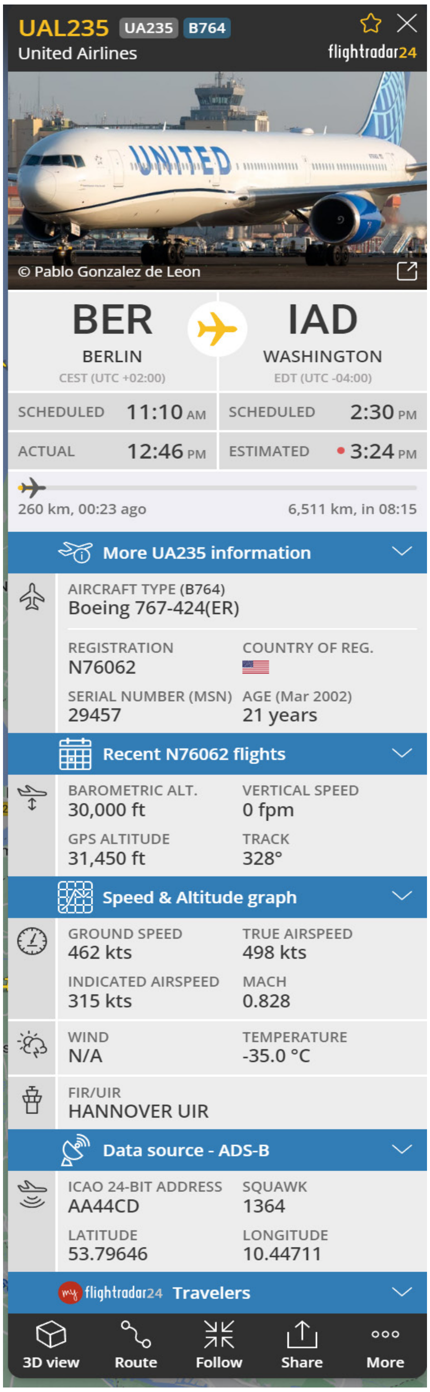


Figure 4.15: Flightradar24 details for N76062. Flight data like the outside temperature, altitude and Aircraft type are shown. Source: Flightradar24 (2023)

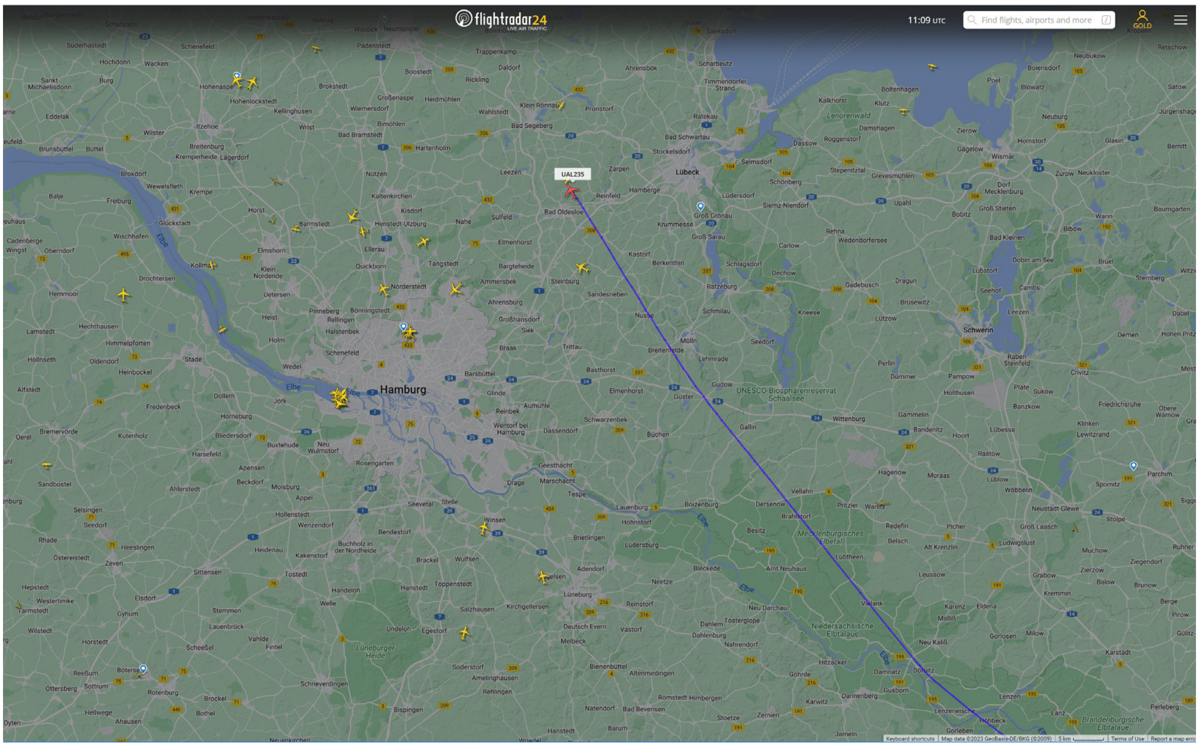


Figure 4.16: N76062 Flightradar24 map shortly after flyby of the Boeing aircraft. The aircraft is to the north of the observer. Source: Flightradar24 (2023)

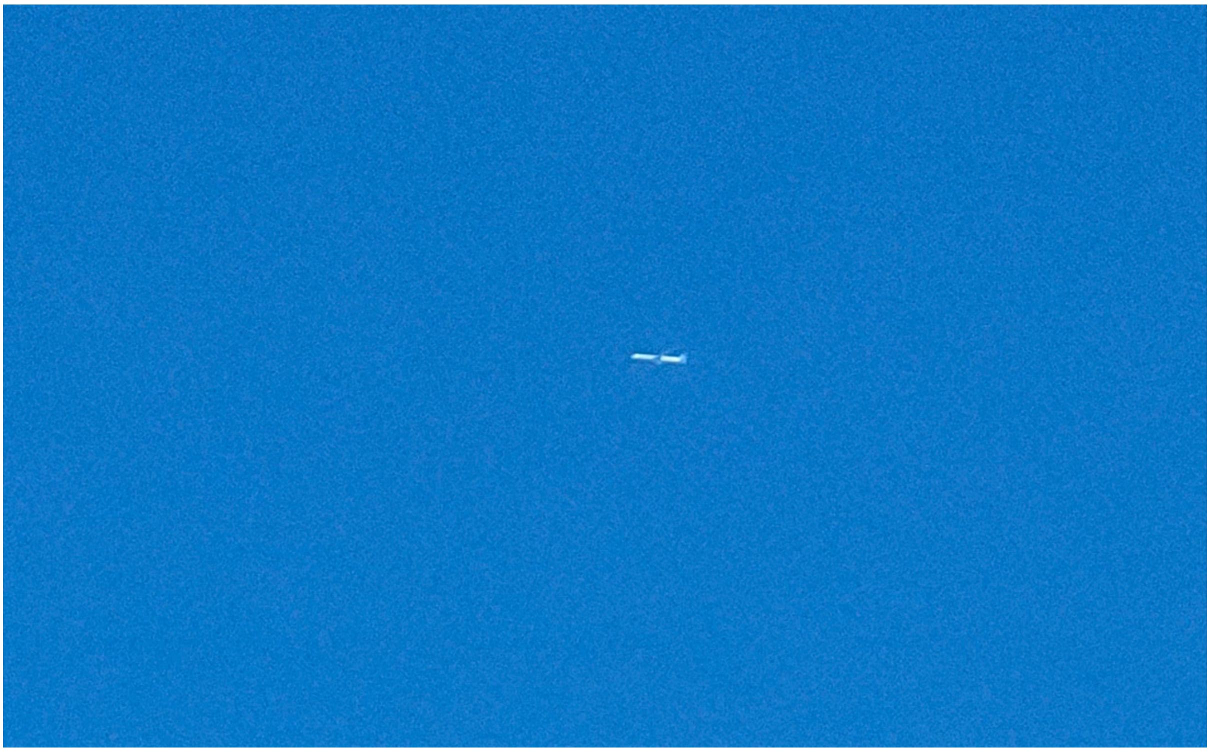


Figure 4.17: Picture of N76062 taken at flyby.

At the time of the fly by some scattered clouds are visible at the satellite image (Figure 4.18). By looking at the whole map of Germany, no contrail cirrus clouds can be spotted.

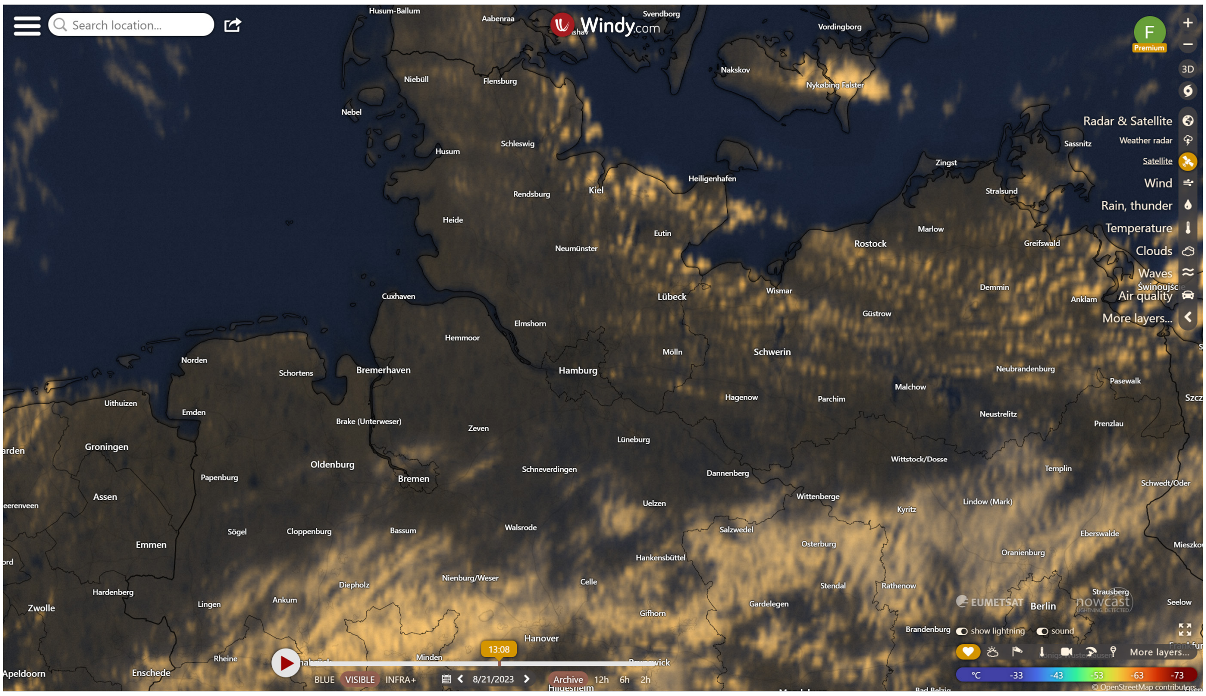


Figure 4.18: Sat image of N76062. Some clouds can be seen in the Hannover region as well as in the vicinity of the Baltic Sea. It appears that they are natural clouds.

In Figure 4.19 the humidity map of windy at 1 PM for FL300 is shown. It’s quite inhomogeneous, but a humidity lower than 50% is expected as the wind blows east and at the 2 PM image the red area which in Figure 4.19 is currently over Hamburg moved east, as can be seen in Figure 4.20.

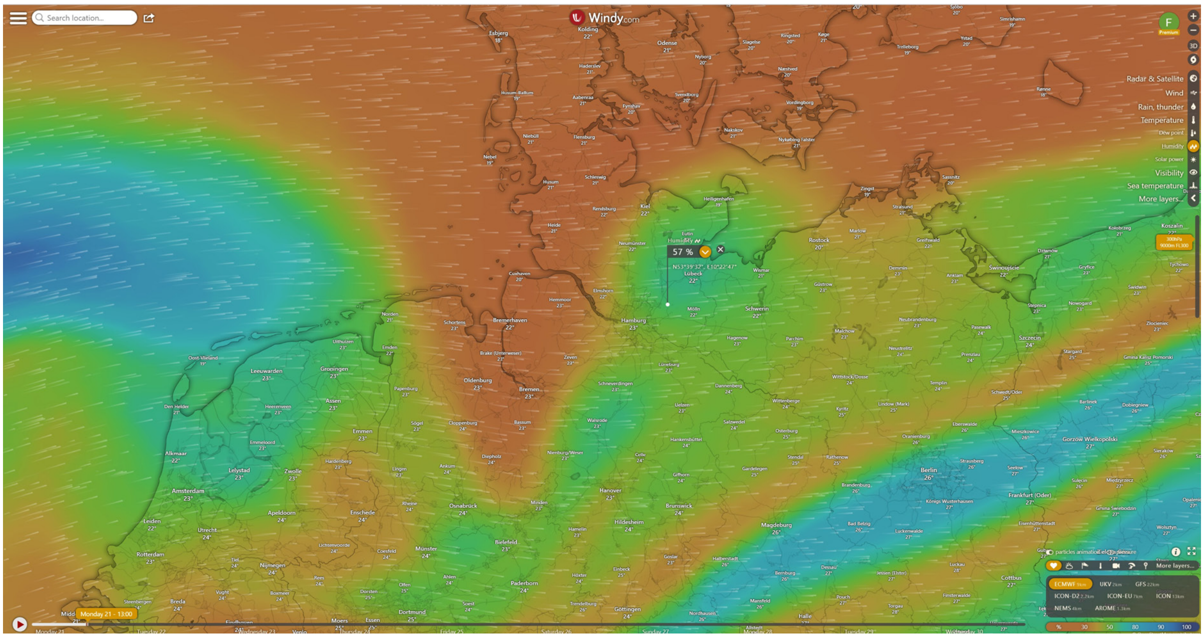


Figure 4.19: Windy data for N76062 at FL300 and 1 PM red (=low relative humidity) as well as green and blue (=higher relative humidity) can be seen. These are arranged in pocket like structures. Source: Windy (2023)

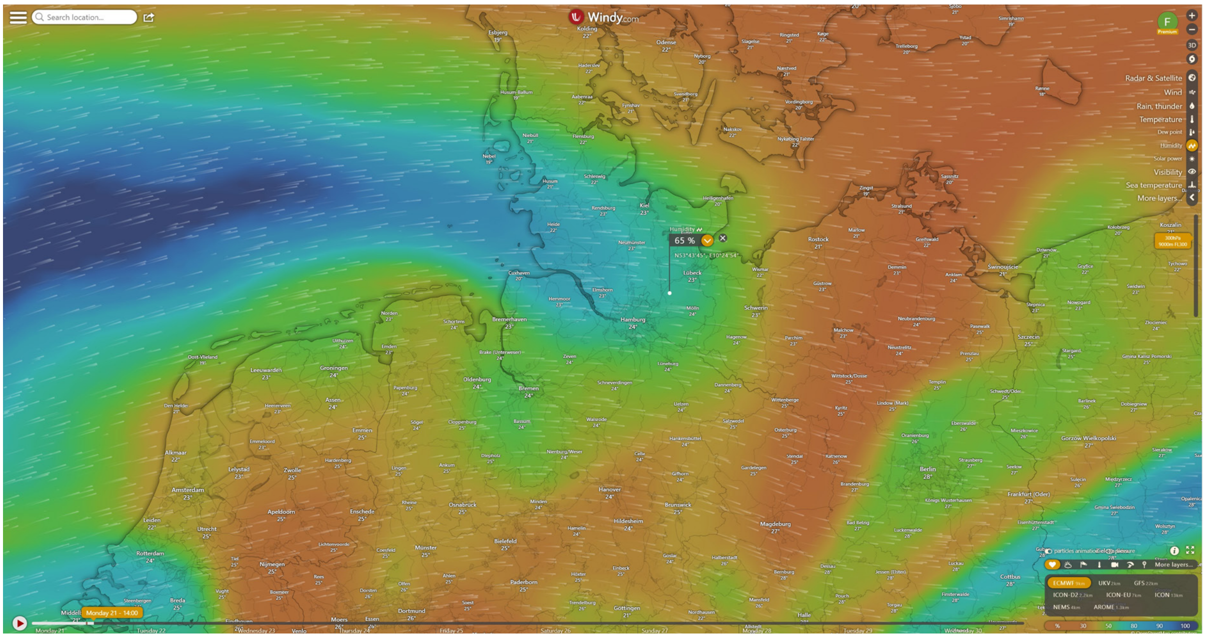


Figure 4.20: Windy Data at FL300 for N76062 at 2 PM. A band with high relative humidity is moving in from the west (blue). The “comets” are an indication of wind direction and speed. Source: Windy (2023)

The author assumes that the red area of FL300 at the time of the flyby is around the airplane. A relative humidity of 35% is therefore assumed.

A look at FL340 also shows a red area. Where the red area also moved to the east (compare Figure 4.21 and Figure 4.22).

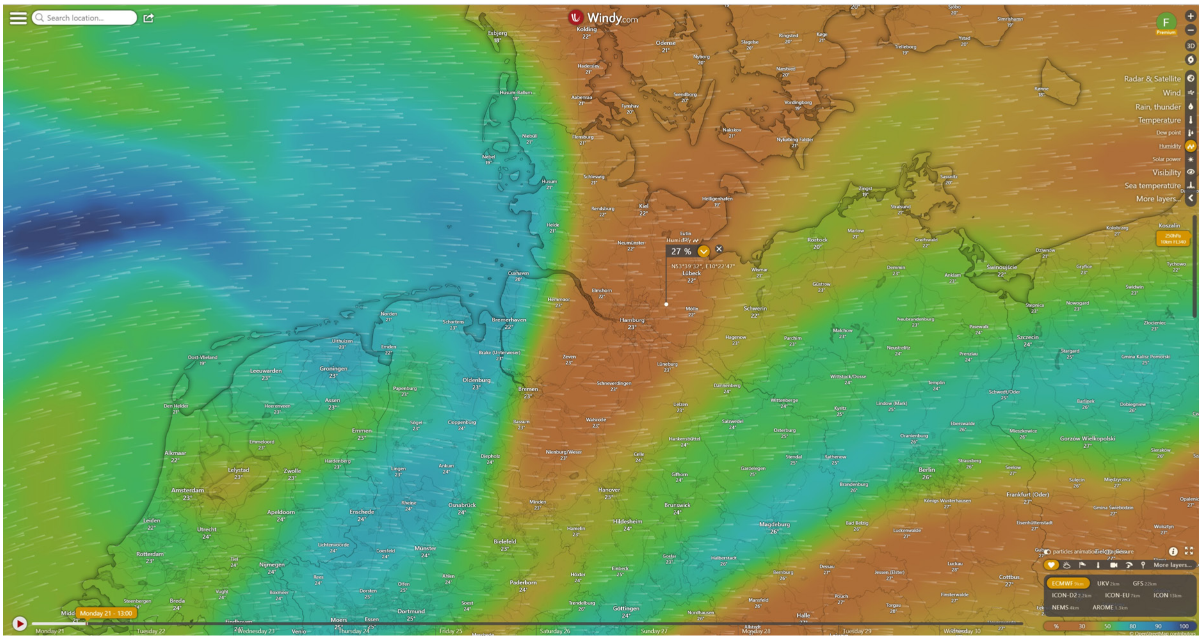


Figure 4.21: Windy data for N76062 at FL340 at 1 PM. A red area with a low relative humidity Is around the observer's location. Source: Windy (2023)

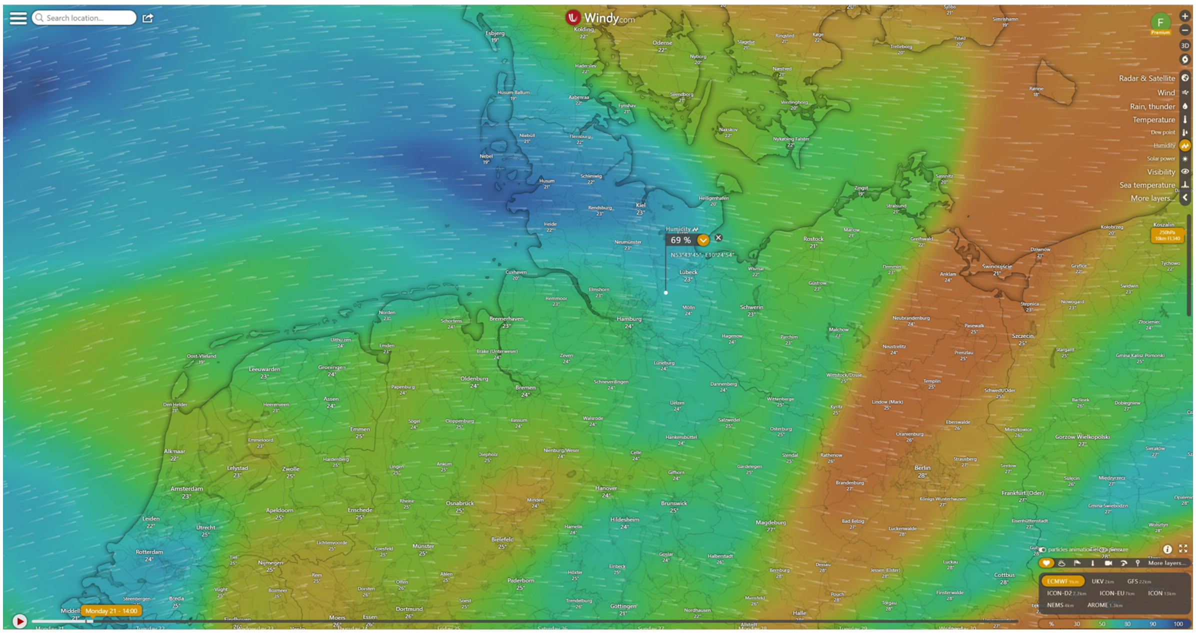


Figure 4.22: Windy data for N76062 at FL340 at 2 PM. The "comets" indicate the wind direction and speed. Over the North Sea, there is a high relative humidity area which is about to move over the northern part of Germany. Source: Windy (2023)

The Contrails Map does not show any contrails. A search for this flight returns no result. The Contrails Map does not expect any contrail to form. This is further proofed in Figure 4.23.

Figure 4.23: Contrails Map for N76062 at 2:50 PM. Many flights are shown but almost no contrails can be seen over central Europe. Source: Breakthrough Energy (2023b)

In Figure 4.24 the Schmidt-Appleman diagram is shown. The outside temperature is compared to other flights quite high and therefore the red cross is far to the right, which means that the Schmidt-Appleman diagram predicts that there is no contrail. According to the SAC sheet, a minimum relative humidity of 70.8% is needed to form a persistent contrail. The curve is shown in Figure 4.25. Using Equation 3.1 yields $R = \frac{35\%}{70{,}8\%} = 0.49$ which is smaller than 0.5. The calculated criterion for no contrail is fulfilled.

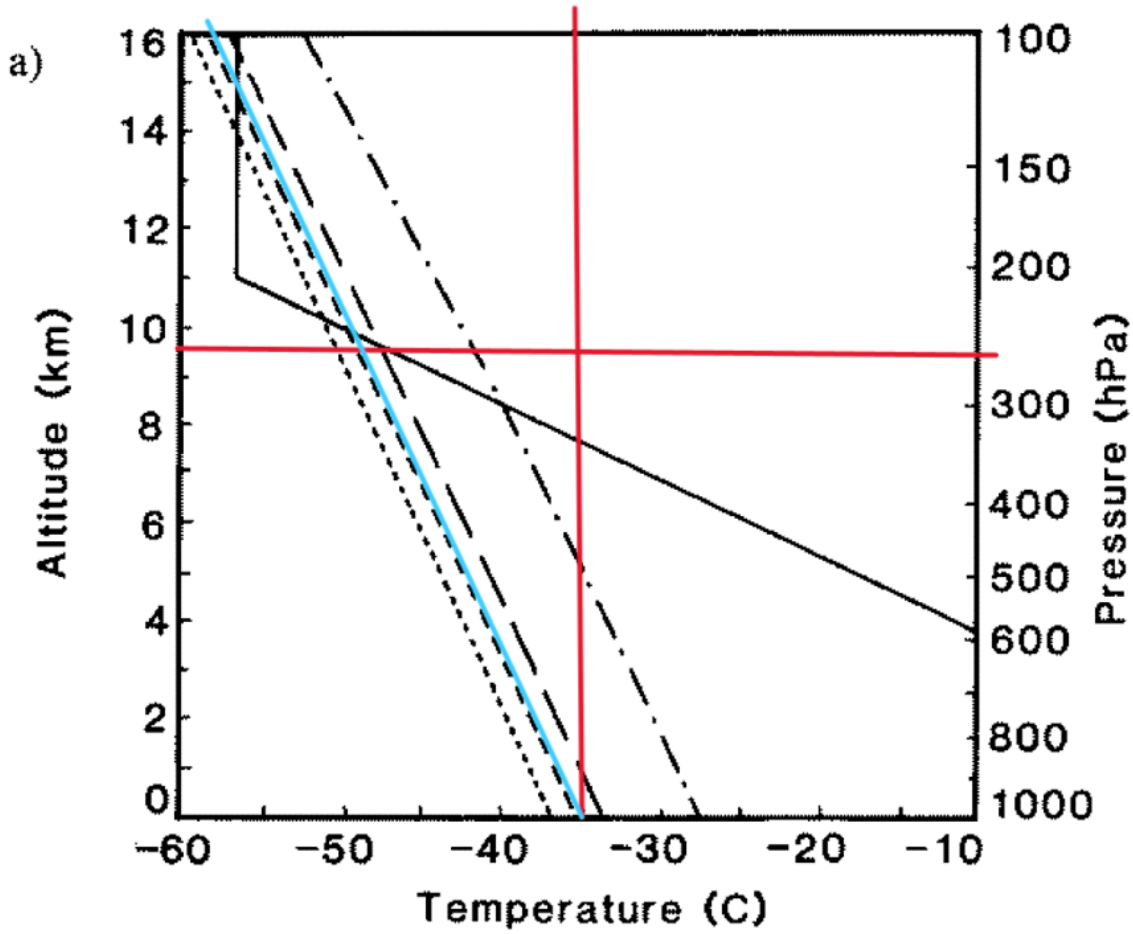


Figure 4.24: Schmidt-Appleman diagram with threshold temperature T_{LC} versus altitude for relative humidity of 0 (short-dashed curve), 30% (medium-dashed), 60% (long-dashed) and 100% (dash-dotted line), and the temperature profile of the ISA (full), for kerosene and a propulsive efficiency of 0.3. Red lines: Temperature and Altitude; Blue line: approximate relative humidity. Source: Schumann (1996)

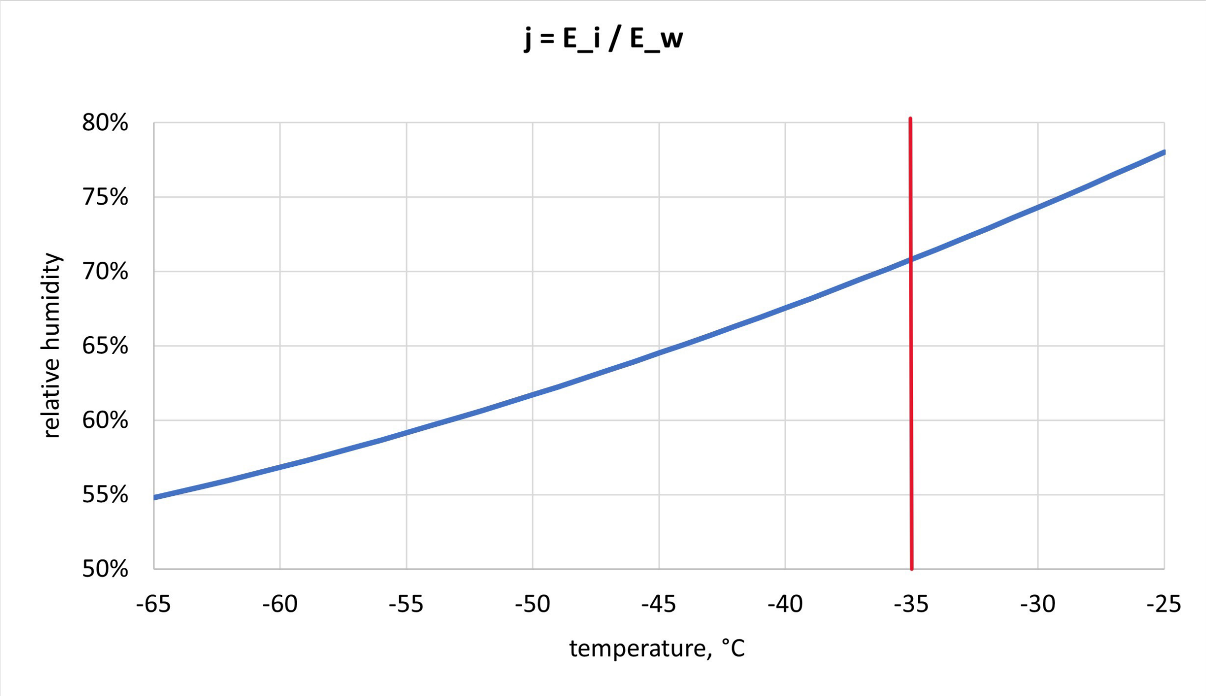


Figure 4.25: Minimum relative humidity for given temperature for persistent contrails. Source: Scholz (2023b)

4.2 Transient Contrails

In the following an example for a transient contrail observation is shown. On August 22, 2023, at 7:10 PM, an aircraft with the registration SP-RSG flew over the east of Hamburg. This aircraft pulled a short contrail behind it, which dissipated after a few seconds. This aircraft was a Ryanair Boeing 737-8AS. The aircraft was moving at a GPS altitude of 39450 ft. The outside temperature was -54 °C. More details from Flightradar24 can be seen in Figure 4.26. The approximate position of the aircraft can be seen in Figure 4.27. The plane and its contrail can be seen in Figure 4.28.

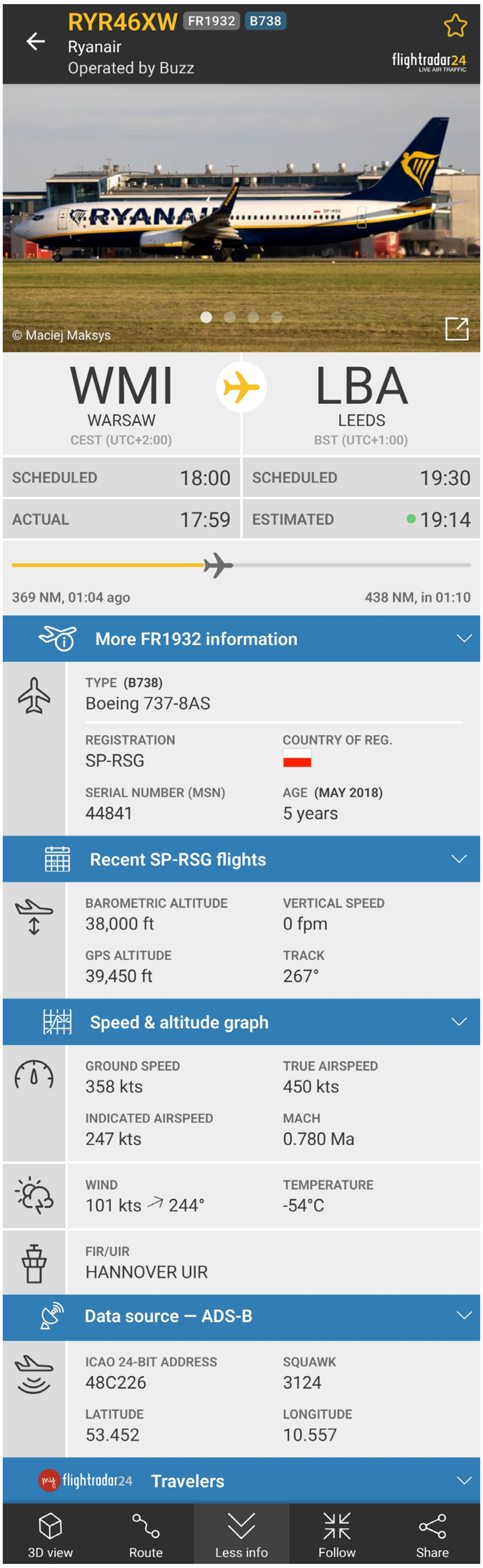


Figure 4.26: The flight-data provided by Flightradar24 for SP-RSG are presented in this picture. Source: Flightradar24 (2023)

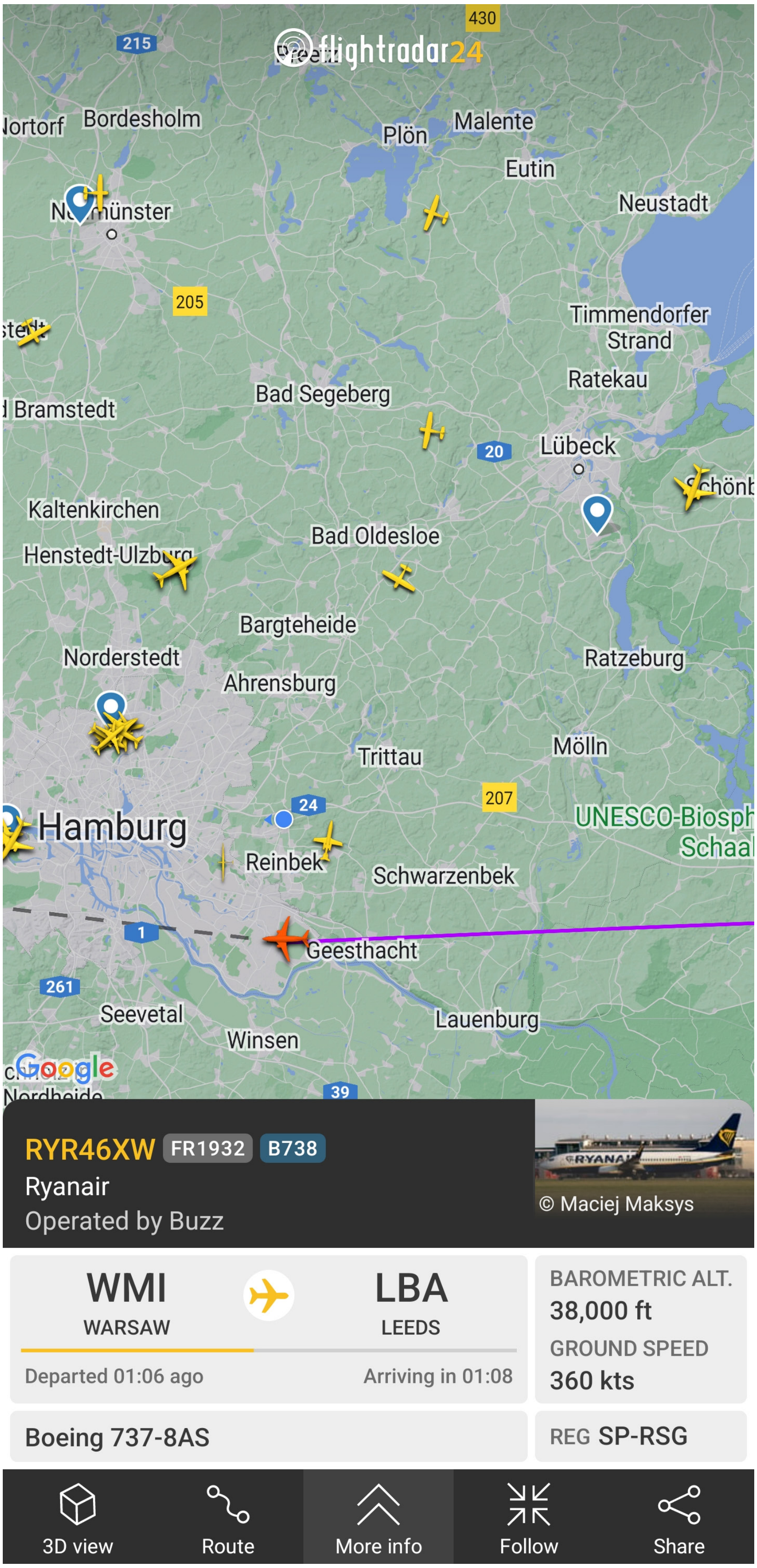


Figure 4.27: Position of SP-RSG. The typical blue dot near Reinbek shows the observers location. The aircraft flew by south to the observer. Source: Flightradar24 (2023)

Figure 4.28: Contrail of aircraft with registration SP-RSG. The contrail is clearly not long lasting.

Approximately an hour before the photo of the flight was taken, there have been some lower clouds north of the observed area (Figure 4.29). Which then moved east. As sunset was 8:33 PM, it already got darker outside, and the visual image is not really usable after 8 PM The satellite image shows no contrail cirrus clouds in the area. Figure 4.30 shows the satellite image which was taken at 7:05 PM

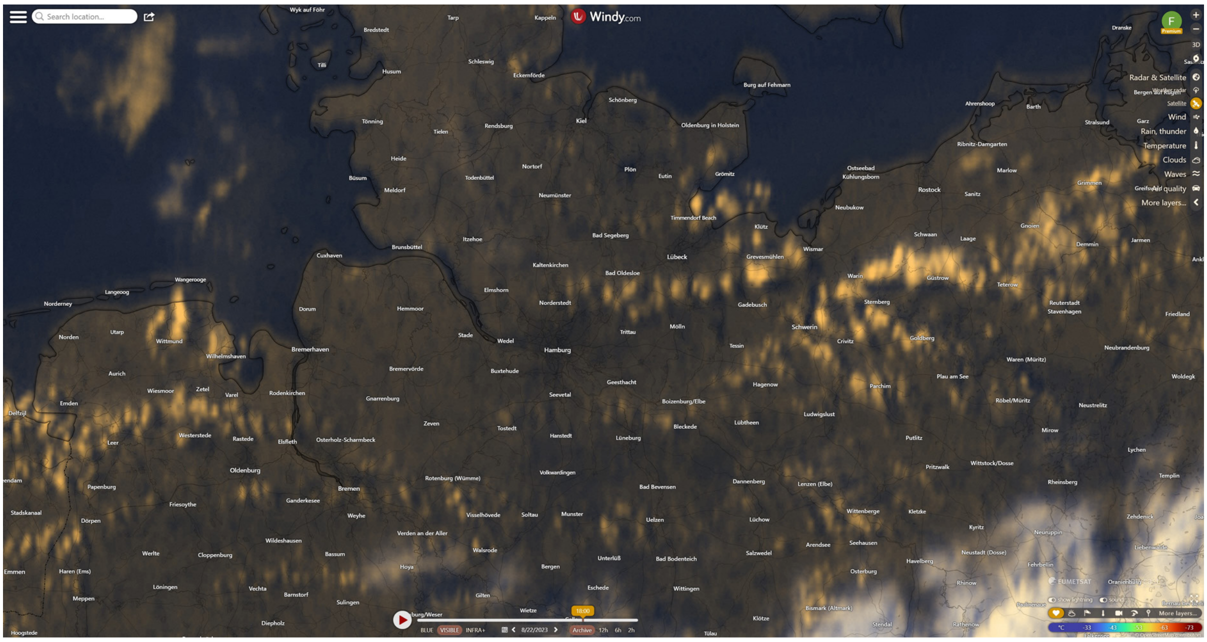


Figure 4.29: Satellite image one hour before flyby of SP-RSG. Several clouds layers can be seen. Source: Windy (2023)

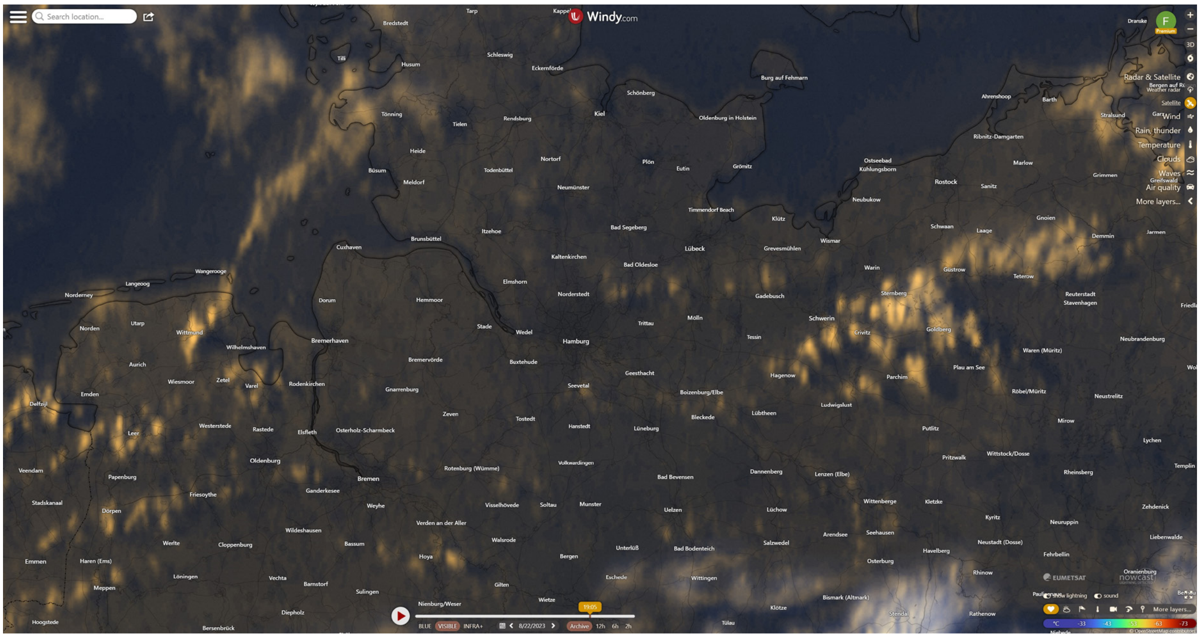


Figure 4.30: Satellite image taken at 7:05 PM, a minute after flyby of SP-RSG. The cloud layer which was before in the bottom right corner moved nearly out of sight. Source: Windy (2023)

With the help of Windy, the relative humidity can be estimated. Given that the photo was taken just 11 minutes past 7 PM, the data for 7PM should be still sufficiently accurate and are therefore used to estimate the relative humidity. As the aircraft is at 39450 ft, so just 450 ft difference to FL390, the data for FL390 should be most accurate and are therefore used to estimate the relative humidity around the aircraft. Figure 4.31 shows a relative humidity of 42% at the approximate position, but the map looks a bit blotchy. In the area of interest there are spots which are orange and some spots which are greenish. The greenish colors stand for a relative humidity around 50%. The humidity therefore can vary a little. The author went for the lowest and therefore most conservative estimate of 42%.

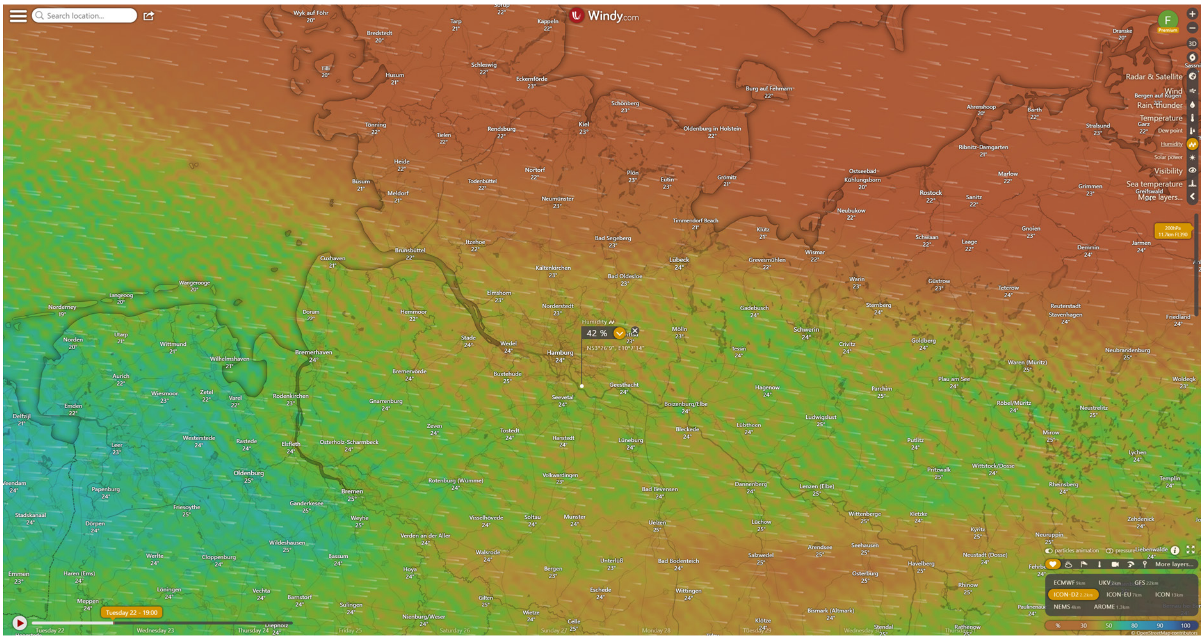


Figure 4.31: Windy data for SP-RSG. To the north the relative humidity is low, to the south medium. A checkered pattern extends around the observer. Source: Windy (2023)

The flight cannot be found on the Contrails Map, which in turn corresponds to the observations, since it is not a persistent contrail. No contrails can be seen over Germany. Take a look at Figure 4.32.

Figure 4.32: Contrails Map for SP-RSG. Some contrails can be seen in the southwestern part of Europe, as well as in the alps area. Most of them are red (=warming), some of them in the bottom left are blue (=cooling). Source: Breakthrough Energy (2023b)

Figure 4.33 shows the Schmidt-Appleman plot with the lines for temperature and altitude plotted in red and the assumed relative humidity in blue. It can be seen that the red cross is to the left of the light blue relative humidity line. The Schmidt-Appleman criterion is therefore fulfilled. The threshold temperature has been reached and contrails can form. This agrees with the observations. What is striking is that the intersection of the two red lines is right on the 0% relative humidity line. According to the Schmidt-Appleman Diagram, formation of contrails would also be possible at 0% relative humidity in the ambient air, at the given temperature.

The Excel Sheet (further explained in Chapter 3.9) is used for proof. The diagram of the SAC-Excel-Sheet is shown in Figure 4.34. The outside temperature is -54 °C. The relative humidity was assumed to be 42%, which is below the blue threshold curve for persistent contrails. The calculation shows a minimum relative humidity of 59.7% for a persistent contrail to form. Even a not that conservative assumption around the 50% mark would also result in a non-persistent contrail. This can be further proofed by calculating R. Using formula 3.1 yields $R = \frac{42\%}{59{,}7\%} = 0.70$ which is in between 0.5 and 1.3. The calculated criterion for a transient contrail is fulfilled.

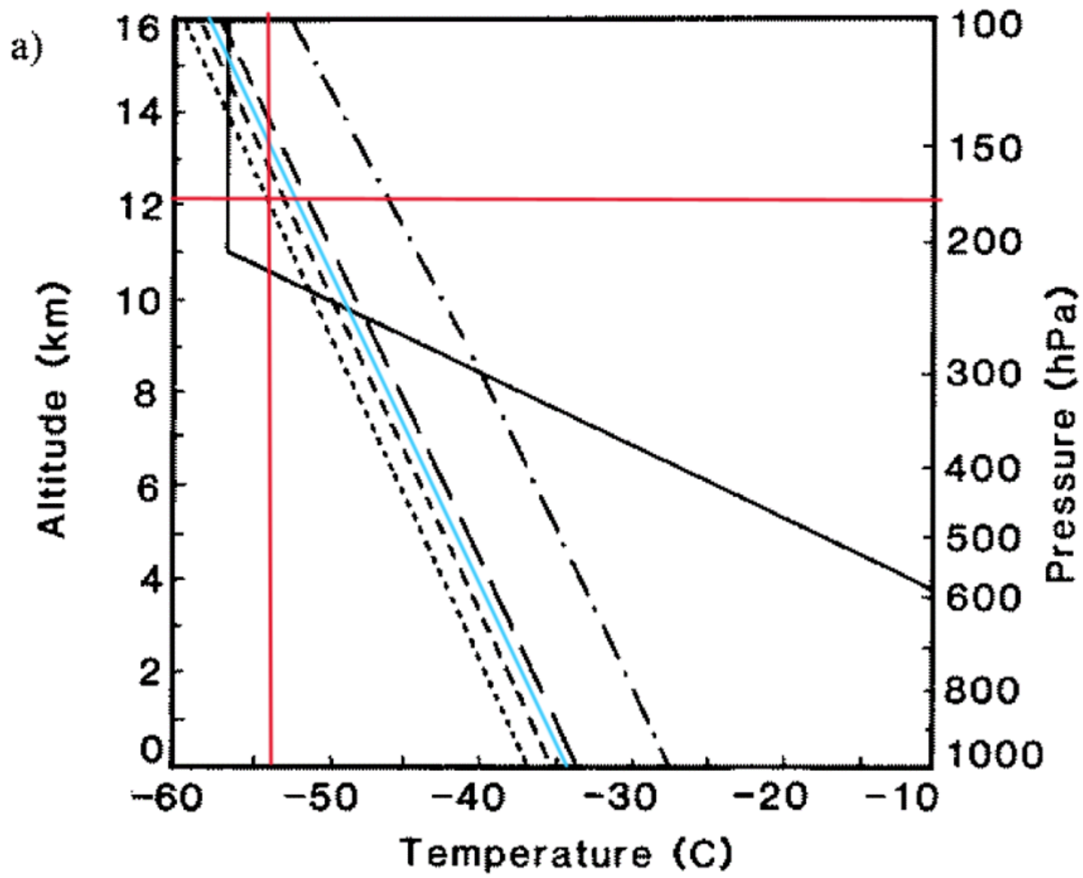


Figure 4.33: Schmidt-Appleman diagram with threshold temperature T_{LC} versus altitude for relative humidity of 0 (short-dashed curve), 30% (medium-dashed), 60% (long-dashed) and 100% (dash-dotted line), and the temperature profile of the ISA (full), for kerosene and a propulsive efficiency of 0.3. Red lines: Temperature and Altitude; Blue line: approximate relative humidity. Source: Schumann (1996)

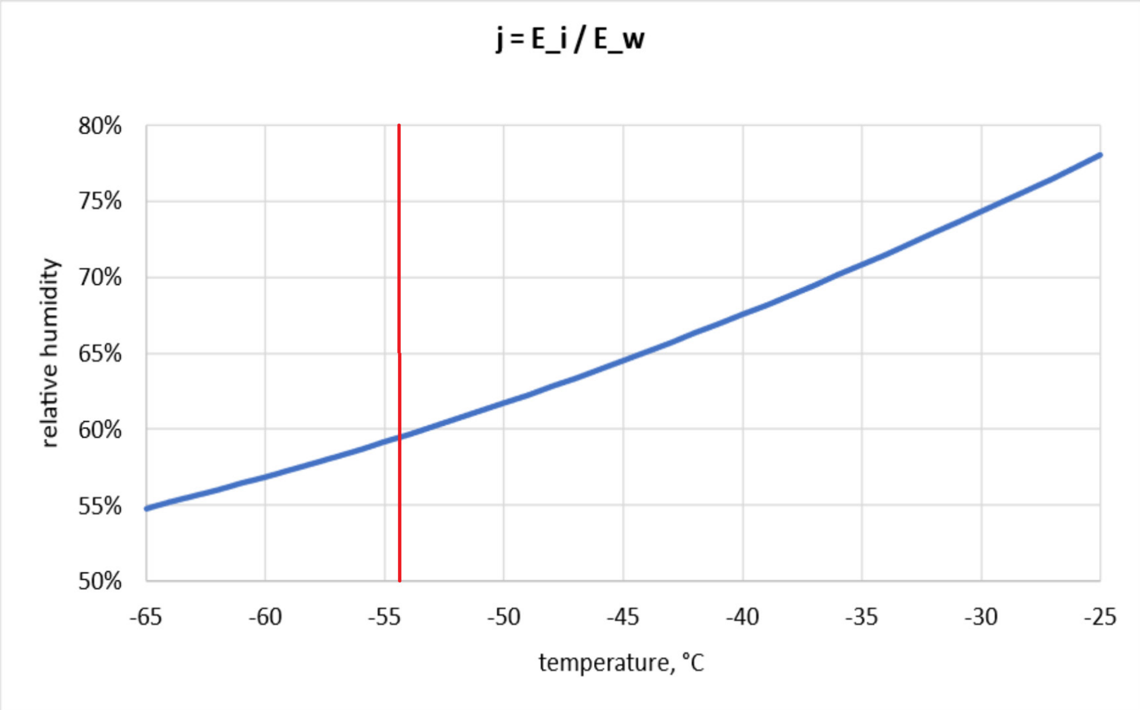


Figure 4.34: Minimum relative humidity for given temperature for persistent contrails. Source: Scholz (2023b)

A second example shall be shown. This time the observation took place at the northern part of Sardinia in Italy. The observed aircraft is a Cessna 560XL Citation Excel, with the registration OK-CAA. This business jet flew by on September 11, 2023, at 5:03 PM The aircraft was traveling at a GPS altitude of 44825 ft. The outside temperature was -61 °C. Further flight data can be seen in Figure 4.35. The approximate Position of the aircraft at time of the observation can be found in Figure 4.36. A picture of the aircraft can be seen in Figure 4.37. A more wide-angle view can be seen in Figure 4.38

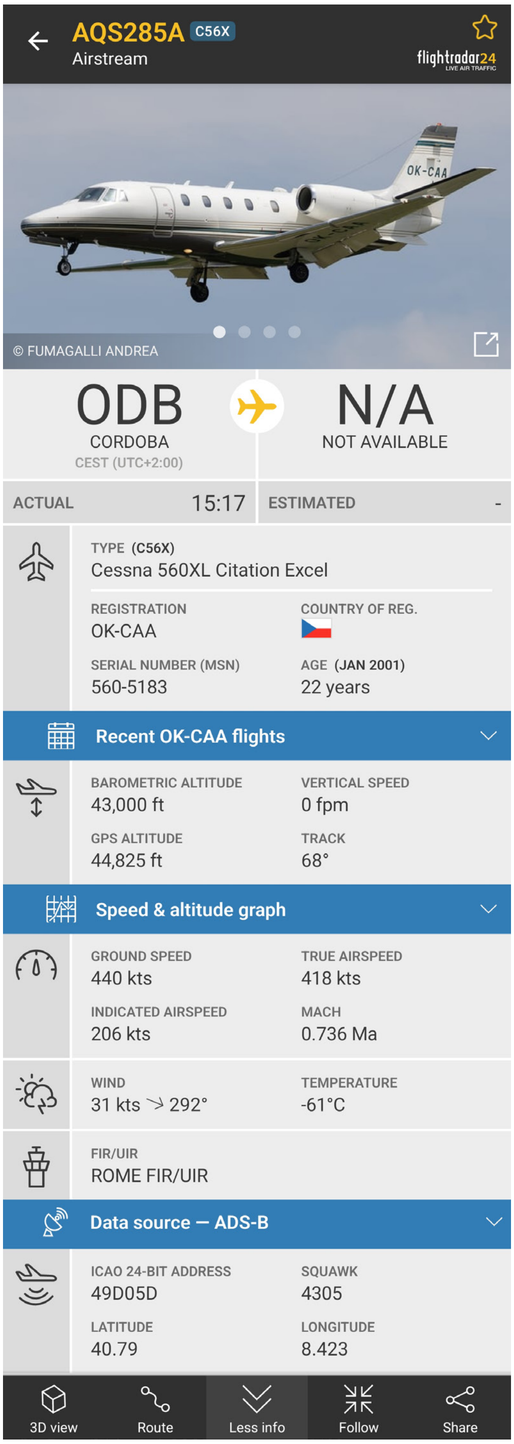


Figure 4.35: Flightradar24 Data for OK-CAA. Data like temperature, altitude and speed are shown. Source: Flightradar24 (2023)

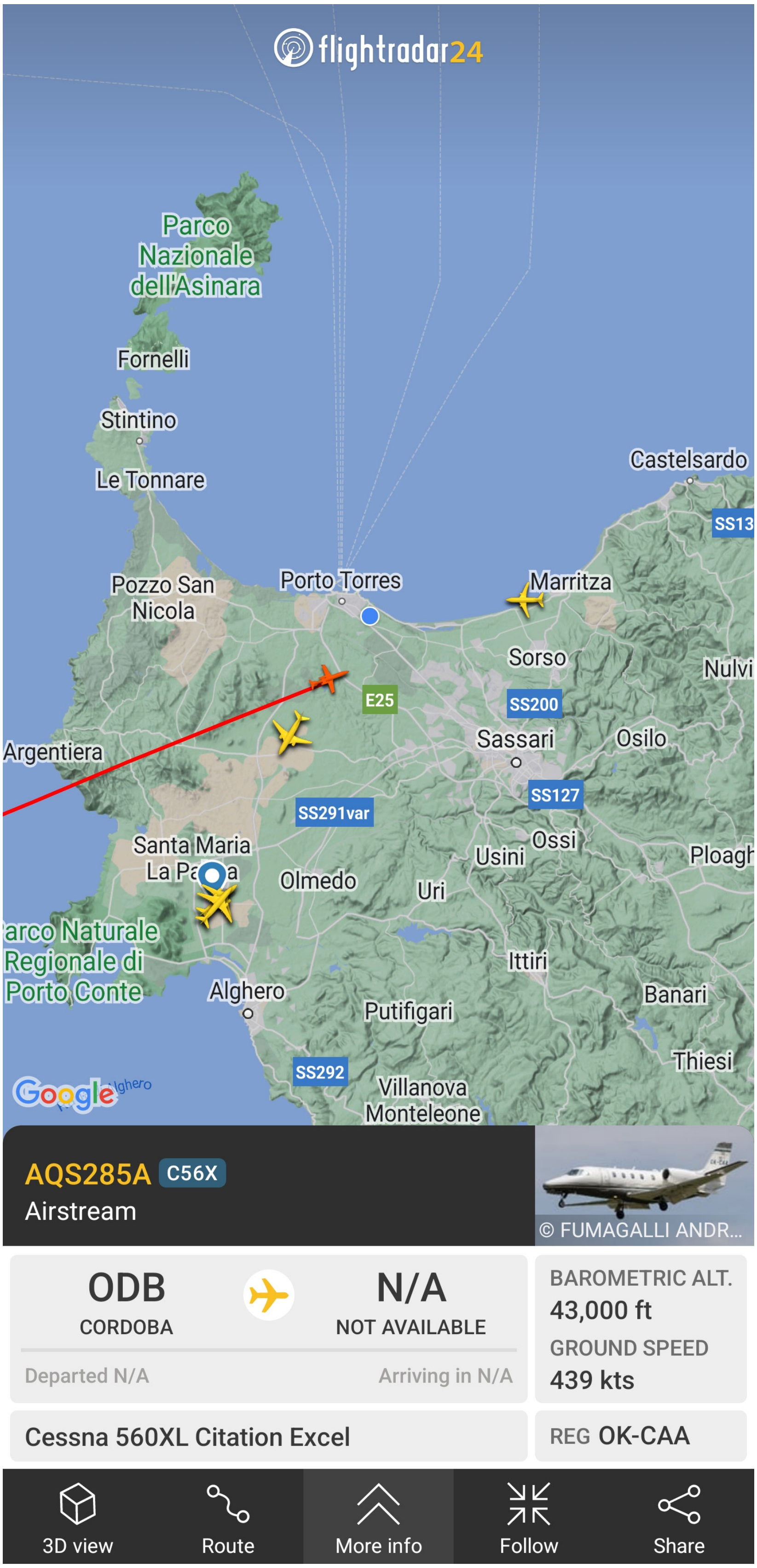


Figure 4.36: Position of OK-CAA over Sardinia. Source: Flightradar24 (2023)

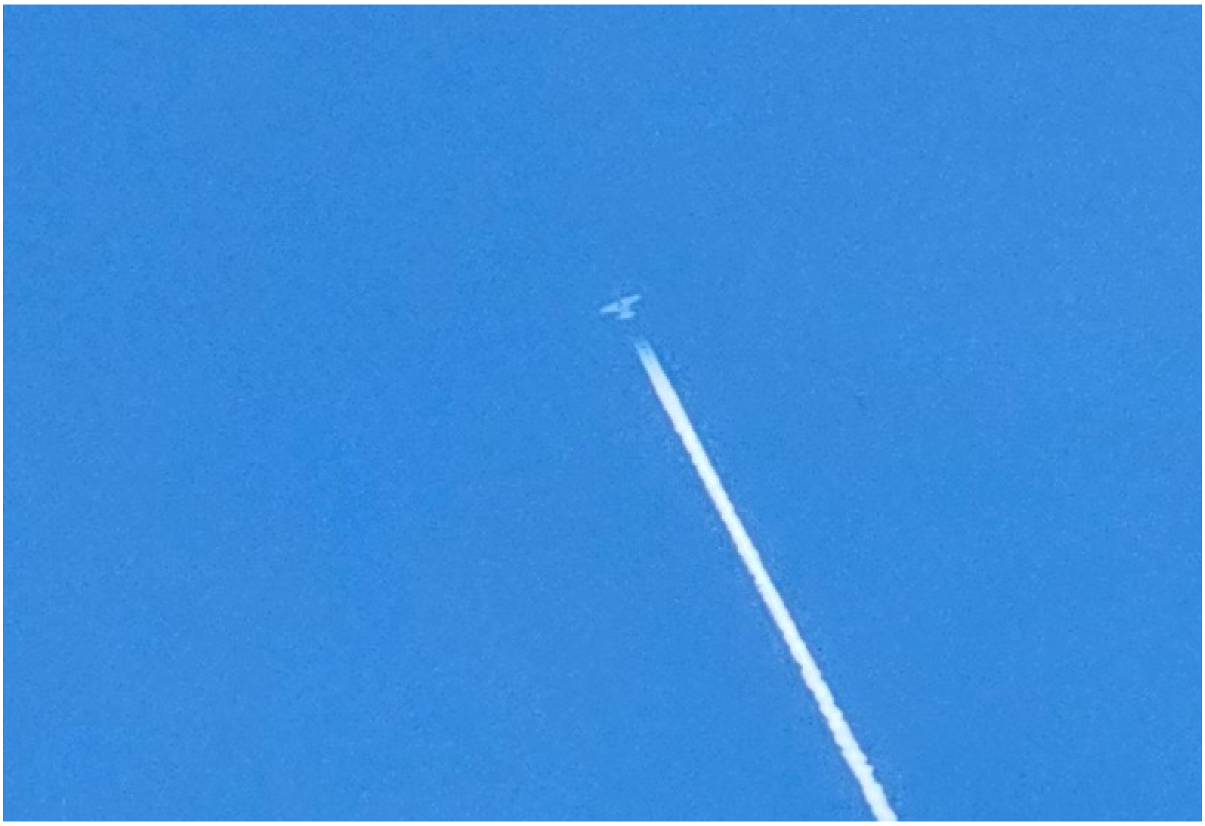


Figure 4.37: Aircraft with registration OK-CAA, slightly zoomed in

Figure 4.38: Aircraft with registration OK-CAA. A more zoomed out view for a better look at the contrail.

The satellite image, which was taken a few hours after the flyby, shows almost no clouds over Sardinia. Contrail cirrus clouds are not visible. This can be seen in Figure 4.39.

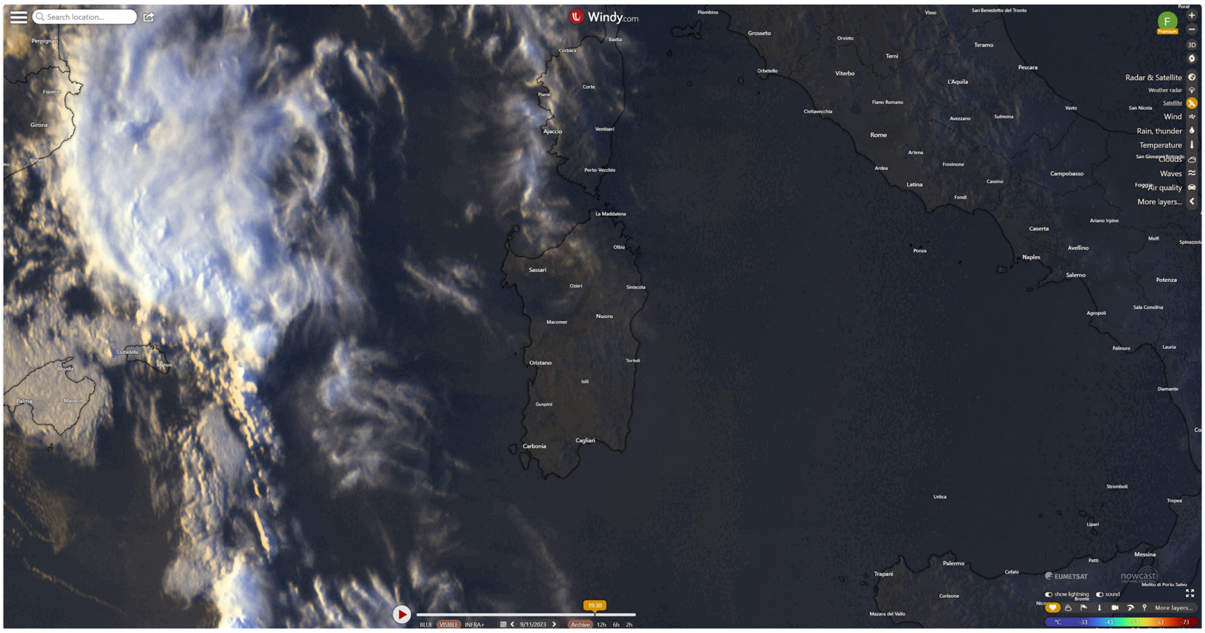


Figure 4.39: Sat image of Sardinia at 7:30 PM A thick layer of clouds can be seen in the west of Sardinia. The northern part is also cloud covered to some extent. Source: Windy (2023)

Since the aircraft was almost traveling at FL450 and it was just 7 minutes after 5 PM Figure 4.40 was chosen to be most accurate. The author assumed that the relative humidity around the aircraft was 24%.

This flight shows that it is important to use the barometric altitude (43000 ft). The relative humidity is now interpolated between FL 390 (51%) and FL 450 (24%). The result is 34%.

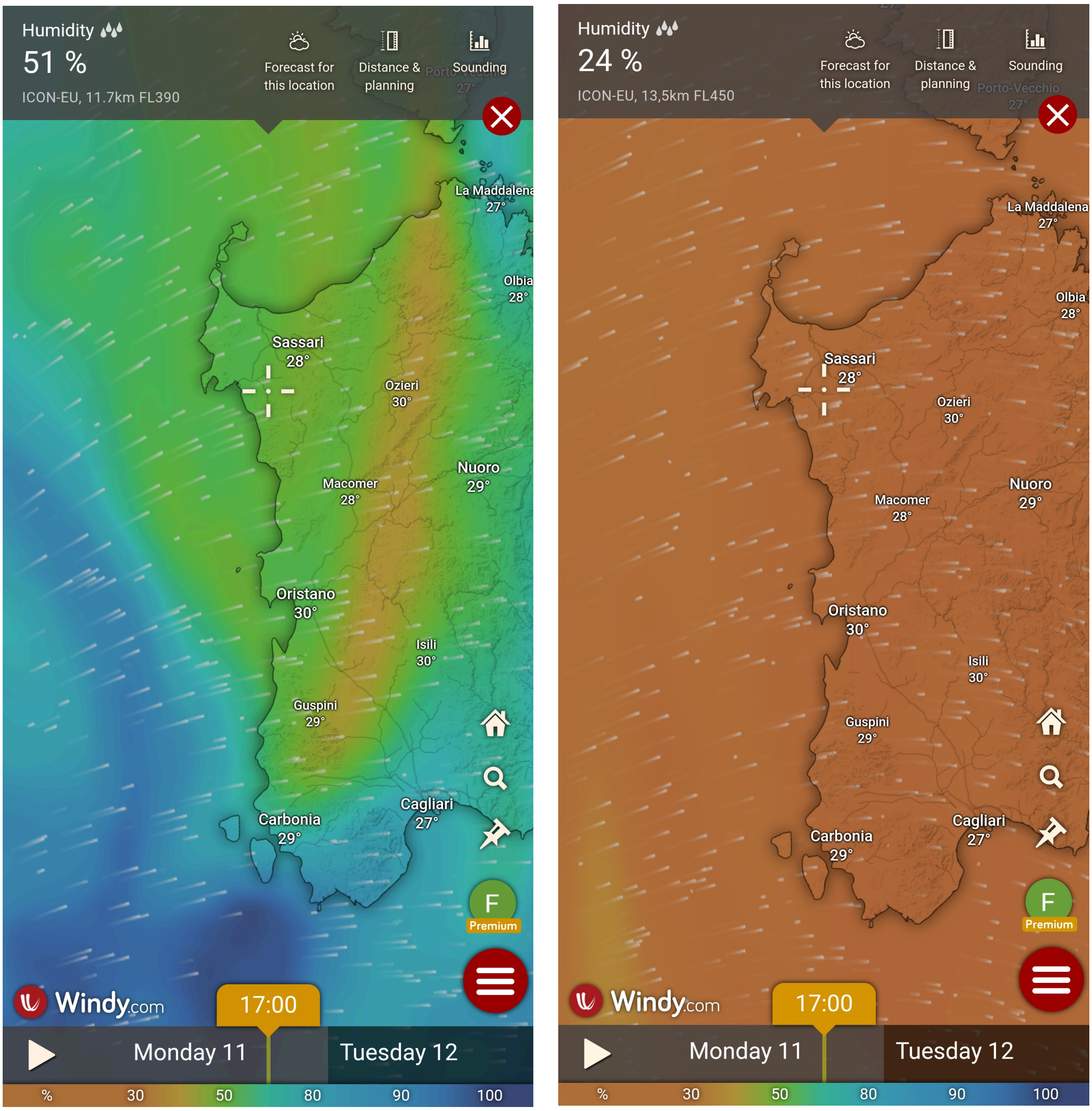


Figure 4.40: Relative humidity at FL390 and FL450 at 5 PM The small "comets" indicate the direction and speed of the wind. Source: Windy (2023)

The Contrails Map shows a few potentially warming contrails over Sardinia at 7:30 PM. This is shown in Figure 4.41. But not as many compared to the southern part of Italy and Spain, in which area a thick layer of potential warming contrails is located.

Figure 4.41: Contrails Map at 7:30 PM showing Sardinia. Some warming contrails (=red) can be seen in the area around northern Italy, as well as over south Germany. Source: Breakthrough Energy (2023b)

The Schmidt-Appleman diagram is shown in Figure 4.43. Since -61 °C is already of scale, no red lines have been added to the diagram. The red cross would be to the left of the diagram and therefore the threshold temperature is reached for every relative humidity. A contrail regarding Schmidt-Appleman will form.

The SAC-Excel-Sheet is shown in Figure 4.42. A persistent contrail regarding this criterion is expected to form if the relative humidity is above the blue threshold curve. The relative humidity was assumed to be 24% in the rather dry stratosphere. According to the SAC sheet, a minimum relative humidity of 56.4% is needed. With Equation 3.1 $R = \frac{24\%}{56,4\%} = 0.43$ which is smaller than 0.5. The criterion for transient contrails is not fulfilled.

However, calculating *R* for a relative humidity of 34% yields *R* = 0.60. Now the criterion of transient contrails is fulfilled!

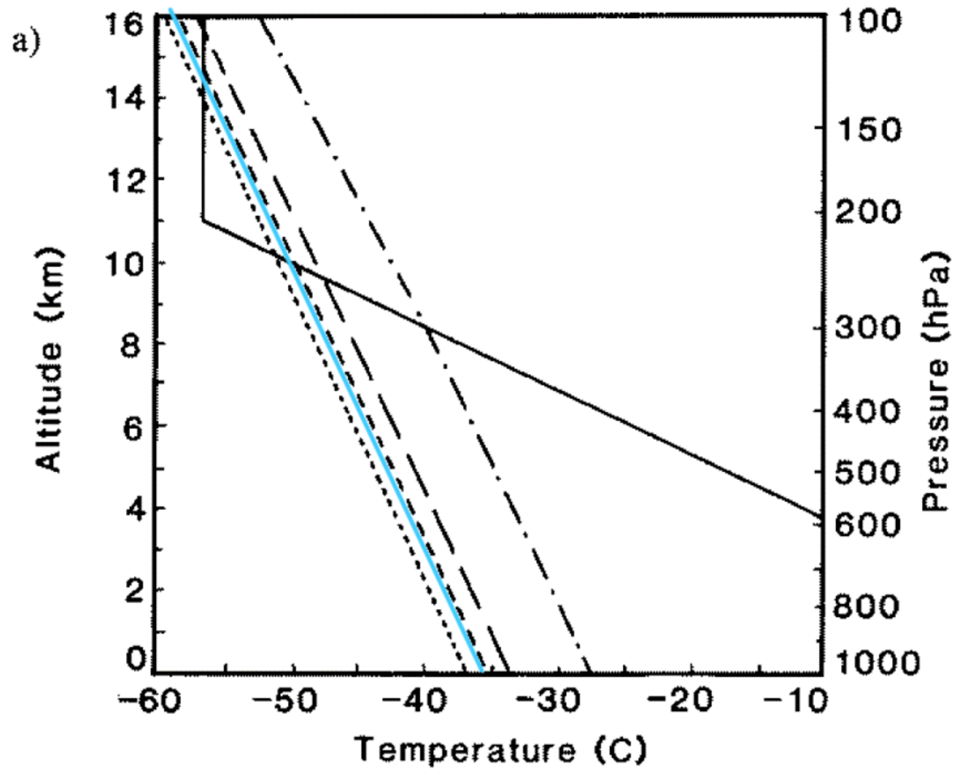


Figure 4.43: Schmidt-Appleman diagram with threshold temperature T_{LC} versus altitude for relative humidity of 0 (short-dashed curve), 30% (medium-dashed), 60% (long-dashed) and 100% (dash-dotted line), and the temperature profile of the ISA (full), for kerosene and a propulsive efficiency of 0.3. Red line, here out of scale: temperature; Light blue line: approximate relative humidity. Source: Schumann (1996)

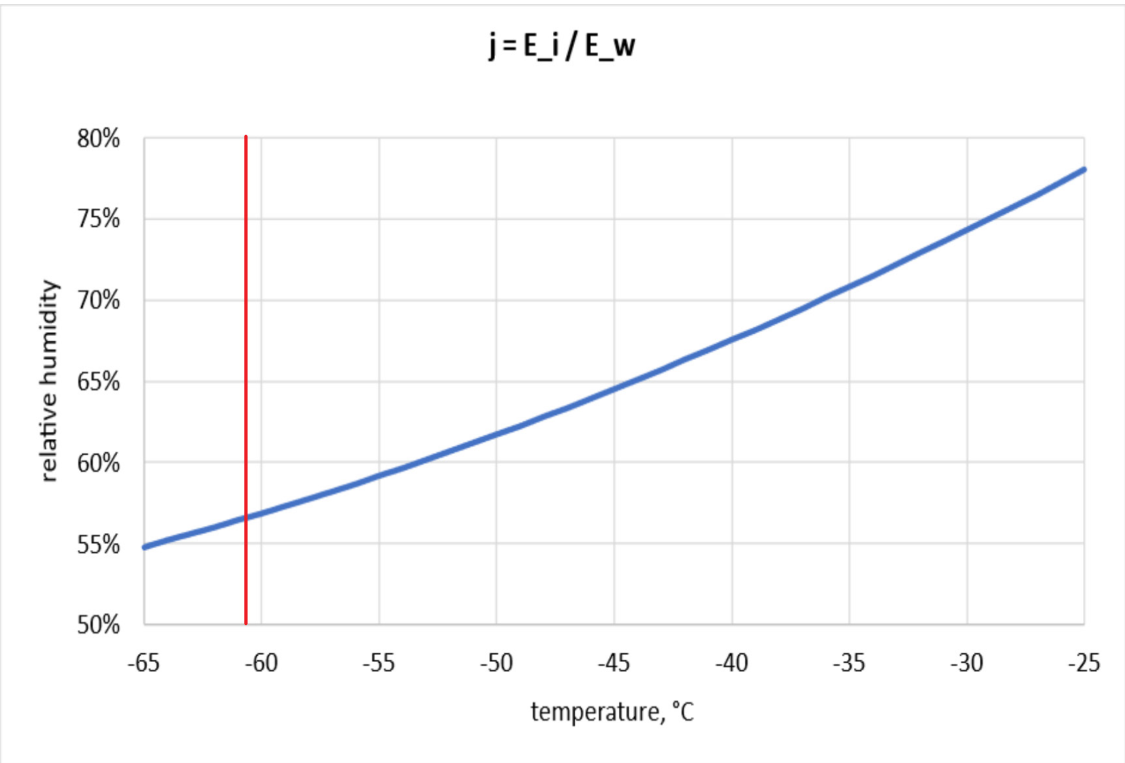


Figure 4.42: Minimum relative humidity for given temperature for persistent contrails to form. If above the blue line, a persistent contrail is expected. Source: Scholz (2023b)

4.3 Persistent Contrails

On August 24, 2023, at 11:32 AM an aircraft with the registration OY-JPZ trailing a long contrail could be spotted at the firmament near Glinde. A Boeing 737-8U3 from Jettime. It was cruising at a barometric altitude of 37000 ft and a GPS-Altitude of 38375 ft. The outside temperature was at -59 °C. More data can be seen in Figure 4.44. The approximate position from Flightradar24 can be seen in Figure 4.45. A Photo of the plane and its contrail can be seen in Figure 4.46.

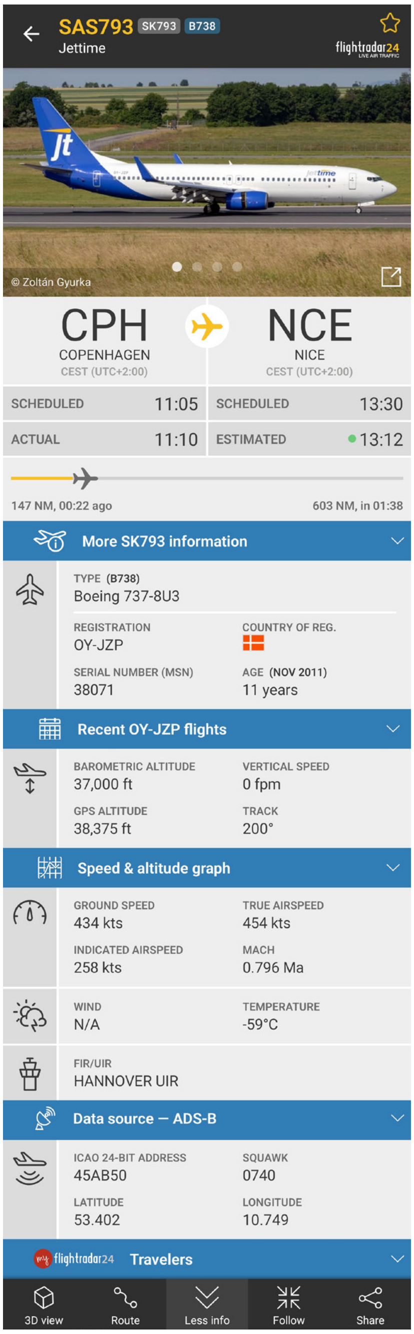


Figure 4.44: Flightradar24 data OY-JPZ. Data like altitude, speed and outside temperature are shown. Source: Flightradar24 (2023)

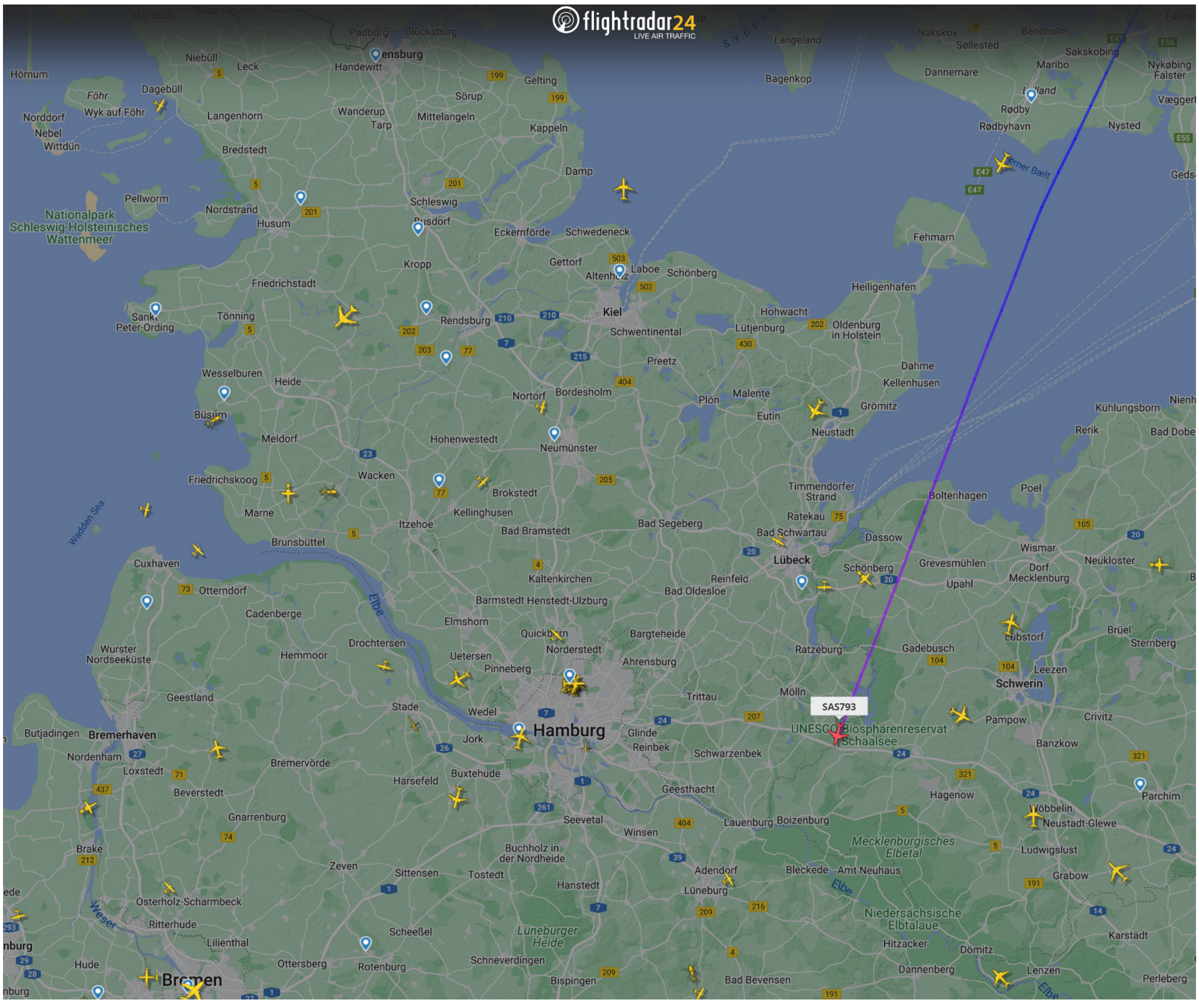


Figure 4.45: Position of OY-JPZ. The aircraft is to the east of the observer. Source: Flightradar24 (2023)

Figure 4.46: OY-JPZ with Contrail in the center of the picture, partly covered by clouds. Several other stretched clouds, most likely contrail induced, can be spotted in the background.

Satellite images show that there are almost no high clouds – which would look blueish – visible at the time the aircraft flew by. One hour later there are still not many high clouds. But there is a front of high clouds approaching from the west which then moved over the area of the observer in the east of Hamburg. Compare Figure 4.47. and Figure 4.48.

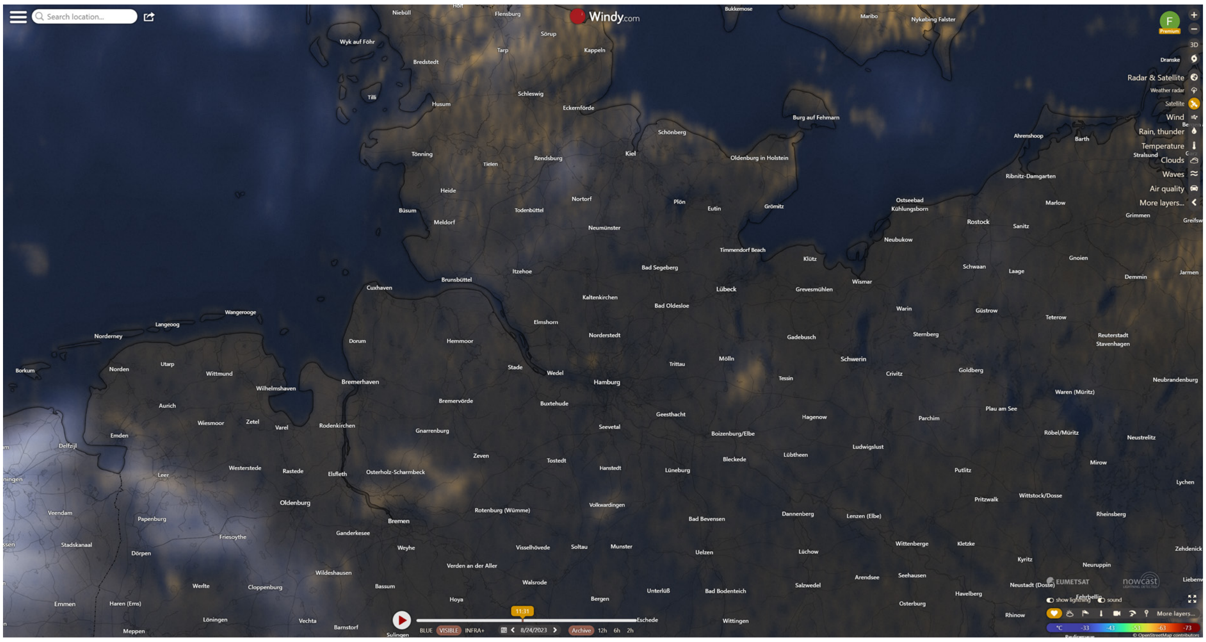


Figure 4.47: Satellite image of northern Germany from Windy, August 24, 2023, at 11:31 AM. A thin layer of clouds over Denmark can be seen. Source: Windy (2023)

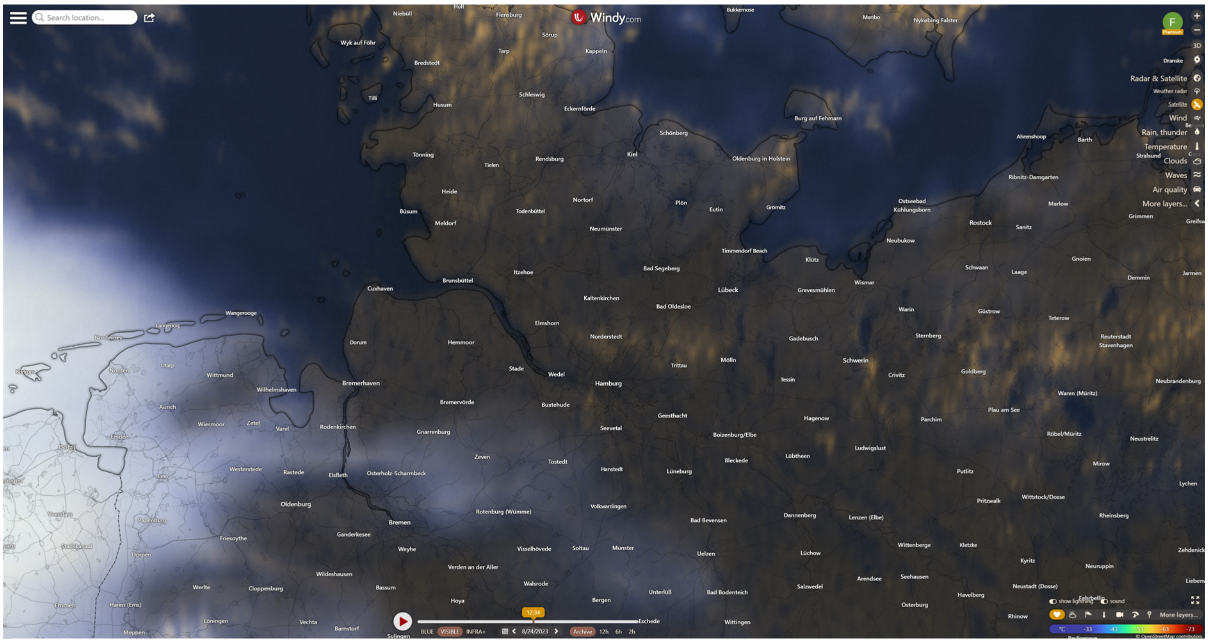


Figure 4.48: Satellite image of northern Germany from Windy, August 24, 2023, at 12:34 AM. A thick layer of clouds is moving in from the west. Source: Windy (2023)

As already mentioned, Windy.com only provide data for the full hours and certain flight altitudes. So, several images must be considered.

Since this is a persistent contrail, high humidity is to be expected. A look at the data provided by Windy can confirm this. In Figure 4.49 and Figure 4.50, the data for FL390 can be seen, which is quite close to the flight level of the aircraft with the registration OY-JPZ and therefore is chosen as the main source.

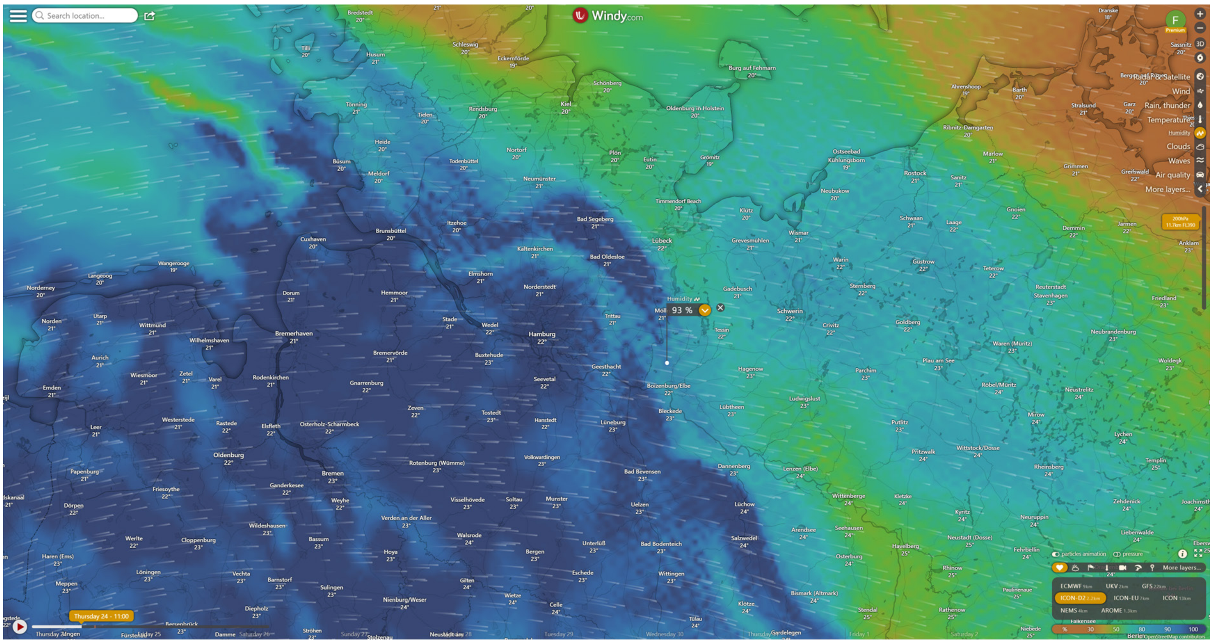


Figure 4.50: Windy Data for OY-JPZ at 11 o'clock. Medium relative humidity in the east, high relative humidity in the west (blue), can be seen. Source: Windy (2023)

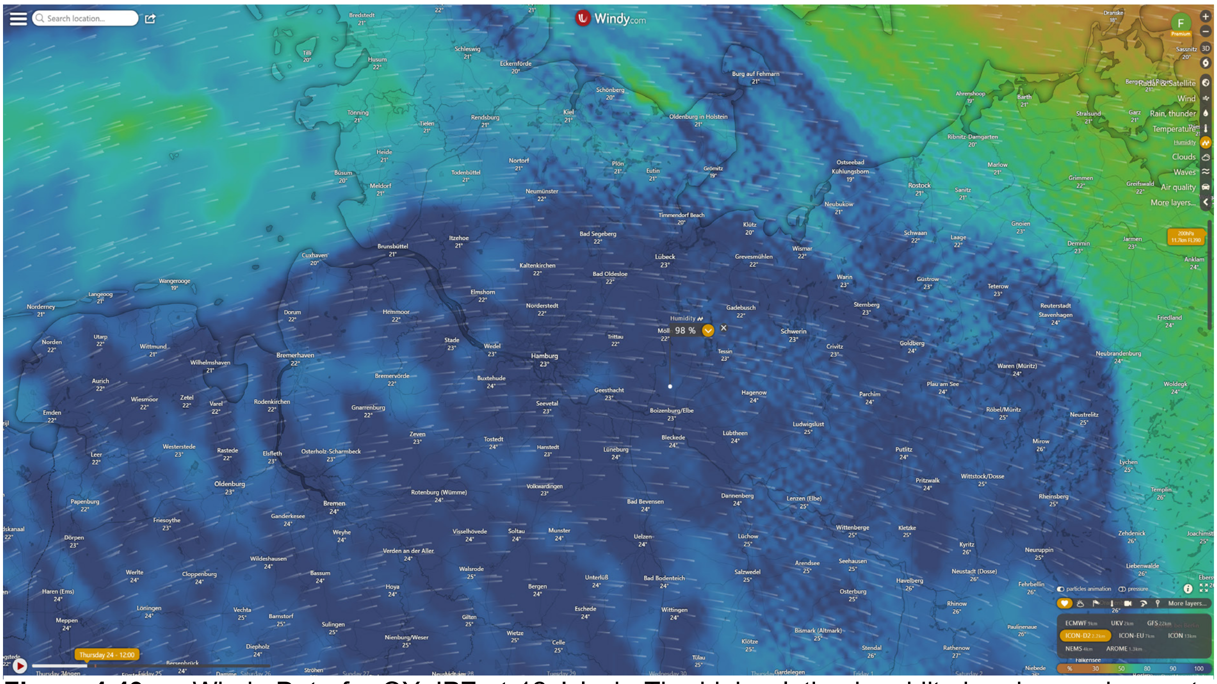


Figure 4.49: Windy Data for OY-JPZ at 12o'clock. The high relative humidity band moved more to the east. The" comets" show the wind direction and speed. Source: Windy (2023)

It can be seen that the humid air has moved towards the east over the observed area and therefore a relative humidity of 100% at this flight level is assumed, although areas with lower humidity can be seen in between. As the aircraft itself is not very far below this flight level, as can be seen in the Flightradar24 data, a relative humidity around the aircraft of 100% is assumed.

The contrails map does not list the specific flight number and the map from 2 hours after the aircraft flew by and shows no contrails in the region where the created contrail might be (Figure 4.51). So, it seems like the contrails map did not predict the observed contrail. But it indeed can be seen that at the map there are some contrails which pretty much end at the observer's location. The observer has indeed seen some clouds that resemble contrails in the south of his location. In addition, these parts ended in the region of the observer.

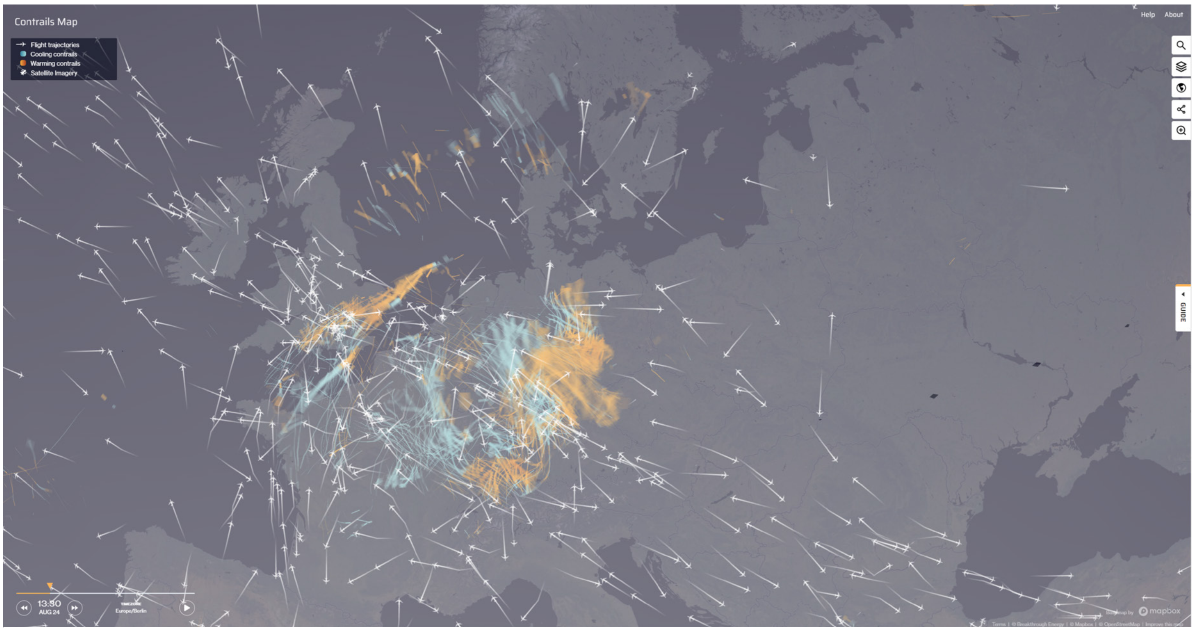


Figure 4.51: Contrails Map, August 24, 2023, at 1:30 PM local time. Many contrails can be seen in the center of Germany. There are cooling ones (blue), as well as warming ones (orange). Source: Breakthrough Energy (2023b)

In Figure 4.52 the Schmidt-Appleman diagram is shown. Since the saturation curve for 100% relative humidity (here marked with light blue) is well to the right of the intersection of the red lines for temperature and height, contrails will occur according to Schmidt-Appleman. After taking a closer look it gets obvious that at this temperature contrails may occur at every level of humidity as the saturation curve for 0% relative humidity is also to the right of the intersection of the red lines.

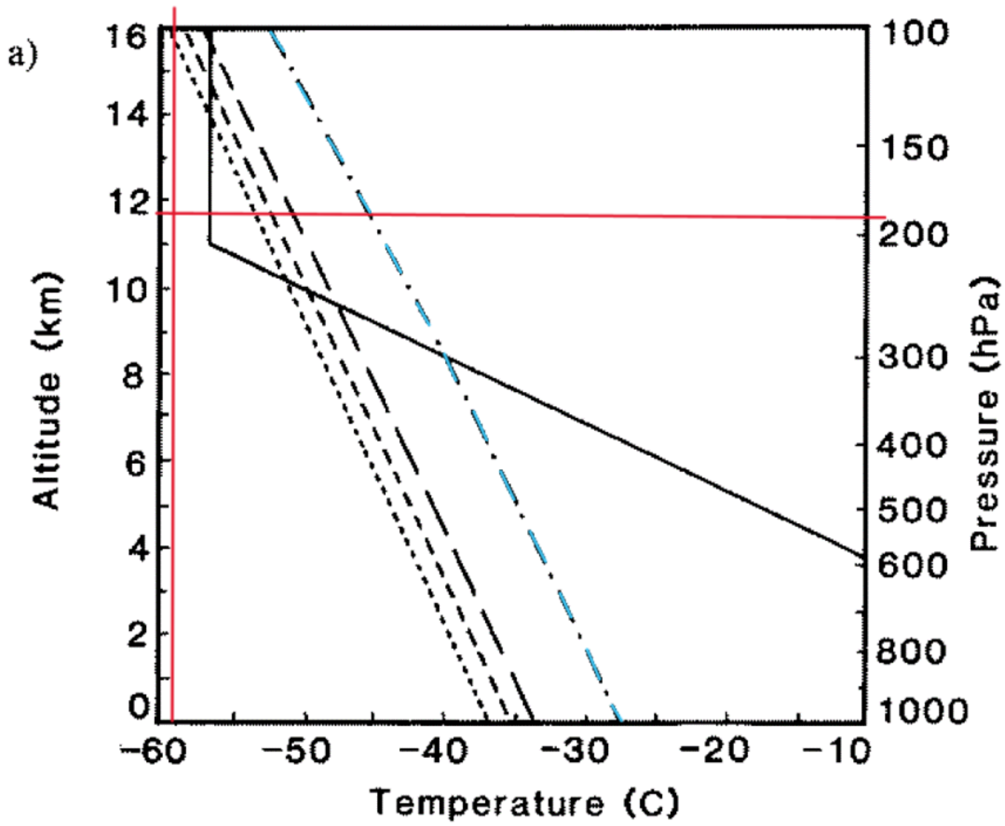


Figure 4.52: Schmidt-Appleman diagram with threshold temperature T_{LC} versus altitude for relative humidity of 0 (short-dashed curve), 30% (medium-dashed), 60% (long-dashed) and 100% (dash-dotted line, highlighted in light blue), and the temperature profile of the ISA (full), for kerosene and a propulsive efficiency of 0.3. Red lines: Temperature and Altitude; Light blue: approximate relative humidity. Source: Schumann (1996)

Figure 4.53 shows the diagram from the SAC-Excel Table in which the minimum relative humidity for given temperature to form a persistent contrail is given. The outside temperature of OY-JPZ is -59 °C and the assumed relative humidity is 100%. The calculations state that a minimum relative humidity of at least 57.3% has to be reached to form a persistent contrail. Using formula 3.1 yields $R = \frac{100\%}{57{,}3\%} = 1.75$ which is above 1.3. Accordingly, a persistent contrail is expected which is proven by the observation.

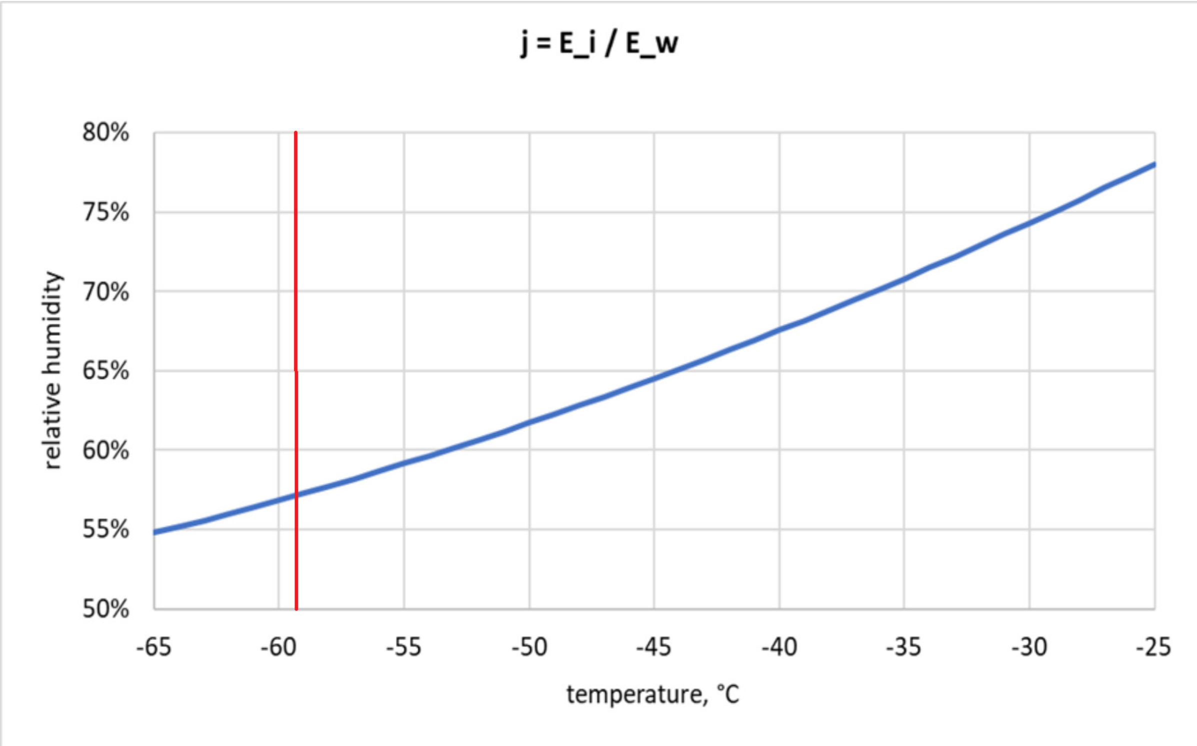


Figure 4.53: Minimum relative humidity for given temperature for persistent contrails to form. Above the blue line persistent contrails are expected to form. Source: Scholz (2023b)

A second example is given in the following. At 10:53 AM. on September 3, a Boeing 737-8AS, registration SP-RKP, was flying eastbound. This plane left a persistent contrail. The aircraft was at a GPS altitude of 38800 ft. The outside temperature was -53 °C. Further information can be found in Figure 4.54 and Figure 4.55. A picture of the aircraft and its contrail is shown in Figure 4.56.

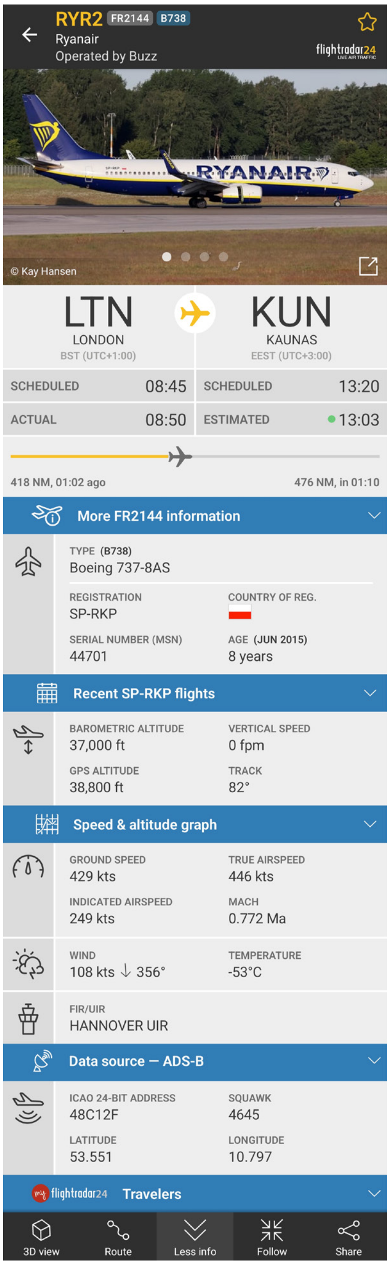


Figure 4.54: Flightradar24 data for SP-RKP. Data like the outside temperature, the altitude and speed can be seen. Source: Flightradar24 (2023)

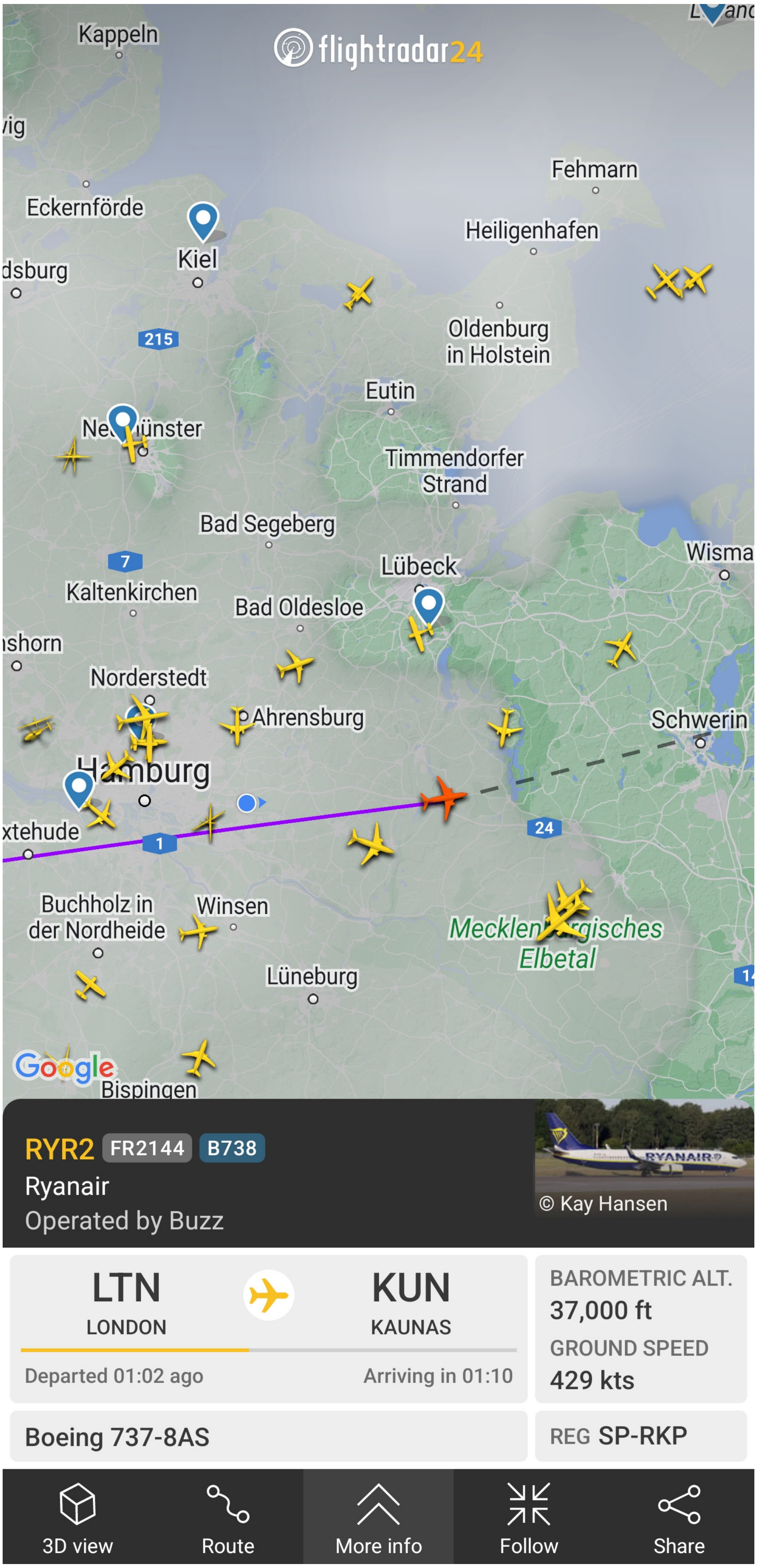


Figure 4.55: Position of SP-RKP at time of the observation. The current cloud layer is unfortunately also activated. The observer is near Reinbek. Source: Flightradar24 (2023)

Figure 4.56: SP-RKP with a long contrail, spotted east of Hamburg.

Taking a look on satellite images, especially in northern to central Germany, many cirrus clouds can be spotted. Some clouds are even a kind of streak, so they most likely come from contrails left by airplanes. Take a look at Figure 4.57.

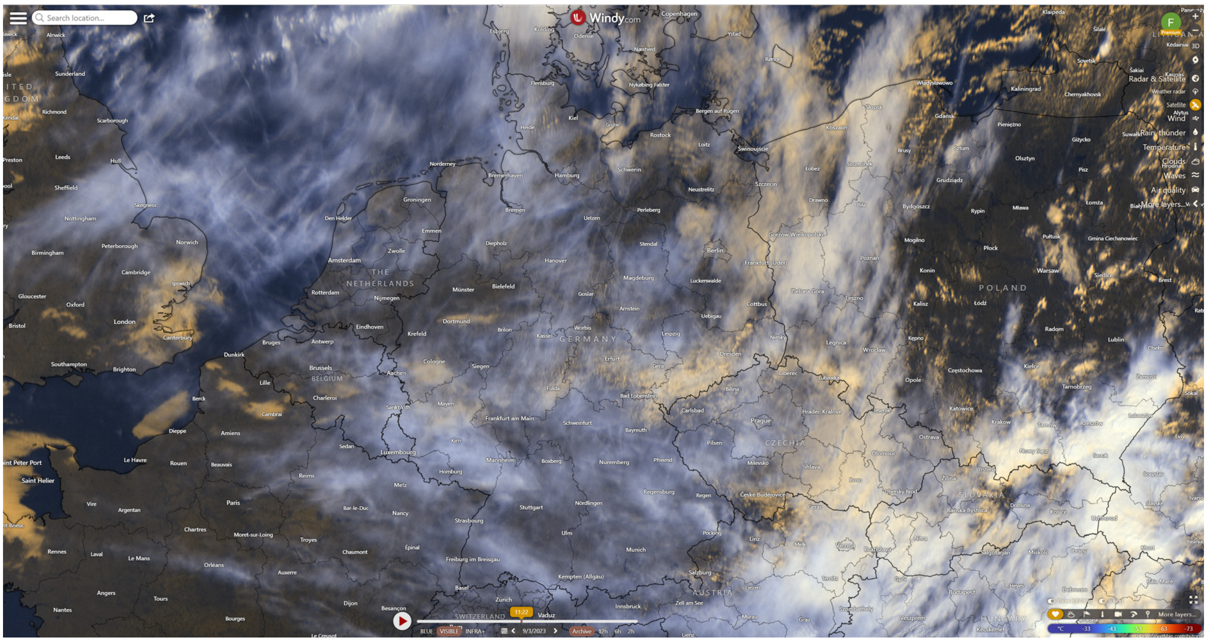


Figure 4.57: Satellite image at 11:22 AM showing Germany. A layer of contrail like clouds can be seen over Germany. Source: Windy (2023)

The website Windy.com showed a humidity of about 100% between 10 AM and 11 AM at almost all flight altitudes. The author therefore assumes a humidity of 100%. In Figure 4.58 and Figure 4.59 the most relevant screenshots of them are shown, the others can be found in the raw database.

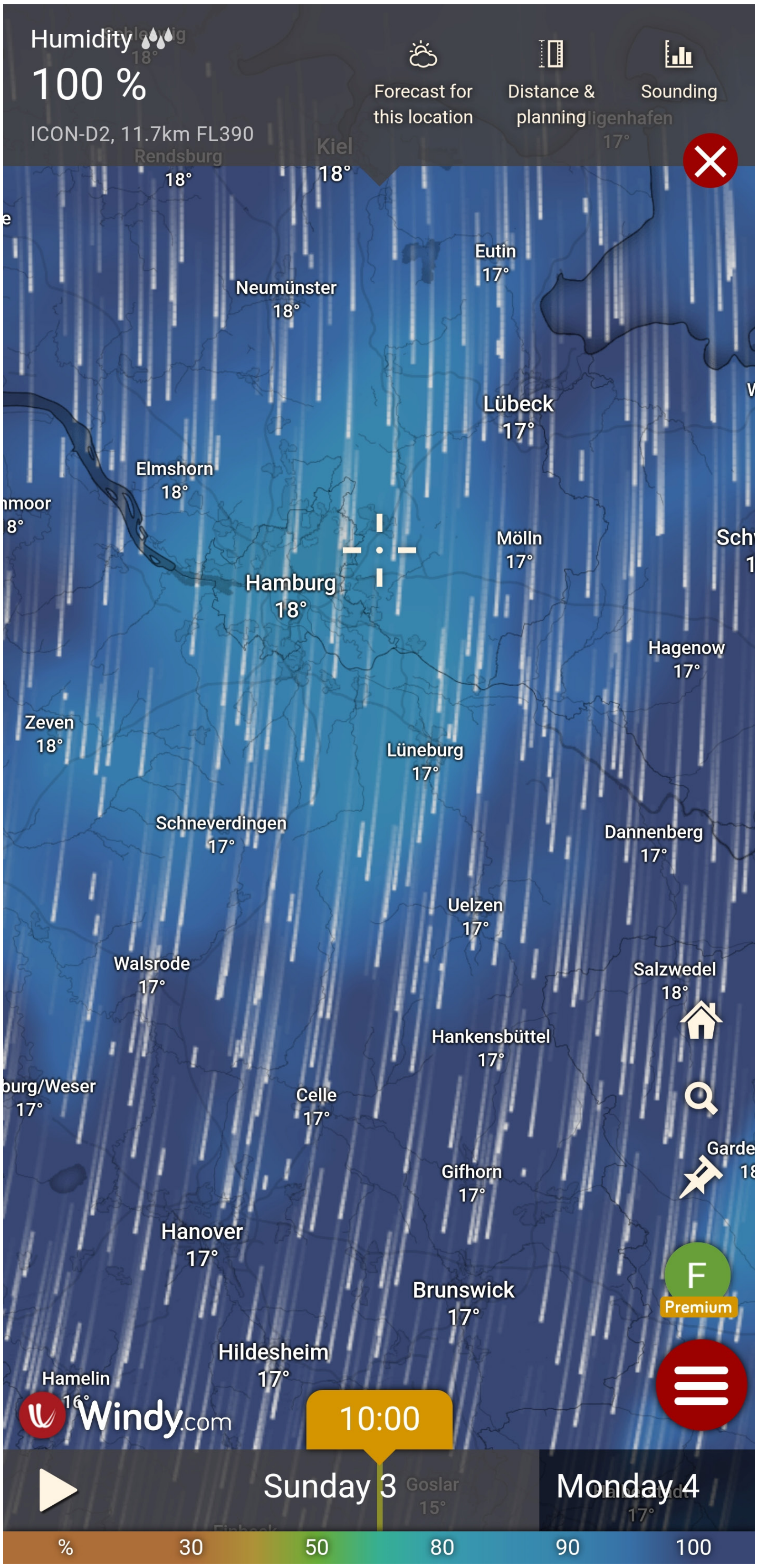


Figure 4.58: Windy Data at 10:00 AM for FL390. The "comets" indicate a quiet strong wind from the north. The blue color admits that there is a high relative humidity around. Source: Windy (2023)

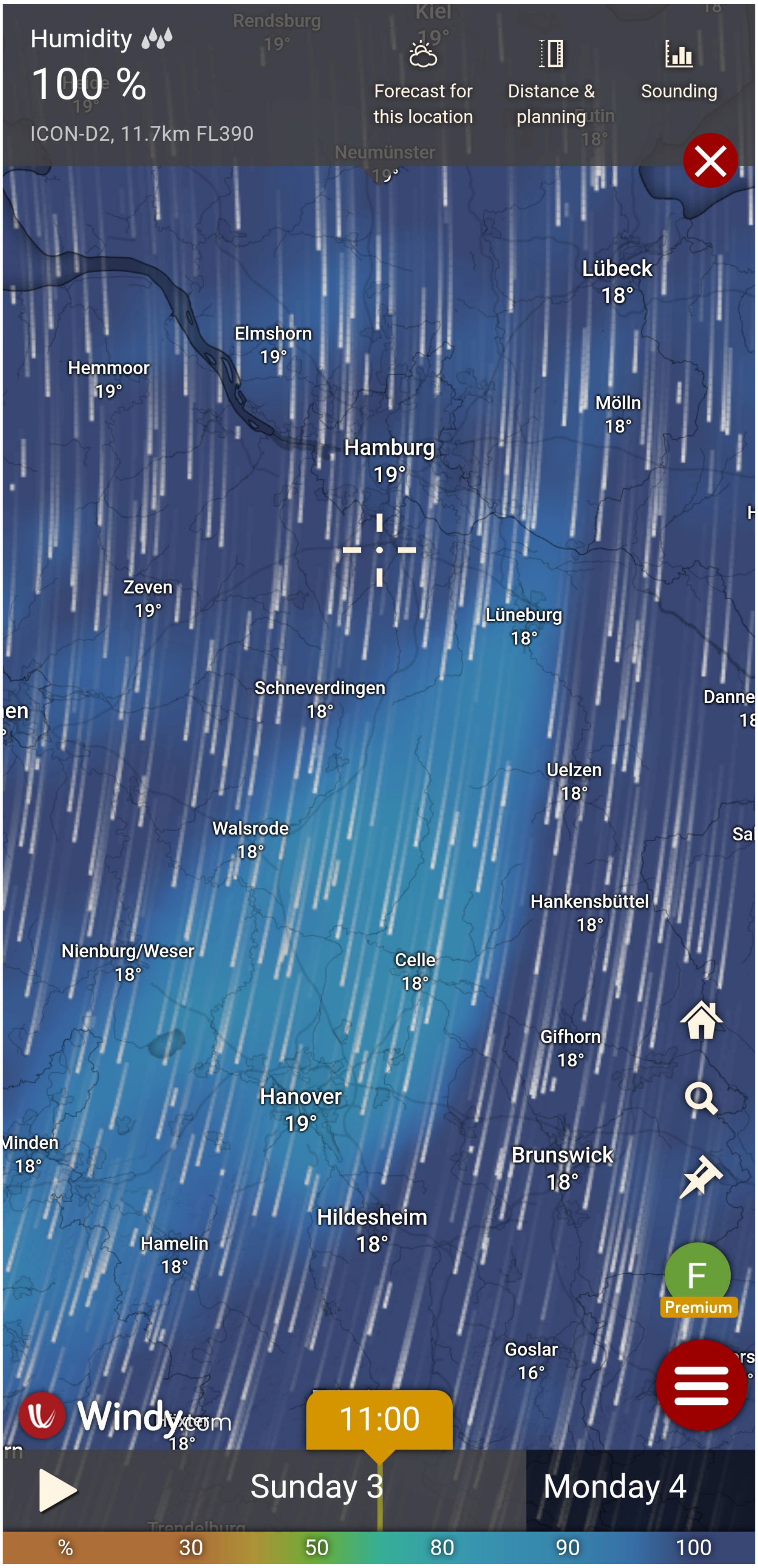


Figure 4.59: Windy data for 11:00 AM for FL390. Compared to Figure 4.58 the light blue pocket moved to the south. “Comets” indicate wind direction and speed. Source: Windy (2023)

This time the contrail can also be found on the Contrails Map website. The contrail is to be regarded as cooling shortly after its formation. According to the website, the contrail moved further and further south and then dissipated over Bavaria and Austria. In Figure 4.60 and Figure 4.61, the Contrails Map can be seen at two different timestamps. Once shortly after the emergence and once in a more advanced state.

Figure 4.60: Contrails Map at 11:30 AM shortly after formation. A small blue line can be seen under the aircrafts route’s line. Source: Breakthrough Energy (2023b)

Figure 4.61: Contrails Map at 2:40 PM a few hours after formation. The contrail moved to the southern part of Germany. A more detailed view of the diagram in the left corner is shown in Figure 4.62. Source: Breakthrough Energy (2023b)

In Figure 4.62 a time versus altitude diagram of the Ryanair flight is shown. In this diagram can be seen that most of the flight the contrail regarding to the DLR model is cooling. Which then ultimately leads to the assumption that the whole contrail is cooling. Therefore, see the upper left corner of Figure 4.62.

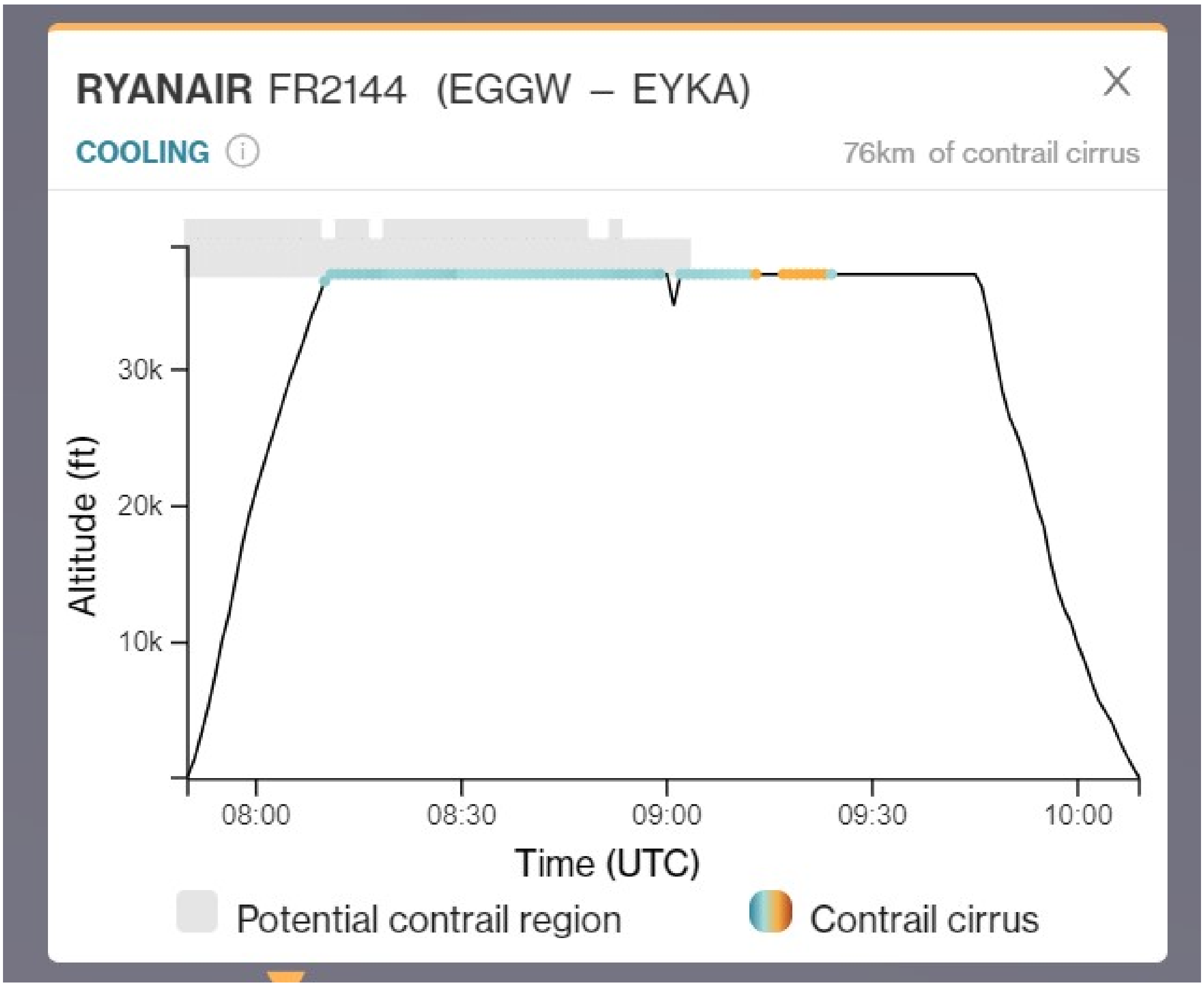


Figure 4.62: Detailed of the diagram of Figure 4.61 in the left bottom corner **.** A time versus altitude diagram from the observed Ryanair flight. According to the diagram the contrail clouds are expected to be 76 km long. (top right corner). Source: Breakthrough Energy (2023b)

Finally, the Schmidt Appleman diagram should be considered. The Schmidt Appleman diagram is shown in Figure 4.63. The red cross is far left of the blue line. A contrail is expected to form.

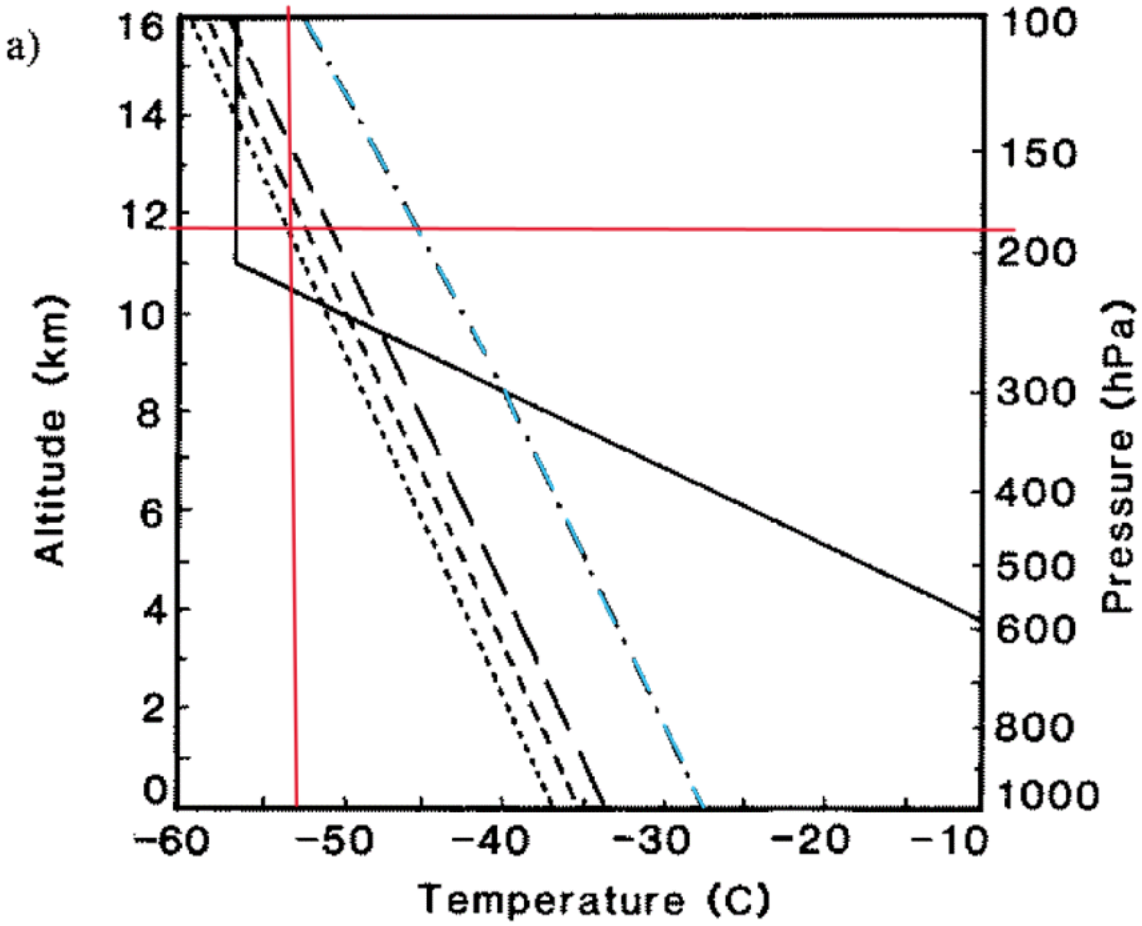


Figure 4.63: Schmidt-Appleman diagram with threshold temperature T_{LC} versus altitude for relative humidity of 0 (short-dashed curve), 30% (medium-dashed), 60% (long-dashed) and 100% (dash-dotted line, highlighted in light blue), and the temperature profile of the ISA (full), for kerosene and a propulsive efficiency of 0.3. Red lines: Temperature and Altitude; light blue: approximate relative humidity. Source: Schumann (1996)

A graph from SAC-Excel-Sheet for minimum relative humidity needed to get a persistent contrail is shown in Figure 4.64. The outside temperature is -53 °C. The relative humidity was assumed to be 100%. The minimum relative humidity for a persistent contrail to form, according to the calculations, is 60.2%. Using Equation 3.1 yields $R = \frac{100\%}{60{,}2\%} = 1.66$ which is above 1.3 and therefore a persistent contrail is expected to form. Proof is given by the observation.

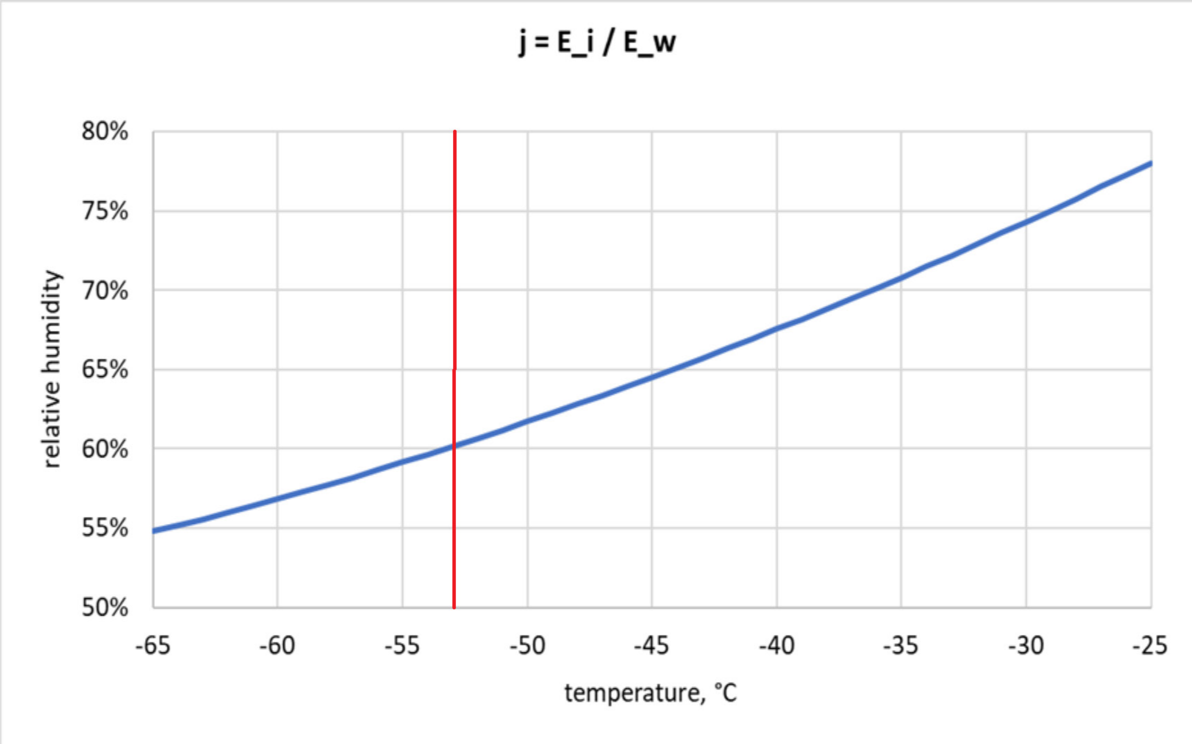


Figure 4.64: Minimum relative humidity for given temperature for persistent contrails to form. If above the blue line persistent contrails are expected to form. Source: Scholz (2023b)

4.4 Discussion

4.4.1 Accuracy of the Results

The summary of presented data on contrail prediction and observation is presented in Appendix A (Table A.1). **When using barometric altitude, all contrails were correctly categoized in one of three categories (no, transient, persistent).**

The flight data from Flightradar24.com are probably very accurate, as they come directly from the ADS-B transponder and thus access the data set available to the aircraft's flight computer. The displayed airspeed and the barometric altitude should correspond to the measured values of the aircraft. Although the outside temperature may be calculated, as at ADS-Exchange (in the reference section ADSBE 2023) it is written that the static air temperature is calculated out of the total air temperature, it should be accurate. The GPS position should also come from the data available to the flight computers and therefore may be very accurate.

As already explained in Chapter 3.7, Windy.com relies on various data sources. These data sources are not directly visible to the user. However, there are all kinds of reports on the Internet that attest to the high accuracy of the data sourced used there.

The ICON-D2 weather model is a very accurate and local weather model, as several reports on the Internet, several other students state. The observations of cloud cover and current satellite images, for example, also match. However, there is a problem: the vertical resolution, for example in humidity, is not very high on the Windy.com website. Weather patterns at thesealtitudes are very local. This can be seen from the fact that sometimes there are large differences in humidity between the different altitude layers. There is an example saved in the “Example pictures” folder where at FL390 there is a humidity of just 4% while at FL340 there is a humidity of 97% at the same spot. Mostly the planes fly in between the available altitude layers, so that an assumption has to be made about how high the humidity is at the flight altitude. In the case of small deviations between the flight altitudes, a linear interpolation makes sense. On the other hand, at higher deviation from the actual height it does not make sense anymore. However, even this interpolation will most likely not represent reality. For larger discrepancies, the author only estimated the humidity. This, too, will not quite reach the value that prevails in reality.

Another point is that **at Windy.com, the altitude is given as flight level (FL), which is based on an altimeter reading (based on pressure) and International Standard Atmosphere (ISA) with 1013 hPa at sea level**. The author compared this initially with GPS altitude. The difference resulted initially in one wrong categorization. This occured in Chapter 4.2 (2. aircraft with transient contrail).

Also, to be able to read the Schmidt-Appleman diagram correctly, the barometric altitude, based on the ISA is needed, because the Schmidt-Appleman diagram is calculated with pressure converted to altitude for plotting. If the temperature deviates only slightly from the ISA temperature, the difference between the true altitude measured by GPS and the barometric altitude is negligible. However, if there are larger temperature differences, then larger percentage differences can be determined. The author has decided to use the GPS altitude, as he thought that he would get more accurate results as the geometric height is not weather depended. But this is false as the aircraft are traveling above the transition height and therefore use the standard pressure for calculation of the barometric height. So, weather should not have an impact onto the barometric height of the different aircraft passing at different days and weather conditions. Small discrepancies may have occurred here.

Furthermore, it was noticed that with Windy, the time information on the slider is not very precise. In Figure 4.65 and Figure 4.66 two different exemplary screenshots can be seen, where the time is set to 11 AM on the slider, but two clearly shifted weather conditions can be seen. The computer time in 24-hour time format can be seen on both images at the bottom right of the image, which in this case shows 15:05. So, these are data from the past and therefore should be more accurate than future predictions.

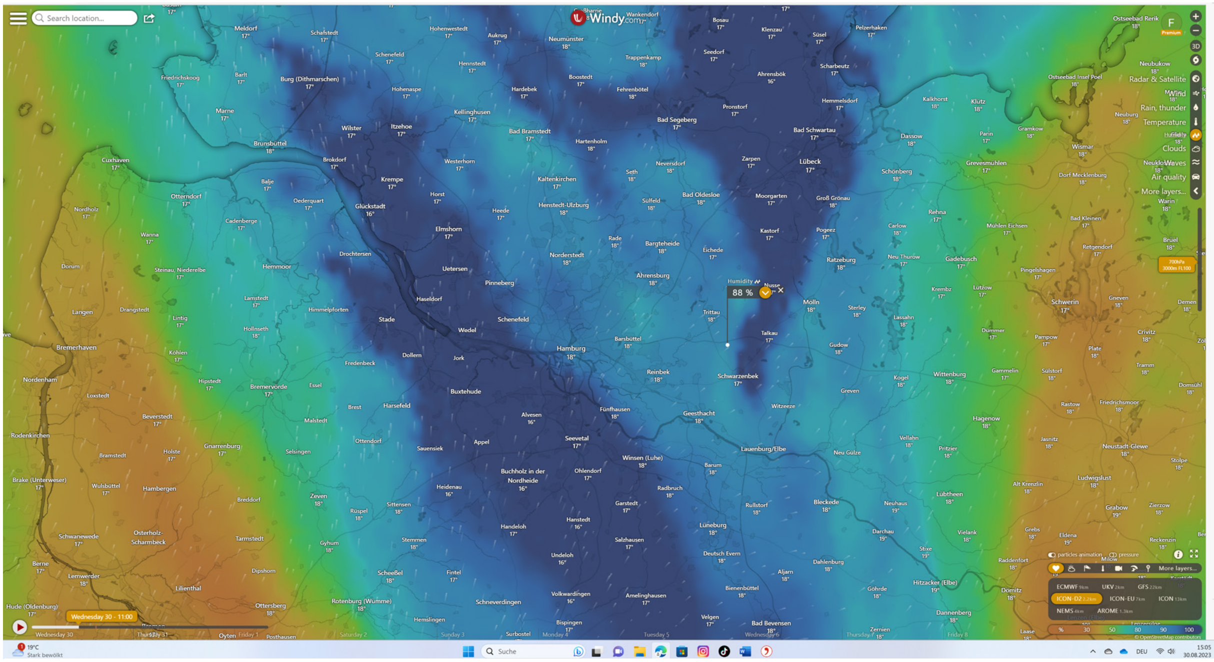


Figure 4.65: Windy at 11 AM first setting. Dark-blue areas indicate areas with high relative humidity. Source: Windy (2023)

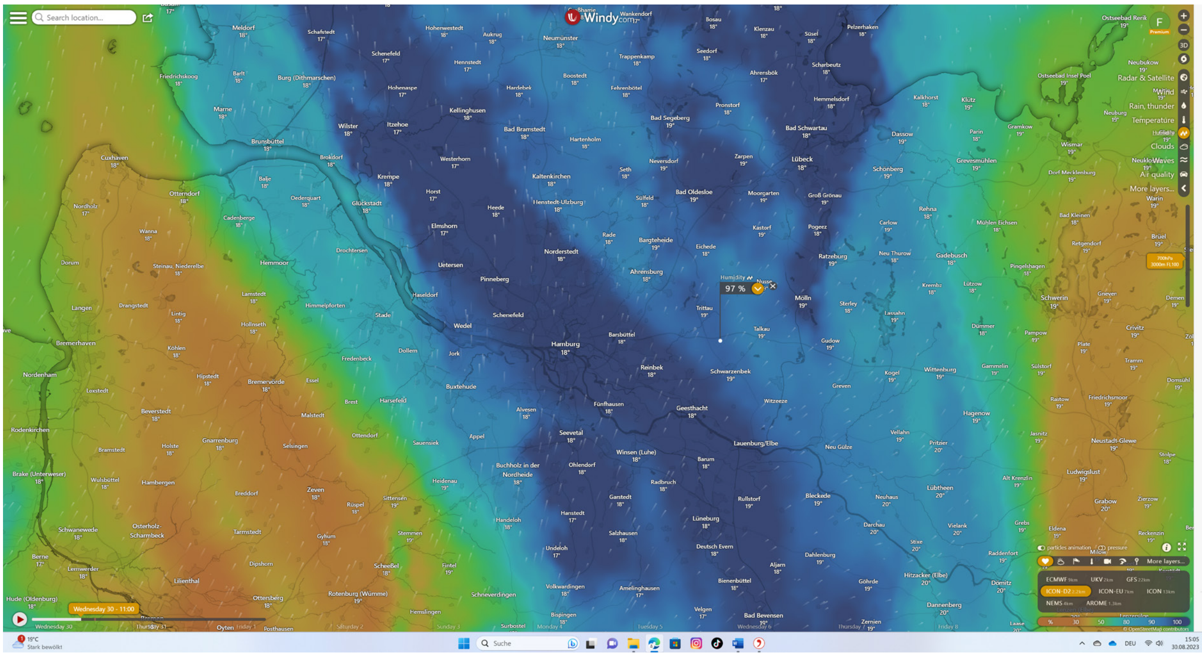


Figure 4.66: Windy at 11 AM second setting. Dark-blue areas indicate areas of high relative humidity. Source: Windy (2023)

So, it seems that, at least with the ICON-D2 weather model in Windy, **several options can be selected within an hour**, but the exact time is not clearly declared. This is another factor in inaccuracies.

Since **relative humidity** at windy.com is **only available hourly and at different altitudes**, the author sometimes simply has to estimate it. Example: It may be that a picture of an aircraft at 42000 ft was taken at 5:30 AM. In the worst-case scenario, the observer has four images from

Windy.com in front of him/her. Two pairs each with the data for FL390 and FL450 at 5:00 AM and 6:00 AM respectively. Because relative humidity is more of a local phenomenon, it can happen that at 5:00 AM alone the humidity between FL390 and FL450 differs by more than 40%. Then there may also be a significant deviation from the screenshots at 6:00 AM. This makes an accurate prediction almost impossible. This is also the reason the author did not include a Schmidt-Appleman diagram for every aircraft recorded in the raw data. It would not be precise enough to make a statement. More precise data regarding relative humidity would be necessary here.

As already told in Chapter 3.8 the website Contrails Map uses the ECMWF weather model which is known to be quite accurate. Furthermore, the website is providing a GitHub link for more details on their used model and some code. The author did not deep dive into these data, but the observations show that in areas where the website estimated contrails, there were indeed (most likely) contrail cirrus clouds. Of course, this does not mean with 100% probability that the model is very accurate, but the author has no other means of further checking the accuracy. The author did not find any competitors, so it seems like it is as good as it gets while using public data.

The expectations regarding the persistence factor proofed to be always right in the six shown examples. To get further proof many more results must be compared but it seems to be quite accurate. It seems like persistent contrails occur when the persistence factor is greater than one.

4.4.2 Contrail Avoidance

The meteorological data collected during the observation showed that there are often **larger deviations in relative humidity** between different flight levels. This can be seen in Figure 4.6 and Figure 4.7 as examples. The observed aircraft mostly flew between FL340 and FL390 during the observation, while business jets usually flew even higher around FL450. Between these flight levels, there are usually larger differences in relative humidity of several double-digit percentage points. A look in the raw data will give further proof to that. If you look at the Schmidt-Appleman diagram, you can see that it can make a difference if, for example, the ambient air has a relative humidity of 60% or 100%. Here it would be possible by clever routing, if advantageous, to fly a slightly higher or (because of the usually higher temperature) lower altitude. This would then have the optimal consequence that the persistent and warming contrails would no longer occur. This would reduce the negative effects on the climate.

It was also noticed during the observation that **the humidity** also **fluctuates strongly** at the flight altitudes themselves **over time**. For example, on some days there is a humidity of almost or zero percent on FL450, but then on the same day in the afternoon a band with almost 100% passes by. This phenomenon could also be observed at the other altitudes. Compare Figure 4.67

and Figure 4.68. The wind carries the band further away with 100% relative humidity. This is followed by the red area, where a relative humidity of almost 0% can be expected. This means that also a small horizontal deviation might help to avoid persistent contrails.

Another aspect that was noticed when collecting the data is how **local** in general the phenomenon of contrails is. For example, the Windy data, which were generated with the ICON D2 weather model, showed checkerboard-like patterns in relative humidity at some points in time (Figure 4.31). These fluctuations could also be observed in some of the contrails of the passing aircraft. (D-AKNT in the raw data) In addition, the author was able to observe an aircraft in descent that initially left a contrail with a lifetime of more than one minute. After it had continued to descend with its sink rate of about 1000 ft per minute, it suddenly left no contrail at all. This example shows that it can be just a few thousand feet to change the picture of contrails and also shows how difficult it could get to avoid all of the contrail creation. This observation may illustrate how local the phenomenon of contrails is but does not provide scientific proof.

It is generally known that flight routes are planned so that you get to your destination as economically as possible, that is, with as **little DOC as possible**. A temporarily different altitude would result in higher fuel consumption, but in the author's view, the consequences if not enough is done for climate protection would be much greater and possibly even financially life-threatening for the aviation company. It certainly depends on the individual case how high these additional costs would be and who would ultimately have to bear them. However, estimating these should not be the subject of this project.

But **not all contrails need to be avoided**. Maybe it would help if only the warming contrails were avoided. In some cases, it might even be beneficial to intentionally create a cooling contrail. There are many factors that influence whether a contrail is warming or cooling. To do this, it must be compared how much thermal radiation the contrail reflects back to the earth and how much thermal radiation the contrail reflects from space. A balance sheet must therefore be drawn up. Contrails, which have a cooling effect, can certainly reduce the climate effects of aircraft.

There are **some basic rules** which may be applied, and which may help to identify warming contrails. According to Ulrich Schuhmann, who was interviewed in a German article (Radtke 2022), one factor that influences whether a contrail is more cooling or warming is, for example, the color of the ground. If the ground is rather light (think about Antarctica white due to the snow) it inherently reflects a lot of heat radiation back into space. A contrail at daytime would have no real effect as the surface is reflecting in a similar way. However, if the clouds formed by contrails are over the sea, where the water can store thermal radiation very well and is not easily emitted back into space, the contrail can certainly have a cooling effect, since they could reflect radiation back into space, which instead would have hit the sea water. But it could also be the other way around by trapping radiation in between the cloud layer and the sea.

Another factor is the position of the sun. If the sun is lower, contrail clouds can better reflect sunlight into space. Here too, a cooling effect is more likely. If the sun is gone by nighttime, contrails may act as a blanket, trapping radiation from the earth and are therefore expected to always have warming effect. One factor that should not be forgotten are the clouds that have formed naturally. If a contrail forms at a low altitude and there are still natural clouds above or below the contrail, it should be clear that this Contrail will no longer have a major influence as there already is a natural cloud.

Can pilots do something about it themselves? In principle, it is possible for the pilots to request a different altitude from air traffic control. It is usually possible to switch to the requested flight altitude, as this is often used in practice to avoid bad weather. But in order to actively avoid the contrails, the pilots themselves need tools to determine whether they are currently leaving a contrail, or a tool to predict where on the route the contrails might appear. The airlines would then be required to integrate this into their flight route planning. It would also be conceivable that on busy routes, for example across the Atlantic, the aircraft flying in front not only notify the pilots behind if there is turbulence, but also ask them at the same time whether they have left contrails, or whether many of them still exist can be seen in the sky. Then these pilots could possibly adjust their flight route slightly and avoid contrails over the sea. Here too, the airlines would be required, as a little more fuel might have to be filled up in order to have enough reserves if the alternative route requires a little more fuel. It is also questionable whether it is possible to change flight altitudes often enough in very crowded airspace, such as over Central Europe. In addition to the airlines, help of air traffic control would also be required here. A system would have to be designed to avoid contrails with negative climate effects. Eurocontrol, the authority responsible for coordinating air traffic control across Europe, has already launched a project. Therefore, look at Eurocontrol 2023a and Eurocontrol 2023b as well as Eurocontrol 2022. It would certainly be an advantage if air traffic control itself also had tools to include contrail avoidance in its own planning. The legislature and the aviation authorities could also use legal rules to create a framework that forces all airlines and possibly also private individuals to actively participate in avoiding contrails, which have a negative impact on the climate. This would ensure that there would be no competitive advantage over airlines that do not actively participate.

To the authors notice, currently there are no airlines actively using strategies to avoid warming contrail formation in their present service. There are some airlines with projects, but they are not using it on a daily basis. As already mentioned in Chapter 2.5

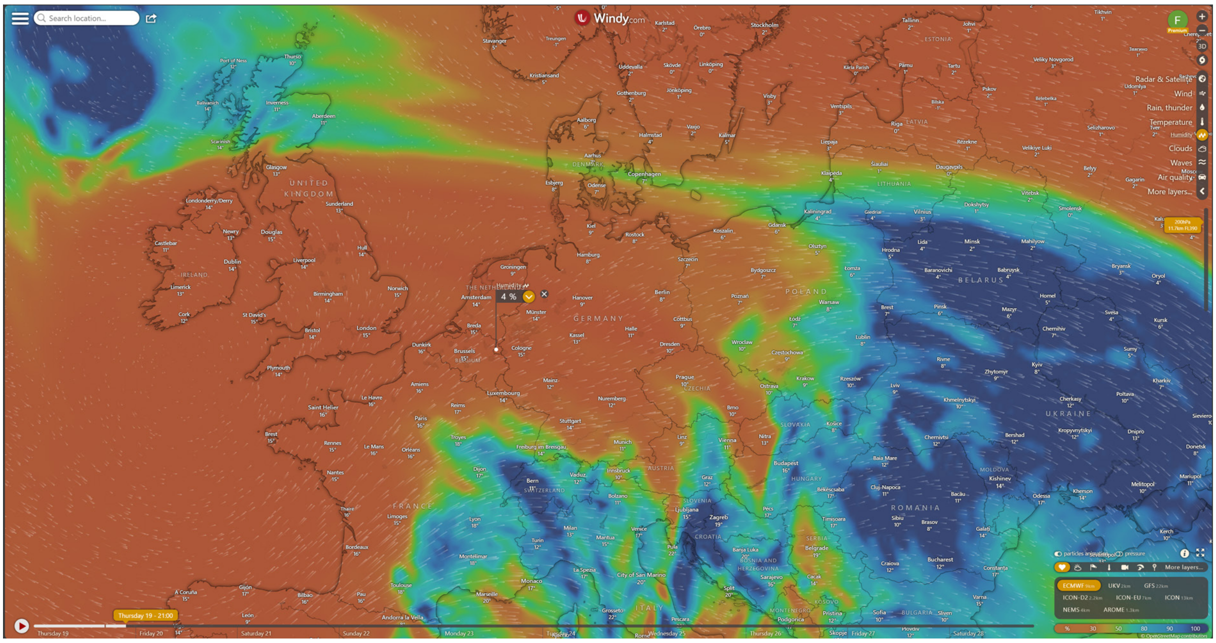


Figure 4.67: Example for the high Variability (1). Source: Windy (2023)

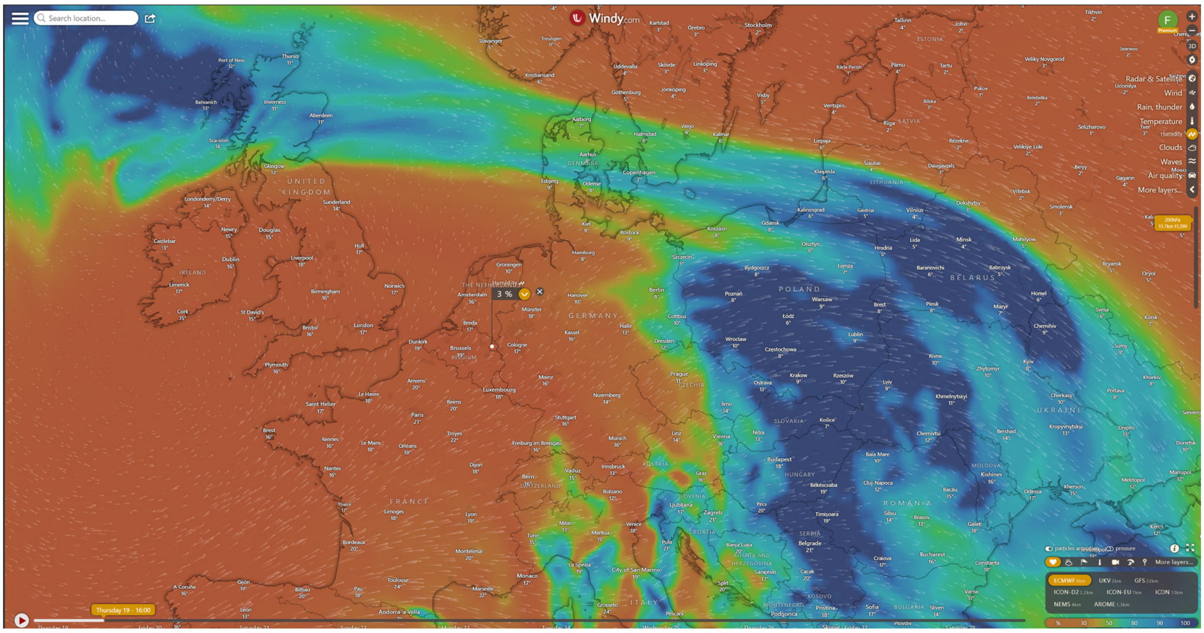


Figure 4.68: Example for the high Variability (2). Source: Windy (2023)

4.4.3 Expenses for Contrail Observation

Would it also be possible to get enough data from the services used in Chapter 4 to predict contrails without the premium versions? Or are the premium versions essential? The author has found a website that could be used to replace Flightradar24. The website is called ADS-B Exchange and can display all kinds of data transmitted by the transponder. The website is a bit too confusing for the author's taste and was therefore not chosen for this project, but it can also display more information such as the static air temperature and the total air temperature. In addition, information about the accuracy of the ADS-B data can be read out directly, which is an advantage over Flightradar24. It is quite possible that the coverage is not as high as Flightradar24, as it is the market leader and probably has the most participants providing data, but at first glance the coverage seems to be the same across Europe. (ADSBE 2023)

Unfortunately, when it comes to weather data, the author has not found an alternative to Windy.com. What is certain is that the free version of Windy can also be used to obtain data on air humidity at different flight altitudes, but the accuracy is then lower. How much more accurate the data is with the premium version of Windy cannot be seen at first glance. But Windy claims that the premium version is more frequently updated and by comparing the premium map with the free version you clearly can spot a minor difference. The premium version also provides more accurate data in mountain areas for example, as the grid density over there is increased (Windy 2023). Nevertheless, the free version should be accurate enough for a rough estimate.

Do you really need such an expensive smartphone that can be used as a camera in this case? In the authors opinion you do not. A mobile phone would be enough. However, it should have a fairly high image resolution. Photos of the contrails can also be taken with less zoom. A disadvantage of this, however, would be that it would be almost impossible to take photos of aircraft that leave no contrails at all, provided they are at cruising altitude. The contrails are usually large enough to be visible on a cheaper smartphone. However, a digital camera or a SLR camera that the imitator may have at home could further increase the quality of the photos.

5 Summary and Conclusions

To conclude, one can say that with the resources that a private person has, and a favorable weather condition, one can make fairly accurate predictions about whether contrails can form or not. It also turned out that there is a number of publicly accessible data. There is a large selection of sources, especially for satellite images and general weather data. However, it was observed that the weather between the flight altitudes can vary locally. Due to this large variance between the flight altitudes, it can be difficult under certain weather conditions to determine the exact relative humidity with the simple means required for the Schmidt-Appleman-Diagram. Here you come across inaccuracies.

It should be noted that currently not much is done to reduce the effect of warming contrails. There are already some research projects, but in practice no strategy is used to avoid such contrails.

It also turned out that it is sometimes difficult to get precise data as a private person. So it may be that the website Windy.com shows a few pictures for one and the same time or the plane simply flies in between two of the flight heights available at Windy at a very unfavorable time, in the middle of two hours. Then there it is very hard to make any precise statement regarding the humidity.

From the author's perspective, it is usually possible to make a sufficiently precise prediction of the formation of contrails even with simple means. Contrail prediction is fairly easy. It’s up to the bigger players like companies and governments to use this knowledge as well as some unknown knowledge to the author to slow down the climate change currently taking place all around the globe. These bigger players then should be able to use and improve the models already existing to get a big impact with reasonably low effort. For example, for avoidance of possible warming contrail forming flight levels.

6 Recommendations

If an airplane flies over you, you can predict with sufficient accuracy whether a contrail will form or not. This only requires a few tools, as shown in this project. However, improvements or extensions could be made in further work.

Barometric altitude must be used instead of the GPS altitude in further projects. The Schmidt-Appleman diagram on pressure converted to ISA. In the same way, also and therefore should be more accurate. This has already been explained in Chapter 4.4.1.

Data of many more flights have been collected, but is so far not evaluated. Many more contrails shoud be evaluated to confirm the hypothesis that contrail persistence can be predicted based on the defined persistence factor.

An attempt should be made to increase the size of the data sets. For this purpose, an automated evaluation should be sought. Perhaps an AI could help with the evaluation of satellite images. (Following the example of Google). A script could also be written that automatically inserts the data from Flightradar24.com, for example, into a database. Automated scripts could then carry out a (graphical) analysis within this database. Perhaps it would also be possible to start a full-time investigation in which several people carry out observations 24/7 and analyze the data at the same time. This would make it easier to obtain data on the lifespan of contrails, for example. It might then be possible to predict the lifespan using simpler models, as is currently the case.

In addition, further work could develop economically efficient concepts for avoiding warming contrails, which could then be actively used by airlines. This would then help to reduce the climate impact of contrails by relatively simple means.

In further work, a comparison could also be made between more precise tools and methods against a relatively simple method as used in this project. It would then have to be examined whether these more precise methods have a significantly higher benefit or whether these simple methods are already sufficient to find an economical solution for reducing the climate impact.

In the author's opinion, the public should also be made more aware of the fact that contrails have an impact on the climate and can be predicted relatively easily. If more people were aware of the non-CO2 effect of contrails and there was a public interest in this, airlines would be forced to pay attention. This would also prompt legislators to take action.

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All online resources have been accessed on 2023-05-31 or later.

Appendix A – Raw Data Collected in This Project

Within this folder there are all the “raw data” which have been collected in this project work. It is recommended to take a look at them. Link:
https://doi.org/10.7910/DVN/9DLURT

Within this folder there is also a PDF which is not using the PDF/A standard which might be useful for higher quality prints without PDF/A restrictions.

Table A.1: Summary of presented data on contrail prediction and observation

Aircraft	Registration	Date	Time	Geo Alt.	Geo Alt.	Baro Alt.	Baro Alt.	Pressure	Temp.	RH	RH_min	R = RH / RHmin	Prediction	Observation
				ft	m	ft	m	Pa	°C					
B737 MAX 8	TF-IHC	05.09.2023	14:54	39250	11963	37000	11278	21662	-51	27%	61.2%	0.44	Category 1	Category 1
B767-424(ER)	N76062	21.08.2023	13:07	31450	9586	30000	9144	30087	-35	35%	70.8%	0.49	Category 1	Category 1
B737-8AS	SP-RSG	22.08.2023	19:10	39450	12024	38000	11582	20646	-54	42%	59.7%	0.70	Category 2	Category 2
Cessna 560XL	OK-CAA	11.09.2023	17:03	44825	13663	43000	13106	16235	-61	24%	56.4%	0.43	Category 1	Category 2
						43000	13106	16235	-61	34%	56.4%	0.60	Category 2	Category 2
B737-8U3	OY-JPZ	24.08.2023	11:32	38375	11697	37000	11278	21662	-59	100%	57.3%	1.75	Category 3	Category 3
737-8AS	SP-RKP	03.09.2023	10:53	38800	11826	37000	11278	21662	-53	100%	60.2%	1.66	Category 3	Category 3

Definition

	R	
Category 1	R < 0.5	no contrails
Category 2	R = 0.5 ... 1.3	transient contrails (lifespan of a few seconds up to five minutes)
Category 3	R > 1.3	persistent contrails