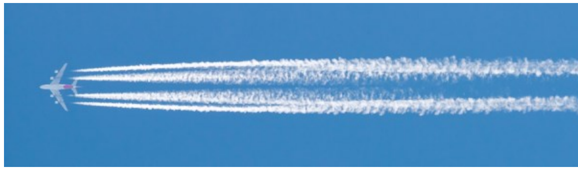
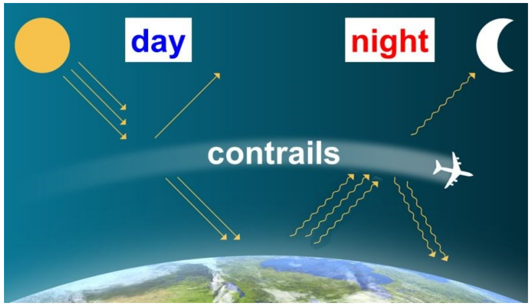
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)



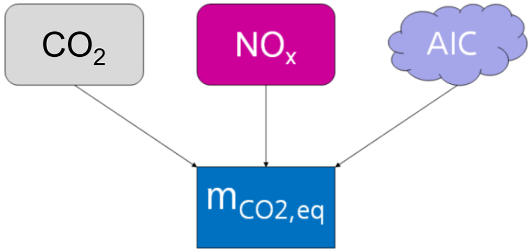
Contrail Management – Now!



Dieter Scholz

Hamburg University of Applied Sciences

Hamburg Aerospace Lecture Series
DGLR, RAeS, VDI, ZAL und HAW Hamburg
20.06.2024
Hamburg University of Applied Sciences
https://doi.org/10.5281/zenodo.12427969

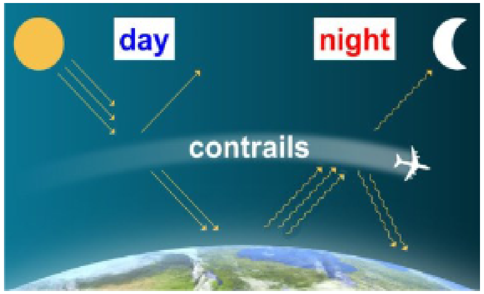


Contrail Management – Now!

Prof. Dr.-Ing. **Dieter Scholz**, MSME, HAW Hamburg

Date: **Thursday, 20 June 2024, 18:00 CET**

Location: **HAW Hamburg, Berliner Tor 5, Hörsaal 01.10**



Flying is booming and with it the CO2 emissions. It is is not easy to decarbonize aviation. Whether electric drives, e-fuels, or green hydrogen, so far there is **no convincing** climate-friendly option for **propulsion in air transport**. And now? In addition to **drastic flight restrictions**, there is another way forward. Flights just need to be rerouted to **fly a little higher or lower**. Why? Large passenger and cargo jets are flying at an altitude of around 11000 m. In these regions water vapor condenses with soot from the engine exhaust to ice crystals forming **contrails behind the aircraft**. They can remain visible for many hours, when humidity is high. Especially at dawn, dusk and at night contrails are warming, because they act like panes of glass in a greenhouse (see picture). **CO2** from aircraft fuel accounts for only **one third** of the warming effect measured in equivalent CO2. In contrast, **contrails** can cause **more than half** of the equivalent CO2. Experts in various fields of aviation explain unanimously that **contrail management could start now!** How is it done? Who knows what? Who is prepared? Who is against it?

Contents

Wissen

NANO vom 8. Mai 2024: Kondensstreifen sind Klimakiller

VERFÜGBAR
bis 08.05.2029

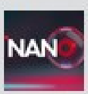
Die Luftfahrtindustrie wird die Klimaziele krachend verfehlen. Neben dem CO2 Ausstoß, der durch den weltweiten Luftverkehr verursacht wird, haben auch Kondensstreifen eine klimaschädliche Wirkung. Lösungsansätze gibt es bereits.

Deutschland 2024

08.05.2024

TEILEN

MEHR



NANO

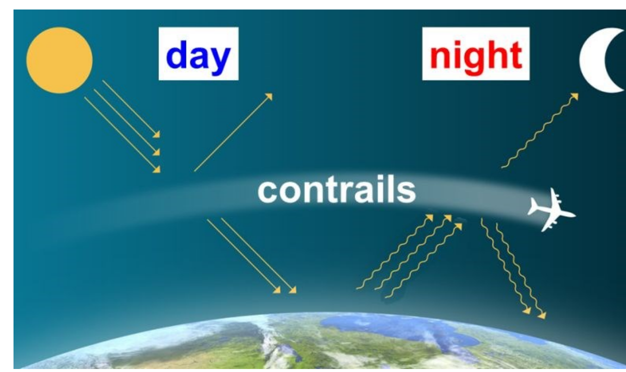
https://youtu.be/HYJawLmiLS8

Moderation: Yve Fehring

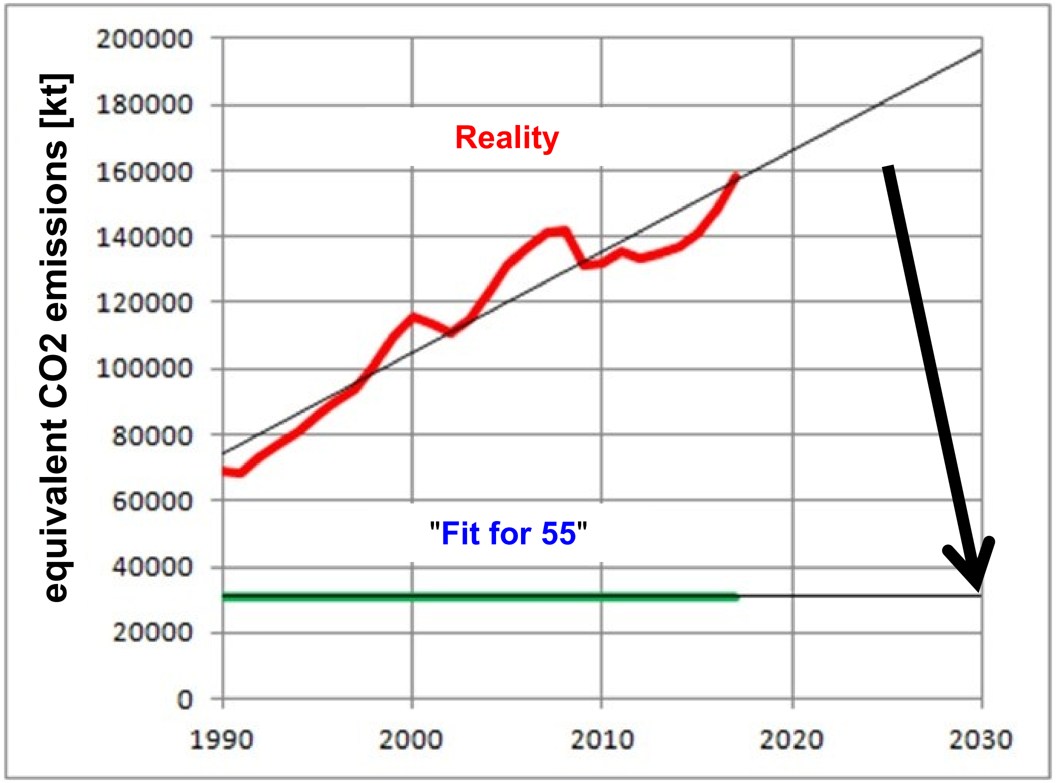
Themen der Sendung

Problem Kondensstreifen

Kondensstreifen sind anthropogene, also vom Menschen gemachte Wolken. Sie haben einen wärmenden Effekt, weil sie die Wärmestrahlung, die von der Erde ausgeht, daran hindert, ins Weltall zu gelangen. Kondensstreifen sind ein wichtiger Faktor bei der Klimaschädlichkeit von Flugzeugen. Doch wie lassen sich diese Kondensstreifen vermeiden?



Climate Goals of the EU? => Drastic Reduction of Flights?



1.) 2019: The EU's "**Green Deal**": "**In 2050, net greenhouse gas emissions should no longer be released**".

2.) 2020: The European climate targets for 2030 were defined under the motto "**Fit for 55**". This is the interim goal of the Green Deal: "**Greenhouse gas emissions are to be reduced by 55% compared to 1990** – i.e. only 45% of the 1990 value. This value is to be achieved by 2030."

https://doi.org/10.48441/4427.225

The 55% reduction compared to 1990 means a reduction of more than 80% for aviation by 2030, i.e. by about 13.5% per year. Fuel consumption has so far been reduced by 1.5% annually through operational measures and technology. **Air traffic would therefore have to shrink permanently by 12% per year from now on for the next 6 years** based on 2024 traffic numbers.

TAB Study: Climate-Friendly Aviation

Prof. Dr. Dieter Scholz (HAW Hamburg) was involved in the TAB Short Study No. 6 as an expert and interview partner.

The short study "Innovative Propulsion Systems and Fuels for more Climate-Friendly Aviation" was approved by the Committee on Education, Research and Technology Assessment and published on 8 May 2024 by the Office of Technology Assessment at the German Bundestag (TAB):
Homepage: Link, Archive.
Study: https://doi.org/10.5445/IR/1000170399
The interview with Prof. Scholz: https://doi.org/10.48441/4427.1517

The study identifies the following fields of action for policymakers, among others

1) **=> Optimization of flight routes to reduce emissions (avoidance of warming contrails) <=**
2) Better support for consumers in choosing more climate-friendly alternatives: More transparency through "climate labels": a) Comparison of aircraft b) Comparison of airlines, b) Comparison of flight routes compared also to other means of transport.
3) Use of book-and-claim concepts (certificates for the use of Sustainable Aviation Fuel, SAF).
4) Reduction of the aromatic content in kerosene.
5) Adjustment of the taxation of aviation by levying a kerosene tax.
6) Business jets: Due to a significant increase in flights, combined with disproportionate climate-damaging emissions: Taxation or inclusion in emissions trading.

Controversy about Monitoring, Reporting, and Verification (MRV)

Press Release No: 14

Date: 30 April 2024

IATA

More Data Needed to Understand Contrails, their Climate Effect & Develop Mitigation

Mr Walsh urges Brussels to make the scheme voluntary and applicable to flights within the EU only - Moe Zoyari/Bloomberg

https://perma.cc/C3CT-9VME
https://perma.cc/3RSS-3WMX
https://perma.cc/NM72-Y63E
https://perma.cc/Z3JU-UFDA

EU plans exemption for long-haul flights from emissions monitoring

Reuters, 19.06.2024

The EU is apparently backing down on the planned monitoring of non-CO2 emissions by airlines. This was actually supposed to be mandatory for all flights. But international resistance is heavy - as the EU has already found out.

FINANCIAL TIMES

Airlines lobby against EU plan to monitor non-CO_2 emissions

Philip Georgiadis in London April 28 2024

The Telegraph

EU suffers backlash over plan to monitor aircraft contrails

Christopher Jasper
Mon, 29 April 2024 at 1:24 pm CEST·2-min read

MRV Put into Perspective by an Environmental Organization

MAY 2, 2024

Plane to see

TRANSPORT & ENVIRONMENT

Why is the monitoring of contrails from planes causing controversy?

■ ■ ■

Their most recent delay tactic has been to oppose the mere monitoring of these contrails. As part of a major reform of the EU's carbon pricing scheme for aviation, lawmakers decided it was time to start monitoring contrail pollution. That scheme will be put in place by 2025. By 2028 the EU must introduce measures to reduce contrail pollution.

But legacy airlines and their political friends are pushing back. The powerful airline lobby IATA and its membership of legacy carriers are opposed to the EU monitoring contrails on long distance flights – which they mostly operate and which cause most of the contrails. Others claim fitting humidity sensors on their jets or reporting some data would be ruinously expensive. We have had 25 years of fear, uncertainty and doubt. There is no time to waste before we start monitoring these emissions.

■ ■ ■

https://perma.cc/7STJ-DA5Z
https://www.transportenvironment.org/discover/plane-to-see
https://www.transportenvironment.org

T&E

Europe's leading advocates for clean transport and energy

Contrails

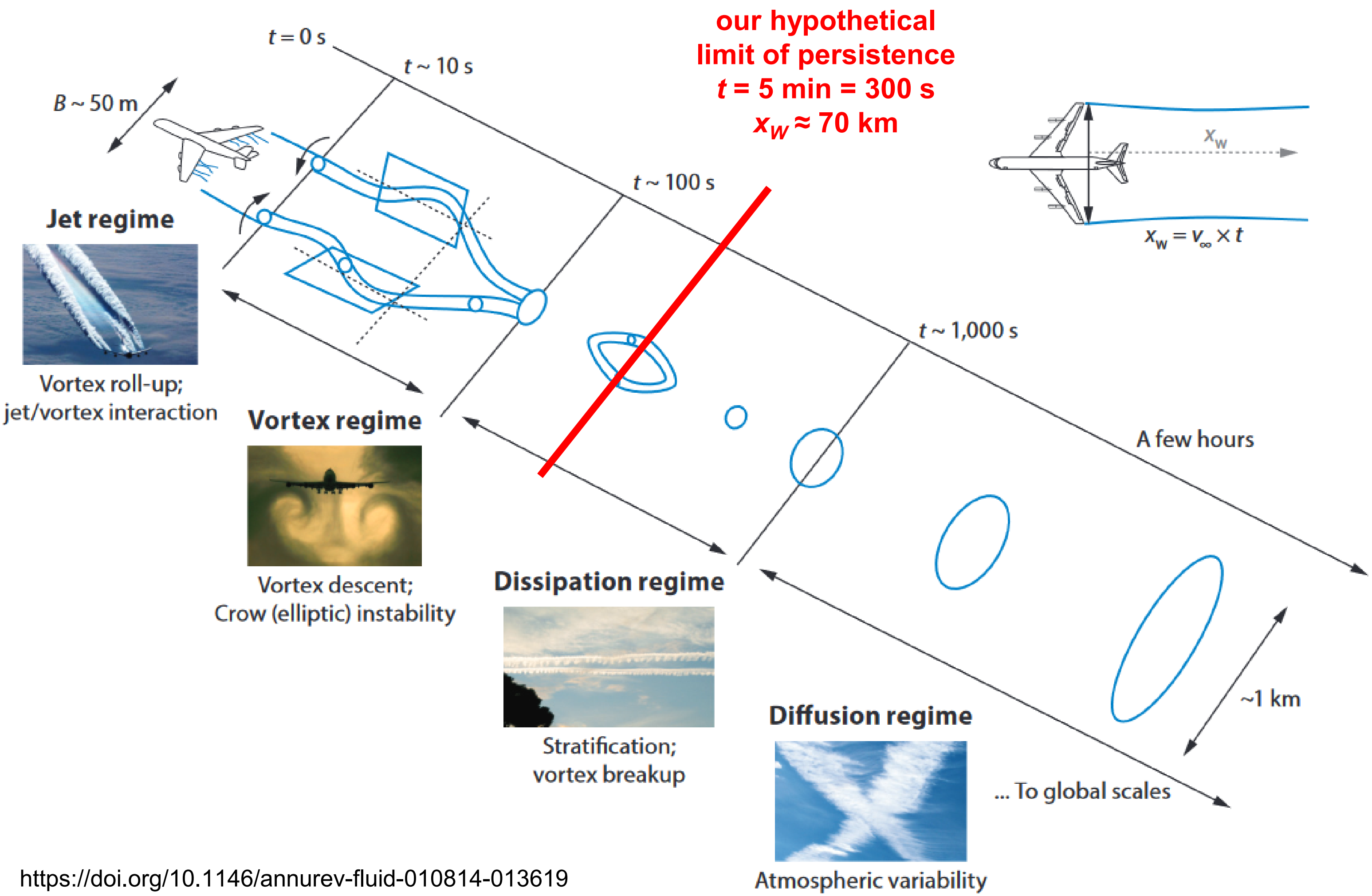
Contrail

Basics

Contrail Life Cycle

KRAFT, Martin, 2016. Kondensstreifen, CC BY-SA, https://de.wikipedia.org/wiki/Kondensstreifen#/media/Datei:MK35097_Contrails.jpg
https://kitskinny.wordpress.com/2013/07/09/jets-clouds-effects

Contrail Life Cycle

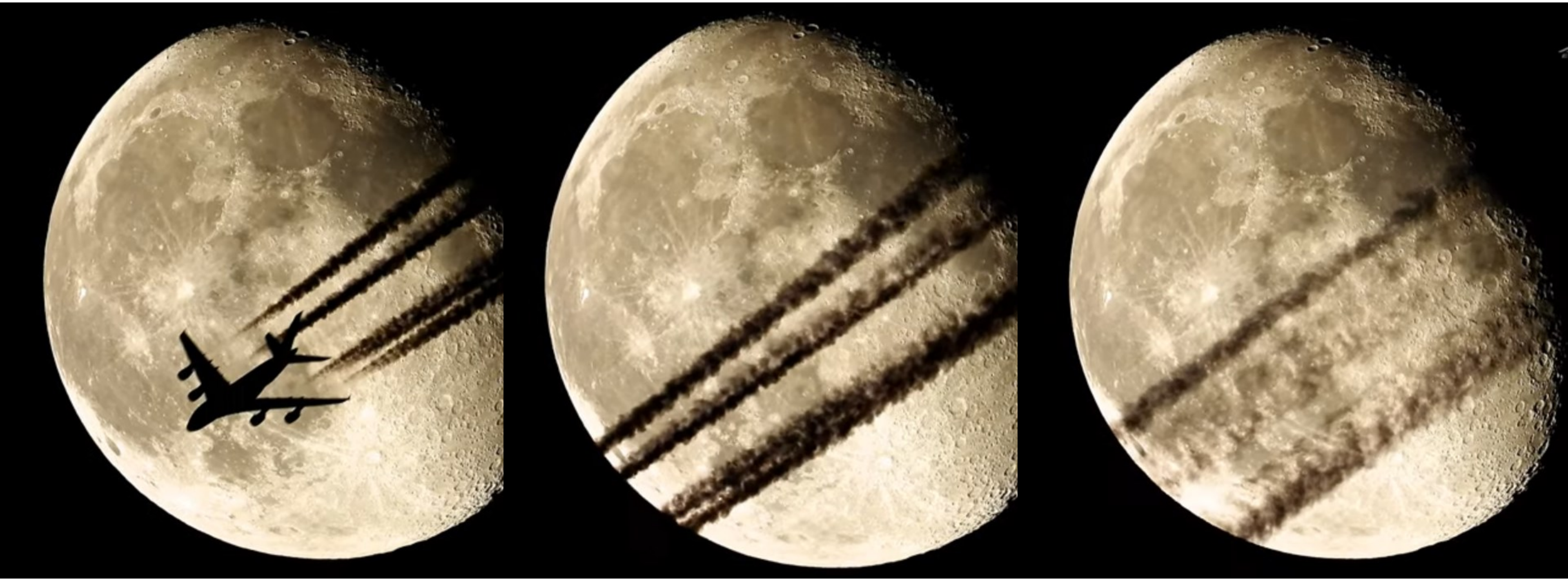


https://doi.org/10.1146/annurev-fluid-010814-013619

Cooling Persistent Contrails (Daytime)

Warming Persistent Contrails (Dawn and Dusk)

Warming Persistent Contrails (Night)

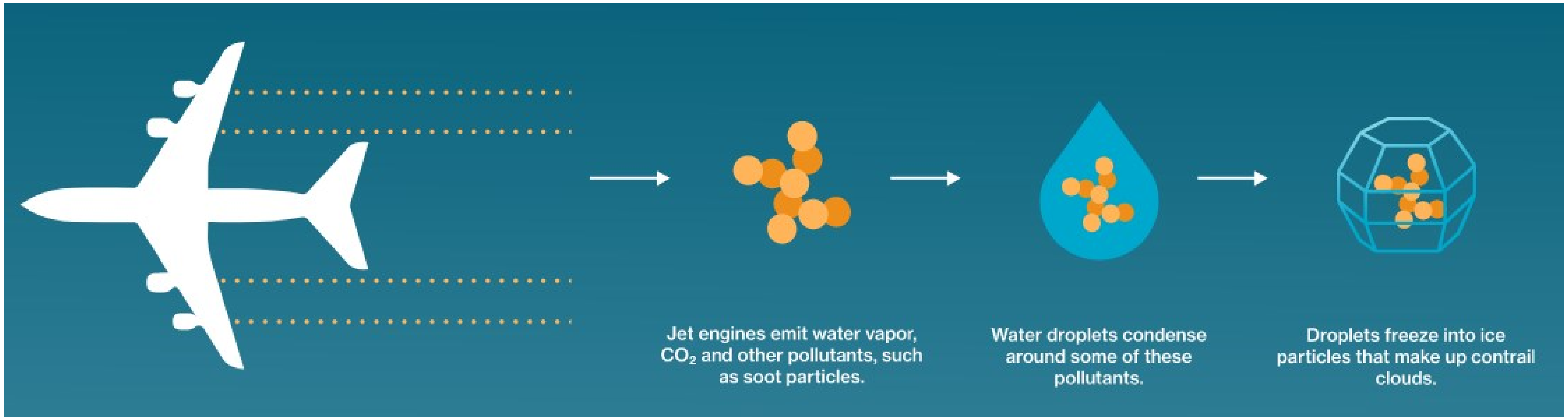


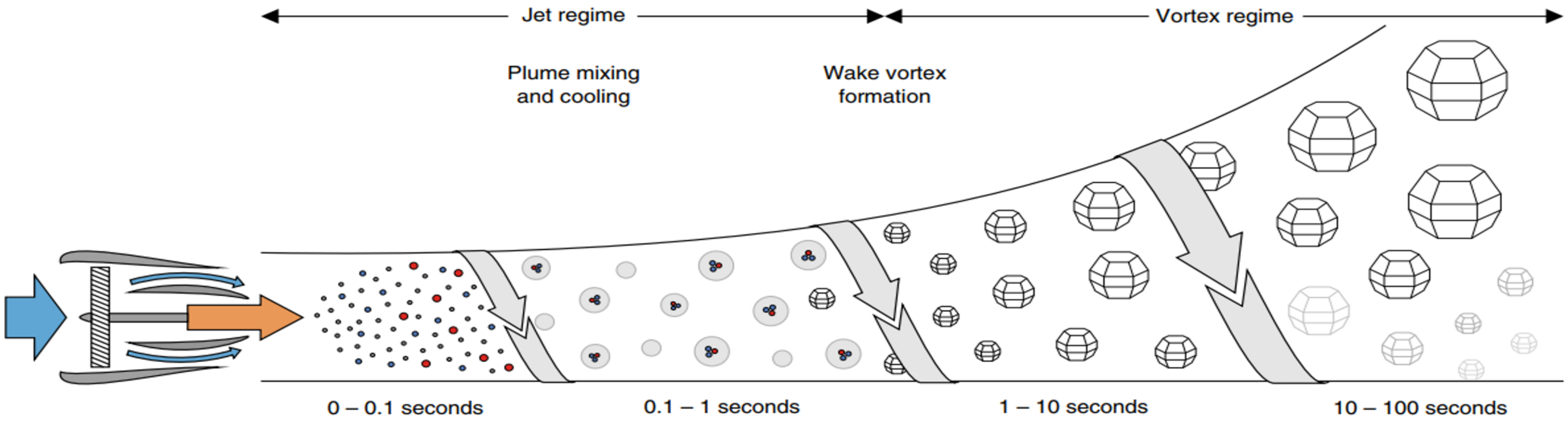
Emirates Airbus A380 registration A6-EKV operating flight EK-232 from Washington Dulles International Airport (IAD/KIAD) destination Dubai (DXB/OMDB) crossing the moon while flying at 39000 feet with ground speed of 497 knots, over Varna city at 01:55 local time on 13 March 2020.

https://www.youtube.com/watch?v=9N1ZxfAsAl0&t=442s

Ice Crystal Growth in Contrails

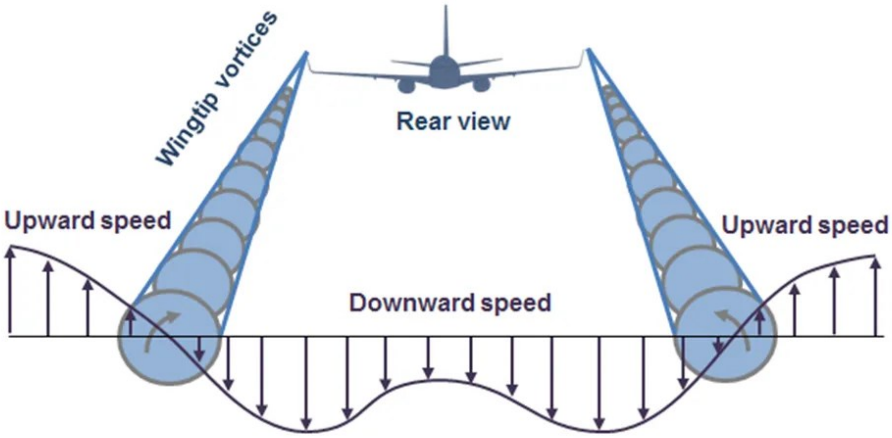
https://contrails.org/science





KÄRCHER, Bernd, 2018. Formation and Radiative Forcing of Contrail Cirrus. In: *Nature Communications*, Vol. 9, Article Number: 1824. Available from: https://doi.org/10.1038/s41467-018-04068-0

Downwash

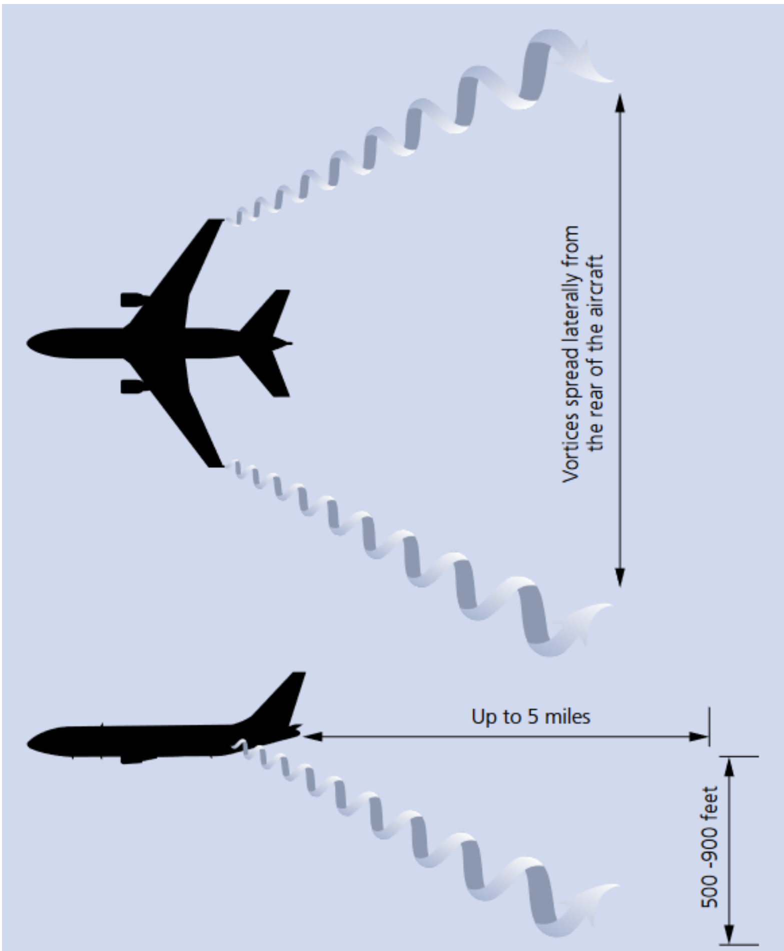


https://medium.com/@devavratatripathy/why-do-airplanes-have-winglets-db25ba41d833
https://www.reddit.com/r/pics/comments/pldog/photo_of_the_downwash_effect_from_a_passing_jet

Downwash

http://www.diam.unige.it/~irro/gallery.html
http://www.diam.unige.it/~irro/gallery/Cessna_downwash.jpg
https://forums.flightsimulator.com/t/aircraft-should-make-trails-through-clouds-wingtip-vortices/258814/16
https://forums.flightsimulator.com/uploads/default/original/4X/4/1/f/41facf8e7393aeb51eceffc9cf1223a347afcd2e.jpeg

Downwash



https://skybrary.aero/sites/default/files/bookshelf/660.pdf

Wake vortices spread laterally away from the aircraft and descend approximately 500 ft to 900 ft at distances of up to five miles behind it. These vortices tend to descend at approximately 300 ft to 500 ft per minute during the first 30 seconds. This is equal to a **descent speed** of **2 m/s**.

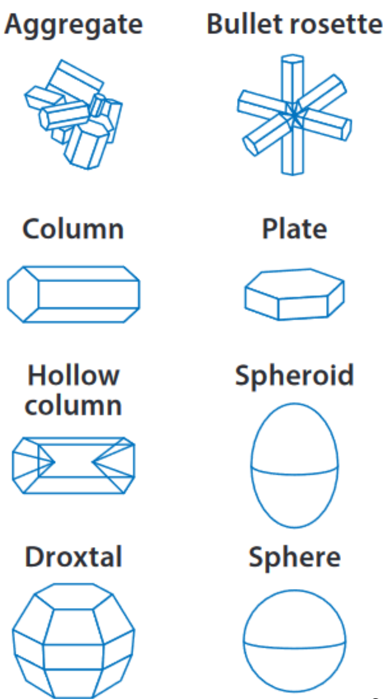
The downwash at the horizontal tail is with about 20 m/s much higher and decreases with increasing distance from the aircraft. (http://hoou.ProfScholz.de, Eq. 11.29)

Aircraft	Max Gross Weight (w) lb	Span (b) ft	Airspeed (V) ft/sec	Vortex Spacing (b') ft	Vortex Sink Rate (w) ft/min	Vortex Radius (r) ft	Max Vertical Velocity (less w) (V_t) ft/min
Convair (C-131)	46,000	92	237	72	162	7	1800
Boeing 727	169,000	108	272	86	372	9	4100
Boeing 707	328,000	145	300	115	366	12	4000
Boeing 747	710,000	196	300	155	432	16	4700
C-5	750,000	222	290	175	354	18	3900
Concorde	385,000	84	338	67	1120	7	12900
Boeing 2707	750,000	143	338	112	760	11	8500

200 ft/min ≈ 1 m/s ≈ **2 m/s**

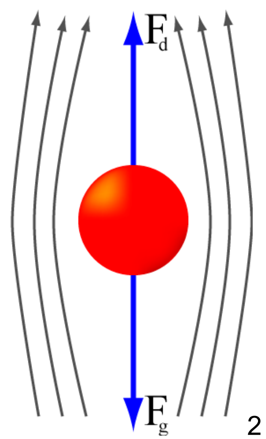
https://web.archive.org/web/20130223191349/
www.airpower.maxwell.af.mil/airchronicles/aureview/1971/jul-aug/carten.html

Sedimentation / Settling



3

"Contrails redominantly consist of bullet rosettes, columns, and plates with sizes ranging from about 1 µm to about 100 µm" [1]



2

Terminal velocity of typical ice crystals in contrails:

$$F_d = \frac{1}{2} \rho_a \cdot v^2 \cdot c_D \cdot S$$

sphere: $S = r^2 \cdot \pi$

$V = \frac{4}{3} \pi r^3$

$c_D = 0.47$ 4

tropopause: $\rho_a = 0.364 \ kg/m^3$

$a = 295 \ m/s$

$$F_g = m \cdot g = V \cdot \rho_i \cdot g$$

ice: $\rho_i = 917 \ kg/m^3$

$r = 10 \cdot 10^{-6} \ m$

$$F_d = F_g$$

$$\frac{1}{2} \rho_a v^2 \cdot c_D \cdot r^2 \cdot \pi = \frac{4}{3} \pi r^3 \cdot \rho_i \cdot g$$

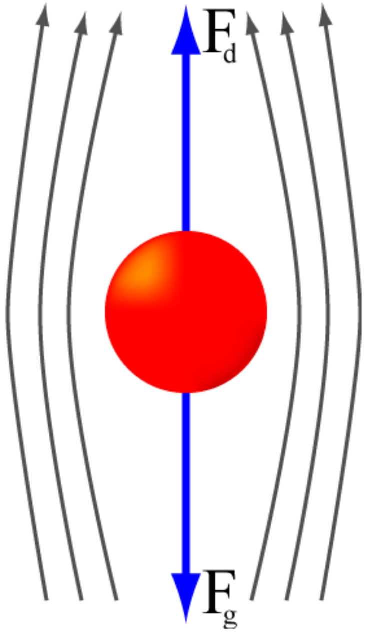
$$v = \sqrt{\frac{8}{3} \cdot \frac{\rho_i}{\rho_a} \cdot \frac{g}{c_D}} \cdot \sqrt{r}$$

$$v = 374 \frac{\sqrt{m}}{s} \cdot \sqrt{r} = 1.2 \ m/s$$

2: JabberWok, CC BY-SA 3.0
https://commons.wikimedia.org/wiki/File:Terminal_Velocity.png
4: https://en.wikipedia.org/wiki/Drag_coefficient (sphere)

1: https://doi.org/10.1016/S0074-6142(02)80023-7
3: https://doi.org/10.1146/annurev-fluid-010814-013619

Sedimentation / Settling



Troposphere: Laps rate, $L = 0.0065\ K/m$

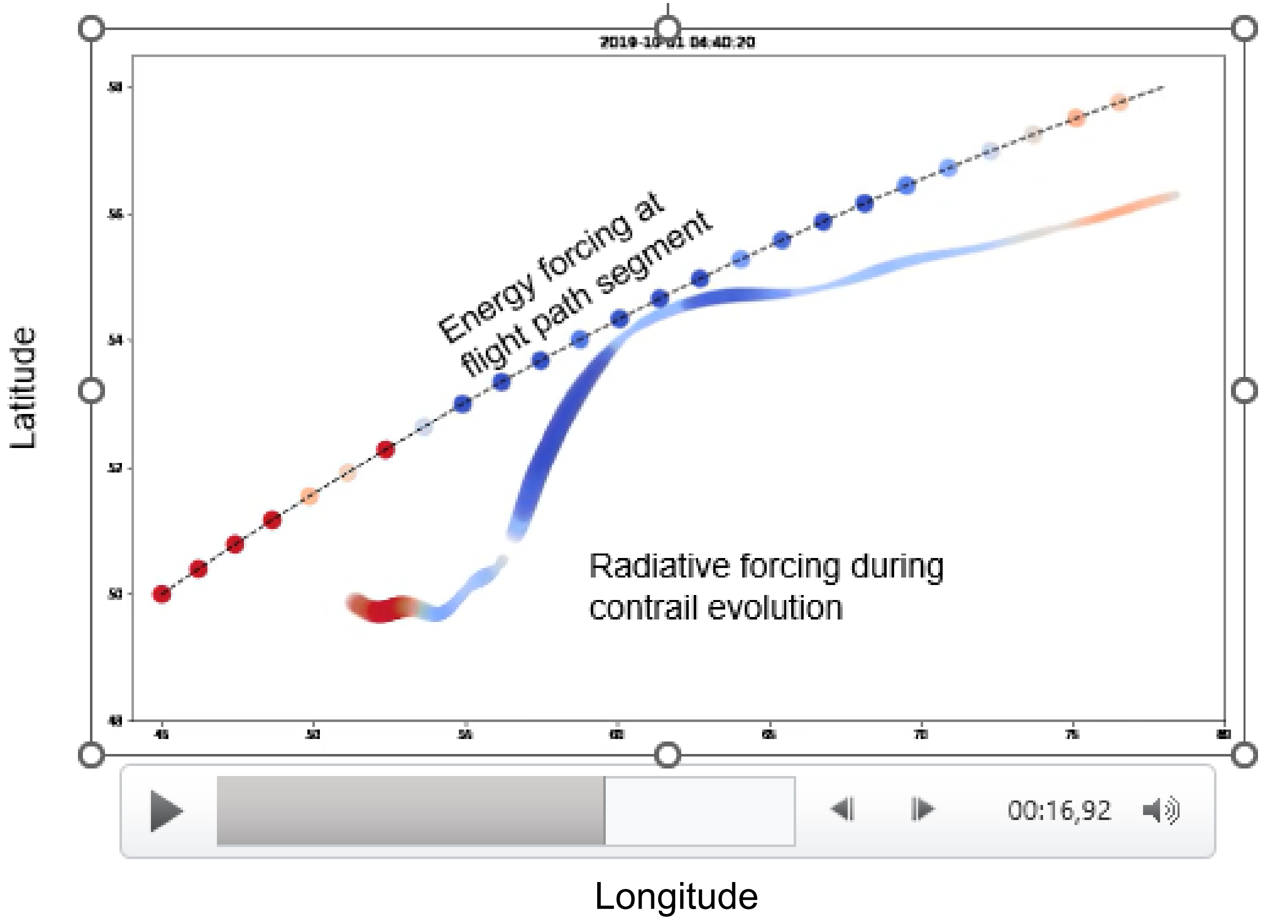
$$L = \frac{\Delta T}{\Delta H} \qquad \Delta H = \frac{\Delta T}{L}$$

$$V = \frac{\Delta H}{\Delta t} \qquad \Delta t = \frac{\Delta H}{V} = \frac{\Delta T}{V \cdot L}$$

$$\frac{\Delta t}{\Delta T} = \frac{1}{V \cdot L} = \frac{1}{3.2 \cdot 0.0065} \frac{s}{K} = \underline{\underline{48\ s/K}}$$

It takes about 48 s for the contrail to sink so far to get into air that is 1 °C warmer. At this temperature vapor pressure over ice is higher and lets the ice sublimate ("dry") faster.

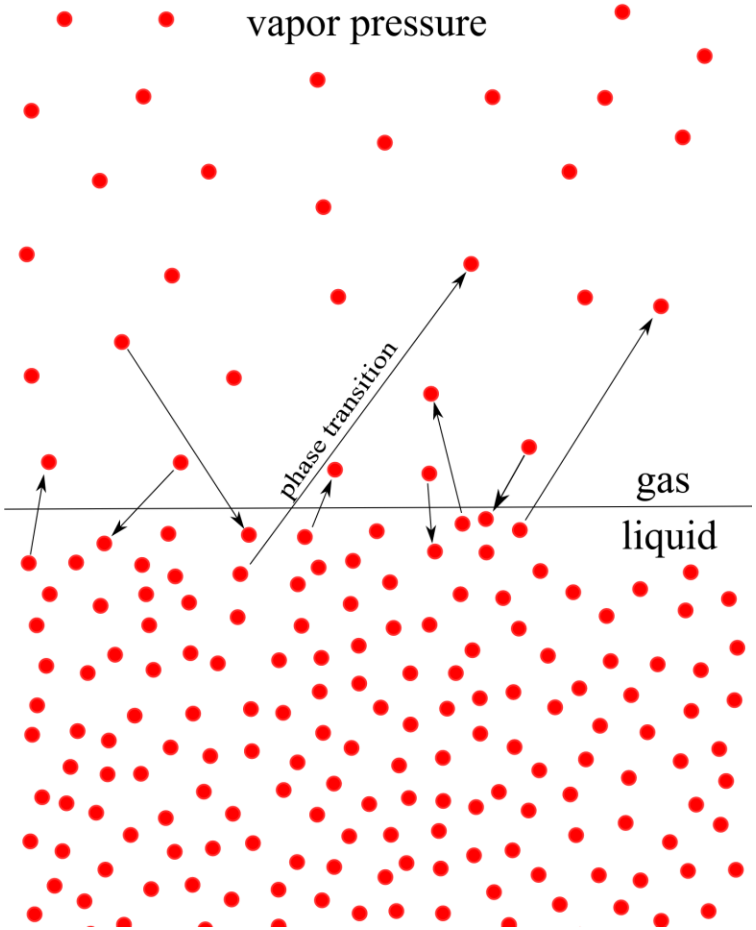
Contrail-Cirrus Prediction Tool (CoCiP)



https://py.contrails.org
(open source)

Flight on
10 Jan 2019, 0:00 to 6:00 h

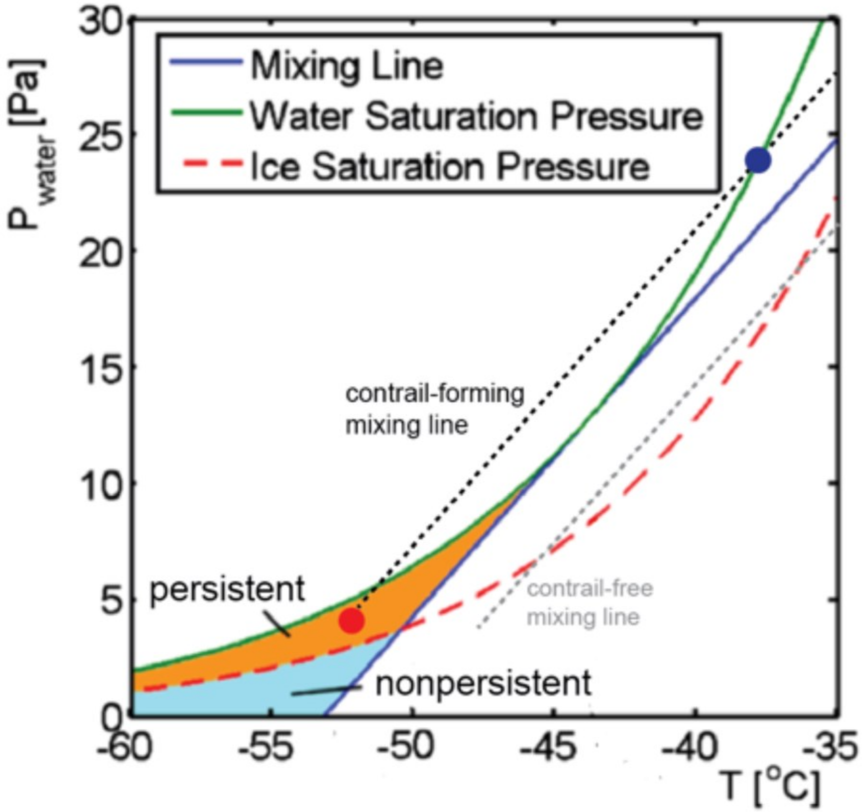
Vapor Pressure



vapor pressure

over water	over ice
evaporation	sublimation
air	air
water	ice

Exhaust Gas Mixing in Ambient Air



Graphical representation of the Schmidt-Appleman criterion analysis. When the mixing line (representing mixing of engine exhaust and ambient air) crosses the water saturation line, a contrail will form. As the mixture continues to cool and water deposits as ice, the mixing may cease in ice supersaturated conditions (shaded orange) where a contrail will persist.

NOPPEL, F., SINGH, R., 2007. Overview on Contrail and Cirrus Cloud Avoidance Technology. In: Journal of Aircraft, vol. 44, no. 5.
Available from: https://doi.org/10.2514/1.28655
via
BREAKTHROUGH ENERGY, 2023. Contrails & Climate Change. Archived at: https://perma.cc/YT8Q-V3KW

Schmidt-Appleman Criterion for Contrail Formation

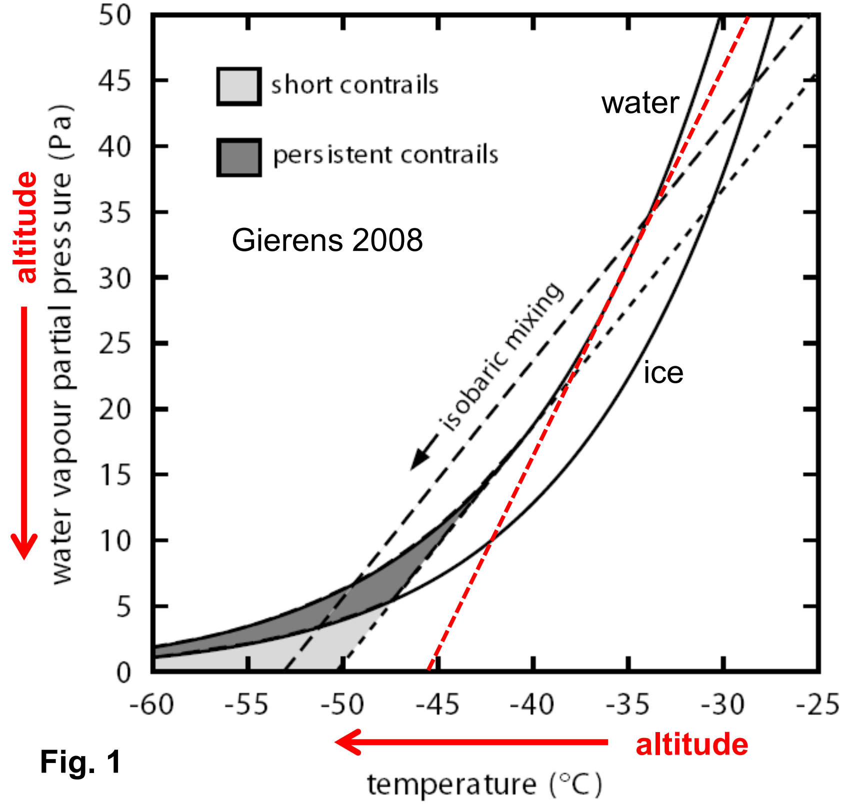


Fig. 1

The mixing process is assumed to take place isobarically, so that on a *T*-*e* diagram the mixing (phase) trajectory appears as a straight line (*e* is the partial pressure of water vapour in the mixture, *T* is its absolute temperature, see Fig. (**1**)). The slope of the phase trajectory, *G* (units Pa/K), is characteristic for the respective atmospheric situation and aircraft/engine/fuel combination. *G* is given by

$$G = \frac{EI_{H2O}\, p c_p}{\varepsilon Q(1-\eta)}$$

where ε is the ratio of molar masses of water and dry air (0.622), c_p=1004 J/(kg K) is the isobaric heat capacity of air, and p is ambient air pressure. *G* depends on fuel characteristics (emission index of water vapour, EI_{H2O} = 1.25 kg per kg kerosene burnt; chemical heat content of the fuel, Q = 43 MJ per kg of kerosene), and on the overall propulsion efficiency η of aircraft. Modern airliners have a propulsion efficiency (η) of approximately 0.35.

G is the slope of the dotted line.
The dotted line is tangent to the water saturation line.

G is the slope of the red dotted line with increased slope. The point on the line tangent to the water saturation line is shifted to the right (to higher temperatures).

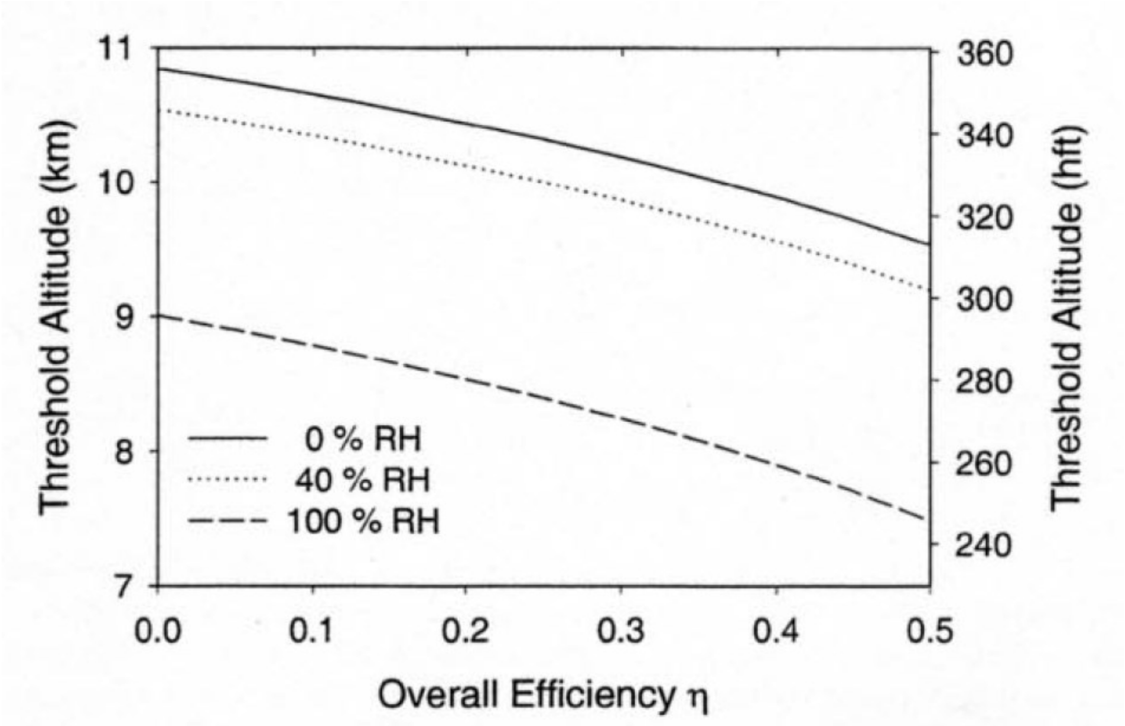
GIERENS, Klaus, LIM, Limg, ELEFTHERATOS, Kostas, 2008. A Review of Various Strategies for Contrail Avoidance.
In: The Open Atmospheric Science Journal, 2008, 2, 1-7. Available from: https://doi.org/10.2174/1874282300802010001

Effect of the Propulsion Efficiency

Propulsion efficiency

$$\eta = FV/(m_f Q)$$

m_f: fuel flow
F: thrust



A lower efficiency, η means a smaller slope, *G* which is tangent to the water saturation line further left (at lower temperatures or increase altitude).

A lower efficiency, η results in more heat losses and a warmer plume, which needs lower temperatures (at higher altitudes) for condensation to form the contrail.

Schumann, 2000, https://doi.org/10.2514/2.2715, Open Access: https://elib.dlr.de/9281

Heating Value Q, Emission Index EI, and Slope G

fuel	Q [MJ/kg]	EI_{H2O} [kg/kg]	EI_{H2O}/Q [kg/MJ]	G_{H2}/G_{Jet-A1}
H2	120	8,94	0,0745	2,58
Jet –A1	43	1,24	0,0288	

The slope G of the dotted line is 2,58 times steeper in case of LH2 combustion.This means: Contrails more often and also at lower altitudes.

2,58 times more water vapor is produced with LH2 combustion compared to kerosene combustion (for the same energy used).

Calculating Saturation Pressure with the Magnus Equation

The saturation vapor pressure for water vapor in the pure phase (absence of air) can be calculated using the Magnus formula recommended by the WMO. This formula has the advantage that it requires only three parameters and is reversible. However, more accurate formulas exist. The ones shown here have an accuracy (standard deviation) of ±0.3% over water and ±0.5% over ice.

Over flat water surfaces

$$E_w(t) = 6{,}112\,\mathrm{hPa} \cdot \exp\left(\frac{17{,}62 \cdot t}{243{,}12\,^\circ\mathrm{C} + t}\right) \qquad \text{für} \quad -45\,^\circ\mathrm{C} \leq t \leq 60\,^\circ\mathrm{C}$$

Over flat ice surfaces

$$E_i(t) = 6{,}112\,\mathrm{hPa} \cdot \exp\left(\frac{22{,}46 \cdot t}{272{,}62\,^\circ\mathrm{C} + t}\right) \qquad \text{für} \quad -65\,^\circ\mathrm{C} \leq t \leq 0\,^\circ\mathrm{C}$$

WMO, 2018. Measurement of Meteorological Variables. In: Guide to Instruments and Methods of Observation, Annex 4.B Formulae for the Computation of Measures of Humidity. Archived at:
https://web.archive.org/web/20220205104246/https://library.wmo.int/doc_num.php?explnum_id=10616
via
https://de.wikipedia.org/wiki/Sättigungsdampfdruck

The Tangent Mixing Line of the Schmidt-Appleman Criterion

Determination of the straight line in the Schmidt-Appleman criterion. We only know the slope, G of the straight line

$$f(t) = G\,t + G_0$$

$f(t)$ is the tangent to $E_w(t)$. At the point of contact, the slope of $E_w(t)$ and $f(t)$ must be the same. $E_w(t)$ is differentiated with respect to t and set equal to G.

$$E_w(t)' = \frac{dE_W(t)}{dt} = G$$

This gives the temperature t_{SAC} at the point of contact (details on next page). The temperature t_{SAC} is the highest temperature at which a contrails can form. Furthermore, $E_w(t) = f(t)$ at point of contact. From this we obtain G_0 .

$$G_0 = E_w(t) - G\,t$$

The Tangent Mixing Line of the Schmidt-Appleman Criterion

$$E_w(t) = a \cdot e^{\frac{bt}{c+t}}$$

$$\frac{dE_w(t)}{dt} = a \cdot e^{\frac{bt}{c+t}} \cdot \frac{b(c+t) - bt}{(c+t)^2}$$

$$= a \cdot e^{\frac{bt}{c+t}} \cdot \frac{bc + bt - bt}{(c+t)^2}$$

$$\frac{dE_w(t)}{dt} = \frac{abc \cdot e^{\frac{bt}{c+t}}}{(c+t)^2} \overset{!}{=} G$$

$$f(t) = G \cdot t + G_0$$

Magnus formula for saturation water vapor pressure over a flat water surface

a = 6.112 hPa

b = 17.62

c = 243.12 °C

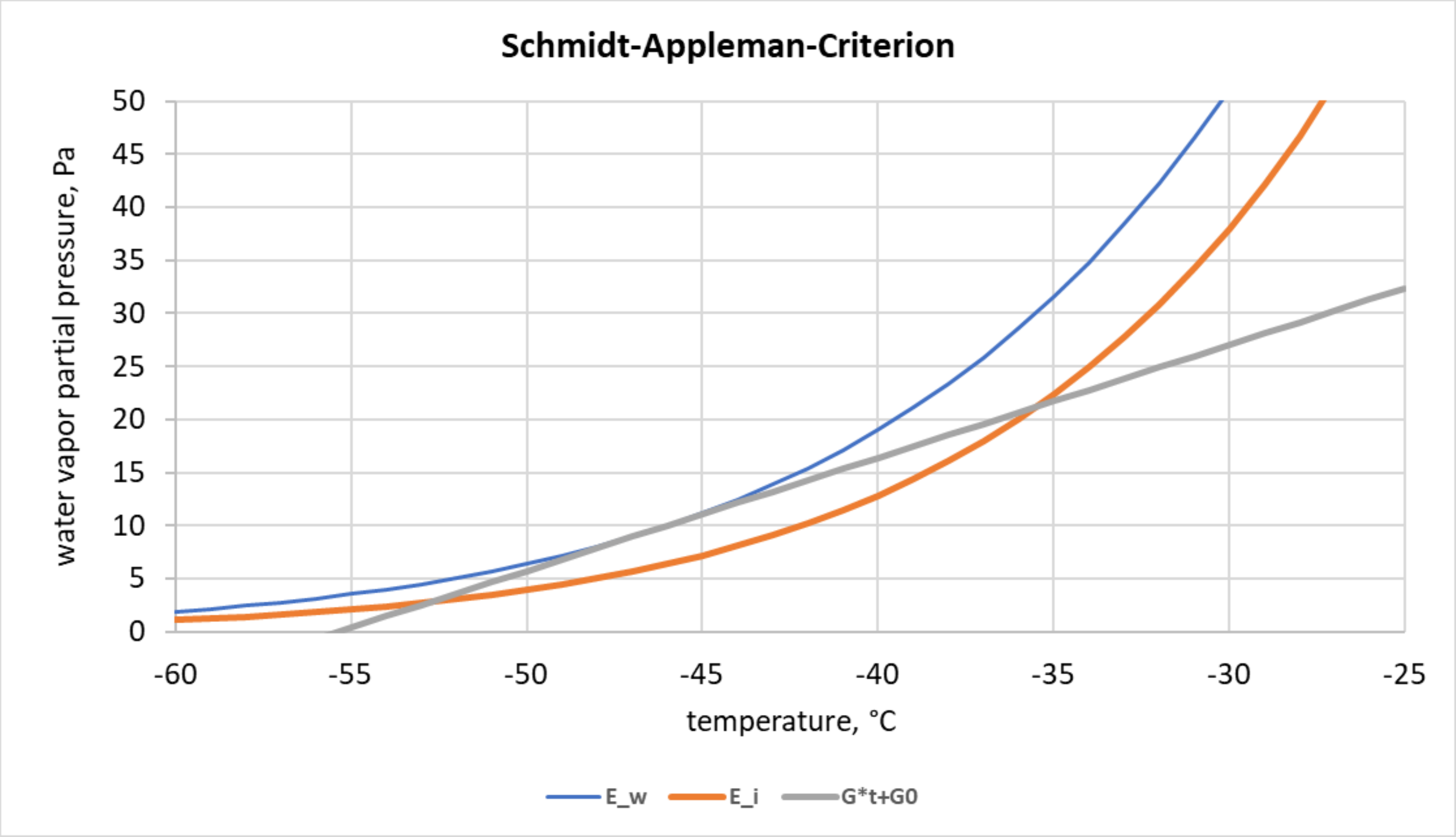
This equation can be solved for *t* with the *Solver* in Excel

$$\frac{abc \cdot e^{\frac{bt}{c+t}}}{(c+t)^2} - G = 0$$

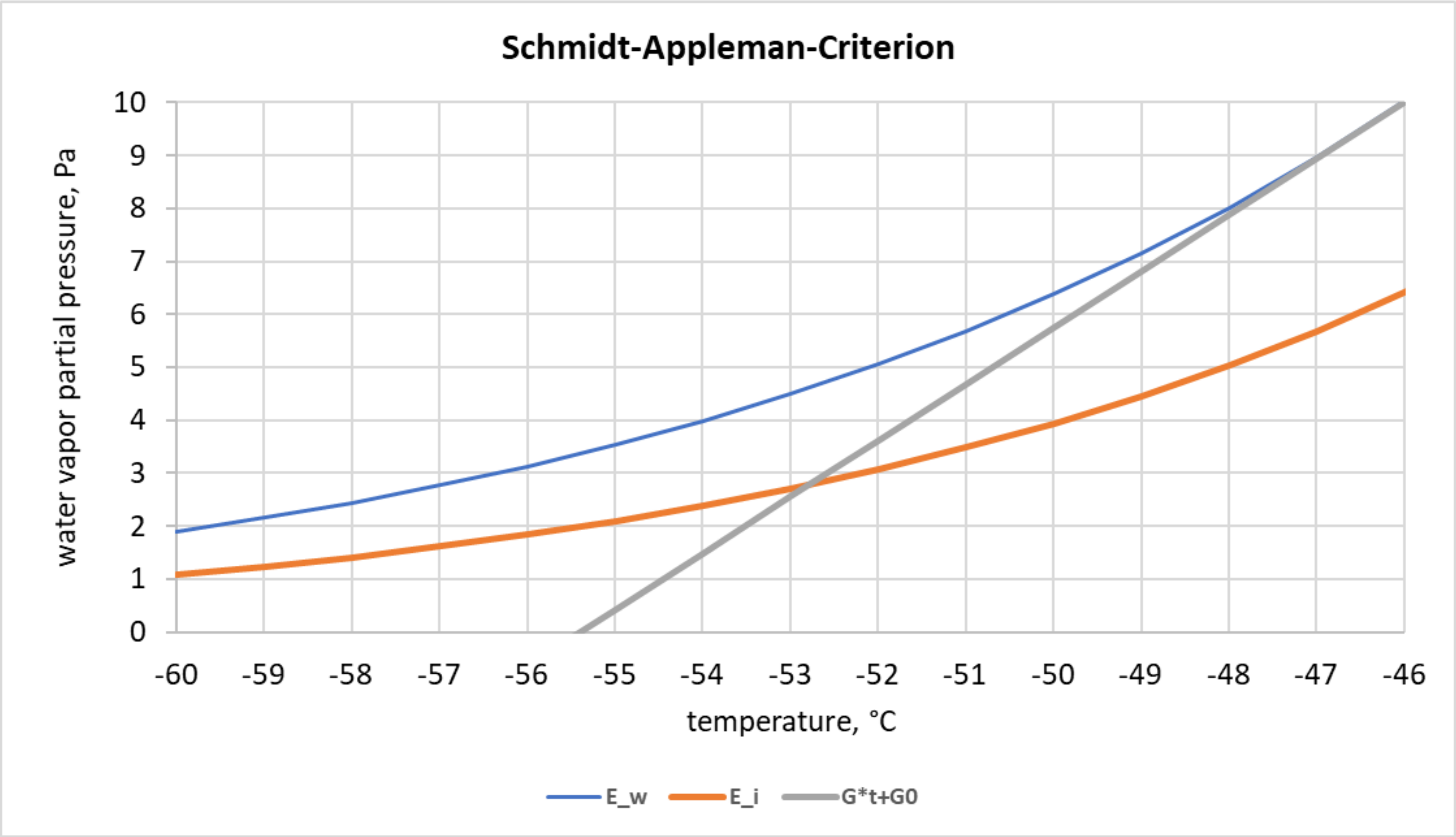
The temperature, *t* is where $E_w(t)$ and f(t) touch. This temperature is call t_{SAC}.
It is the highest temperature for contrails to form.

SAC stands for Schmidt-Appleman Criterion.

Schmidt-Appleman Criterion (Scholz)



Schmidt-Appleman Criterion, Zoom In (Scholz)



Constructing the Schmidt-Appleman Diagram

An aircraft flies at altitude, *H* and air temperature, *t*.
At what relative humidity, φ does it show contrails?

$$G \cdot t + G_0 = \varphi \cdot E_W(t)$$

$$\boxed{\varphi = \frac{G \cdot t + G_0}{E_W(t)}}$$

Exact solution of this equation with Excel's *Solver*.

Results need to be limited, if:

$G\,t + G_0 < 0$ => $\varphi < 0\%$ (not defined)

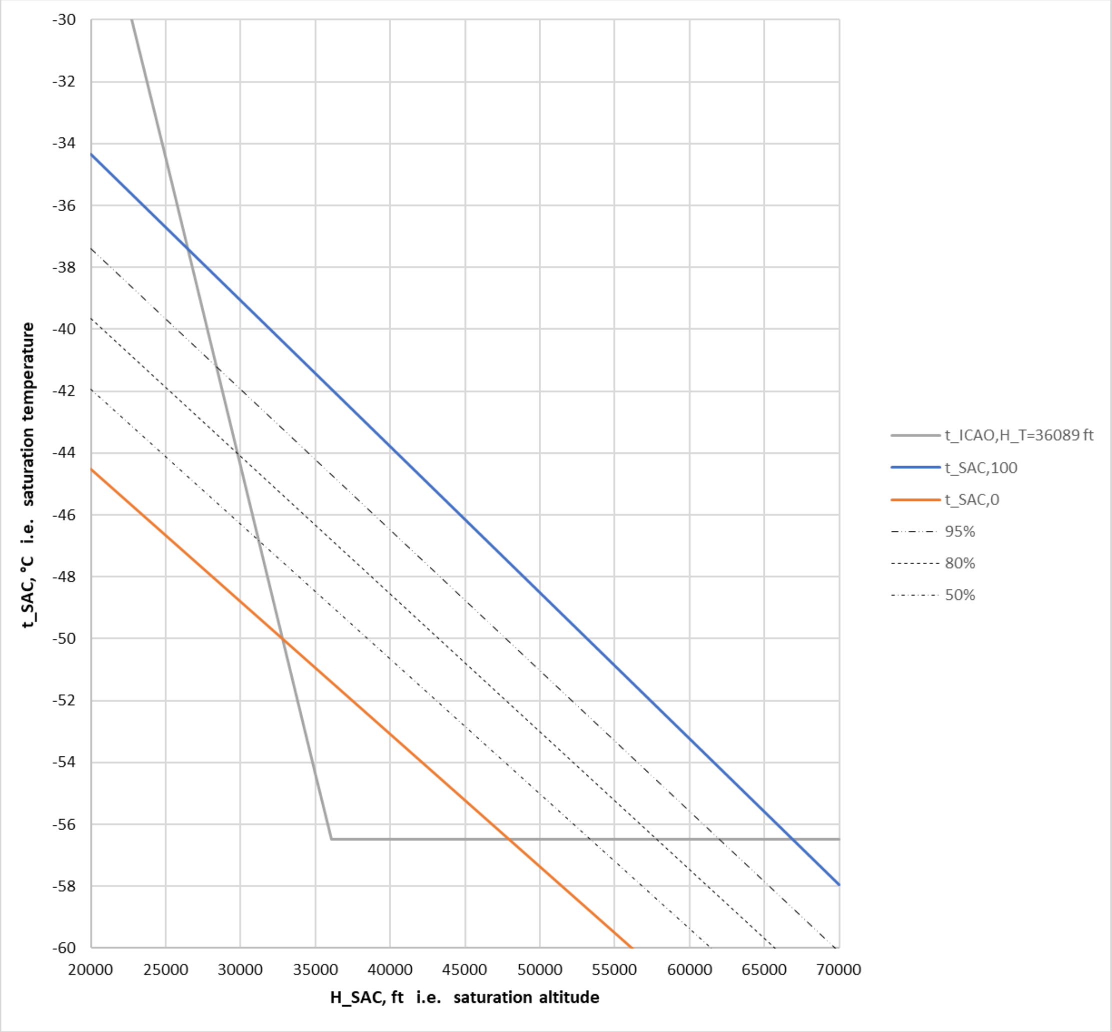
$t > t_{SAC}$ => $\varphi > 100\%$ (not defined)

Constructing the Schmidt-Appleman Diagram

	A	B	C	D	E	F	G	H	I
1	**Constructing the Schmidt-Appleman-Diagram (SAD)**								
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	1,354	3,361	1,354	2,172	1,721	1,634	1,354
7	G0	Pa	72,0	149,1	126,3	105,8	87,7	84,0	72,5
8	H	ft	40000	20000	25000	30000	35000	36089	40000
9	H	m	12192	6096	7620	9144	10668	11000	12192
10	p	Pa	18754	46559	18754	30087	23840	22632	18754
11	t_SAC,100	°C	-43,9	-34,2	-36,6	-39,0	-41,5	-42,0	-43,9
12	t_SAC,0	°C	-53,2	-44,4	-46,5	-48,7	-50,9	-51,4	-53,2
13	Δt,tot	°C	9,26	10,19	9,96	9,73	9,49	9,44	9,26
14									
15	t	E_w	phi	phi	phi	phi	phi	phi	phi
16	-60	1,901	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
17	-59	2,158	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
18	-58	2,447	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
19	-57	2,771	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
20	-56	3,134	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
21	-55	3,539	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
22	-54	3,992	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
23	-53	4,497	0,0595	n.a.	n.a.	n.a.	n.a.	n.a.	0,0595
24	-52	5,060	0,3204	n.a.	n.a.	n.a.	n.a.	n.a.	0,3204
25	-51	5,686	0,5232	n.a.	n.a.	n.a.	n.a.	0,1264	0,5232
26	-50	6,382	0,6783	n.a.	n.a.	n.a.	0,2555	0,3686	0,6783
27	-49	7,155	0,7943	n.a.	n.a.	n.a.	0,4684	0,5571	0,7943
28	-48	8,011	0,8783	n.a.	n.a.	0,1928	0,6332	0,7015	0,8783
29	-47	8,960	0,9364	n.a.	n.a.	0,4147	0,7582	0,8095	0,9364
30	-46	10,010	0,9734	n.a.	0,1403	0,5882	0,8506	0,8878	0,9734
31	-45	11,171	0,9935	n.a.	0,3687	0,7215	0,9163	0,9418	0,9935
32	-44	12,452	1,0000	0,0981	0,5487	0,8217	0,9602	0,9761	1,0000
33	-43	13,865	n.a.	0,3305	0,6885	0,8946	0,9864	0,9945	n.a.

Excel Table download:
https://purl.org/aero/SAC

Schmidt-Appleman Diagram and the ISA (Scholz)

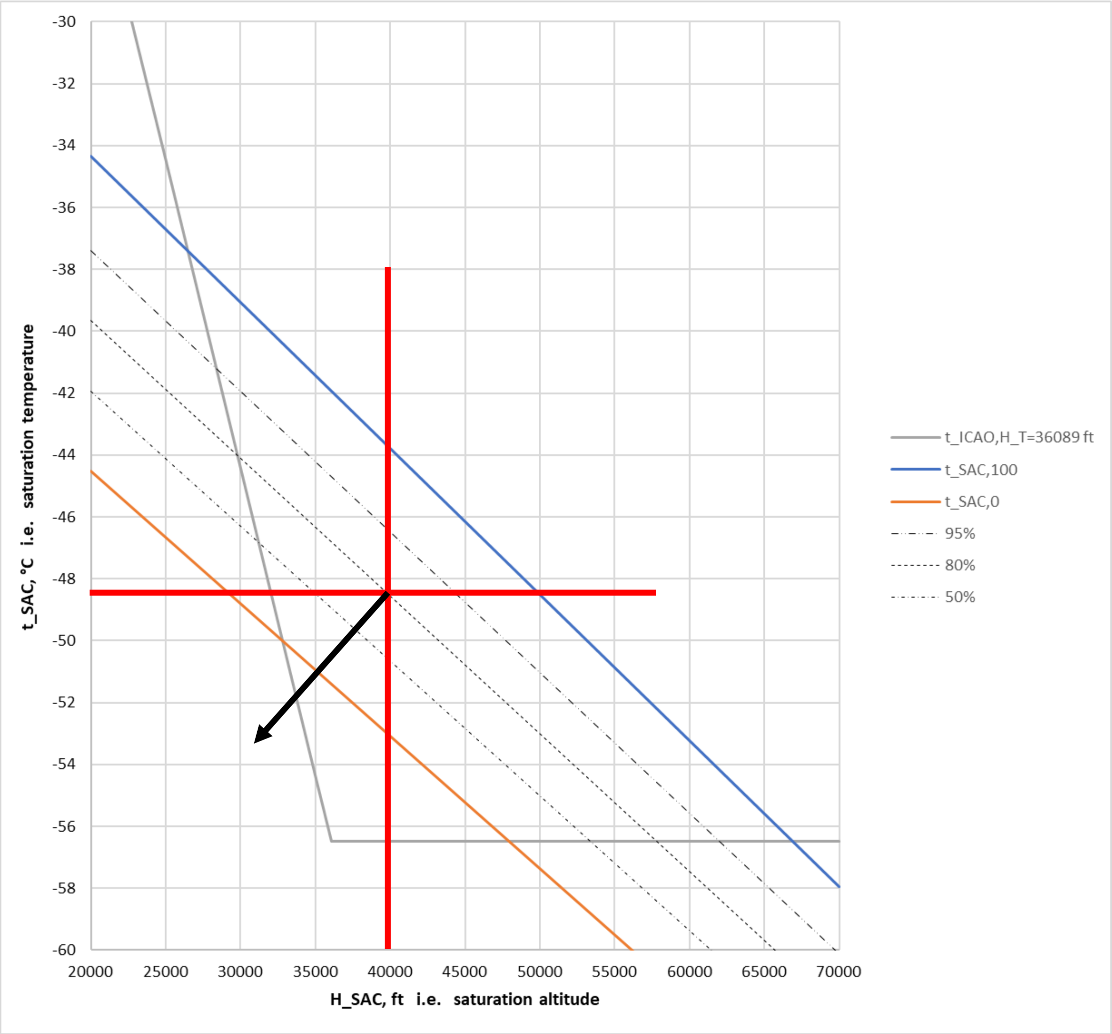


Contrails form down or left of the respective humidity lines.

The International Standard Atmosphere (light gray) shows:

- Conditions exist for contrails to form even with relative humidity of 0%.
- At 100% relative humidity contrails can form down to 27000 ft (but not below this altitude).

Schmidt-Appleman Diagram, Application (Scholz)



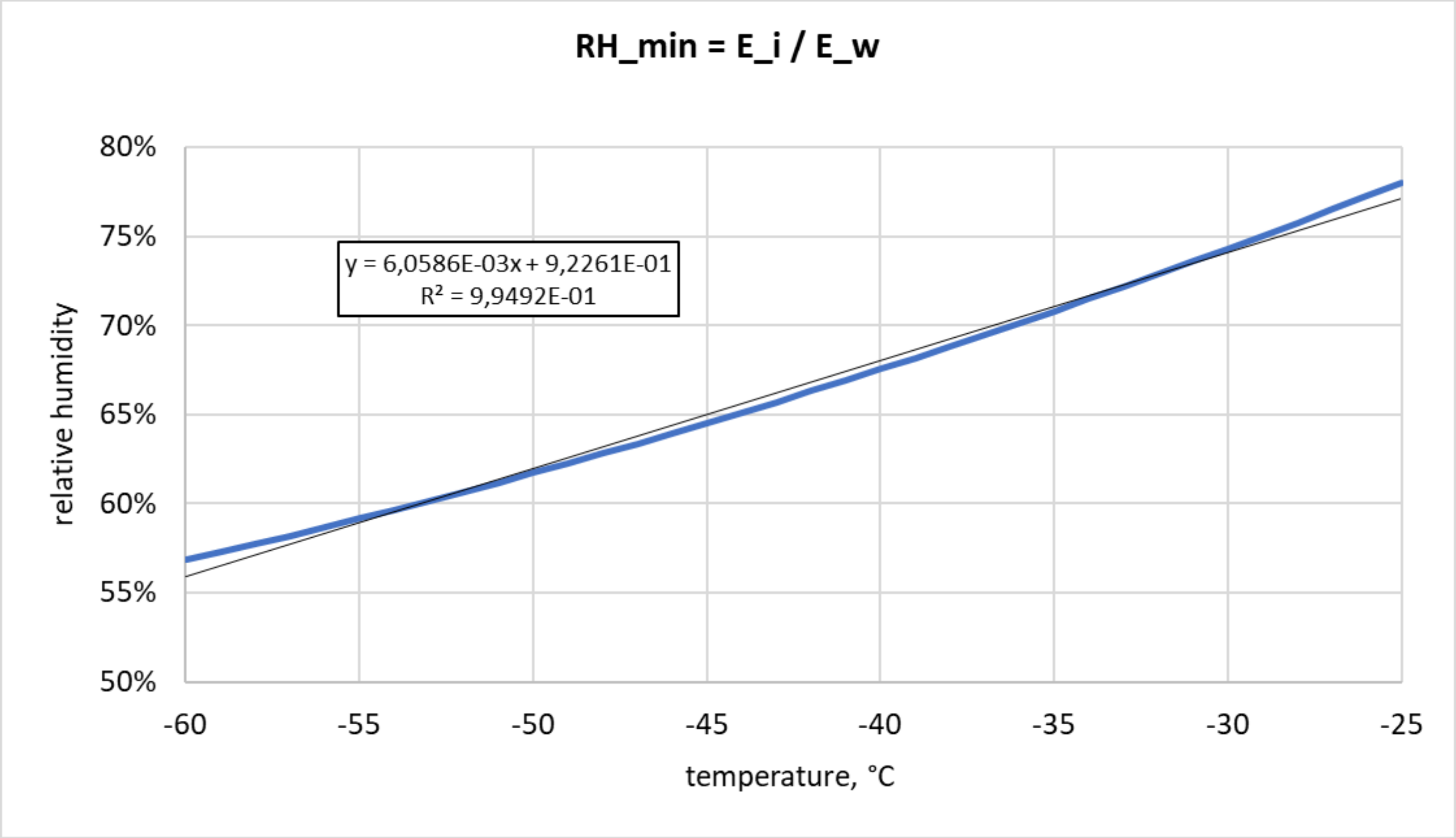
An aircraft flies at altitude, *H* and air temperature, *t*.

The red cross shows: There is one relative humidity, φ at which the aircraft starts to show contrails!

If the relative humidity is less than φ, it must be colder, or the same low temperature must occur at lower altitudes.

Contrails form down or left of the respective humidity lines. See black arrow.

Minimum Relative Humidity for Persistent Contrails



Ice crystals tend to sublimate (go directly from the solid to the gas phase) or dry up, if the air is dry enough. The blue line shows the relative humidity, above which ice does not sumblimate anymore and contrails are persistent.

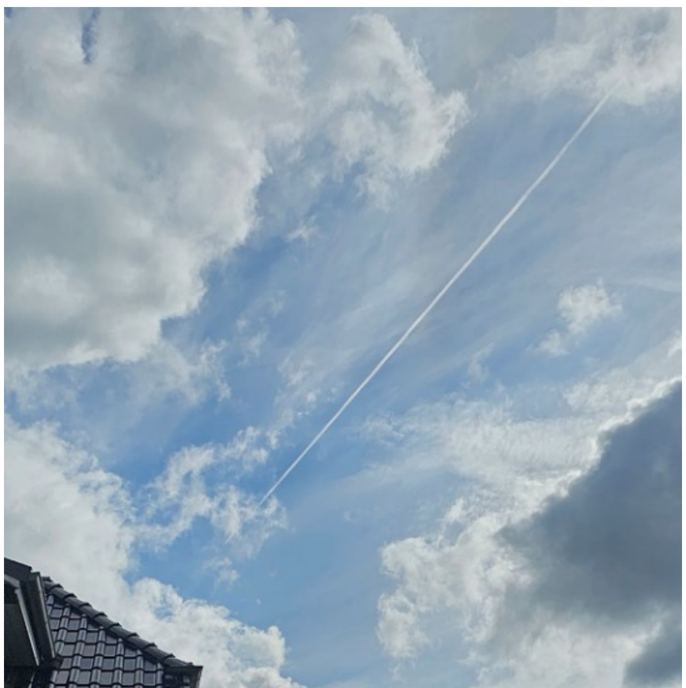
Contrail

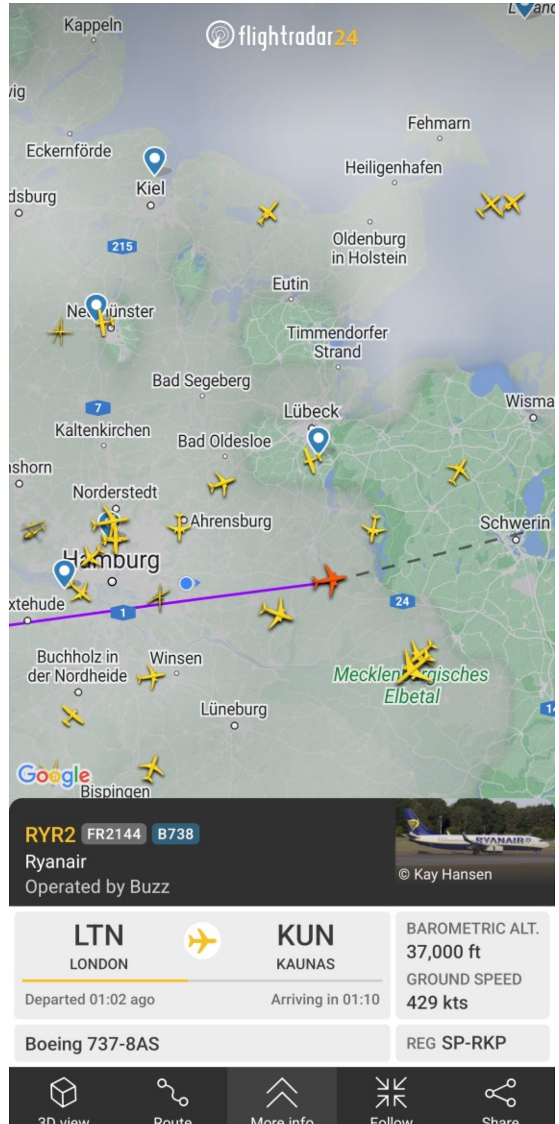
Prediction & Observation

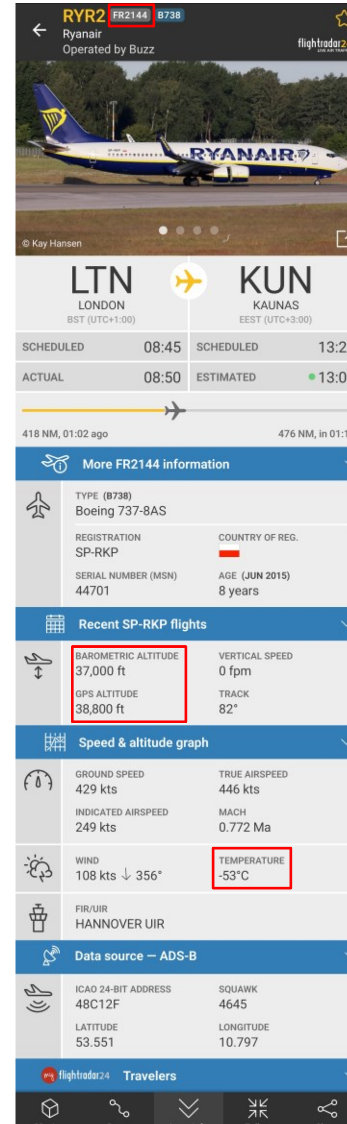
BRIEGERT, Finn, 2024. *Aircraft Contrails – Observation and Prediction*. Project. Hamburg University of Applied Sciences, Aircraft Design and Systems Group (AERO). Available from: https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2024-03-14.019

Observation & Prediction

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 (FL 370). The outside temperature was -53 °C.

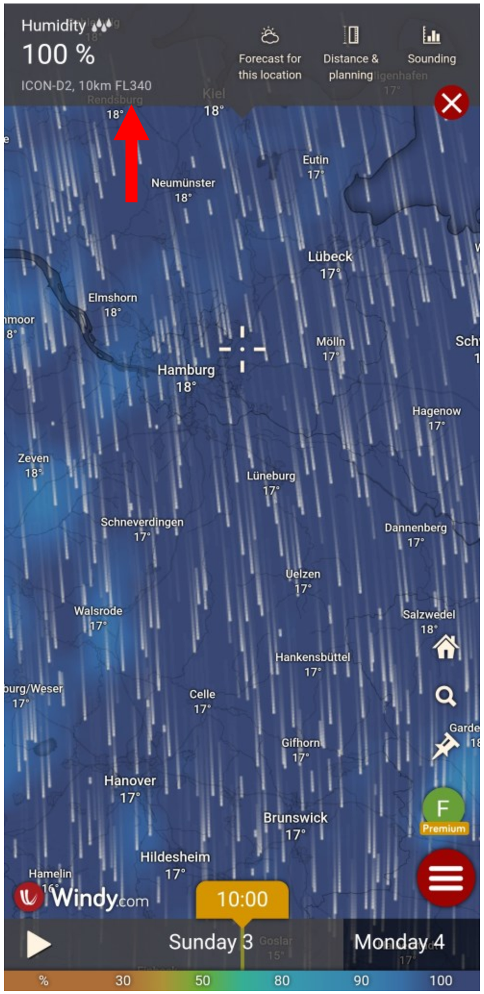


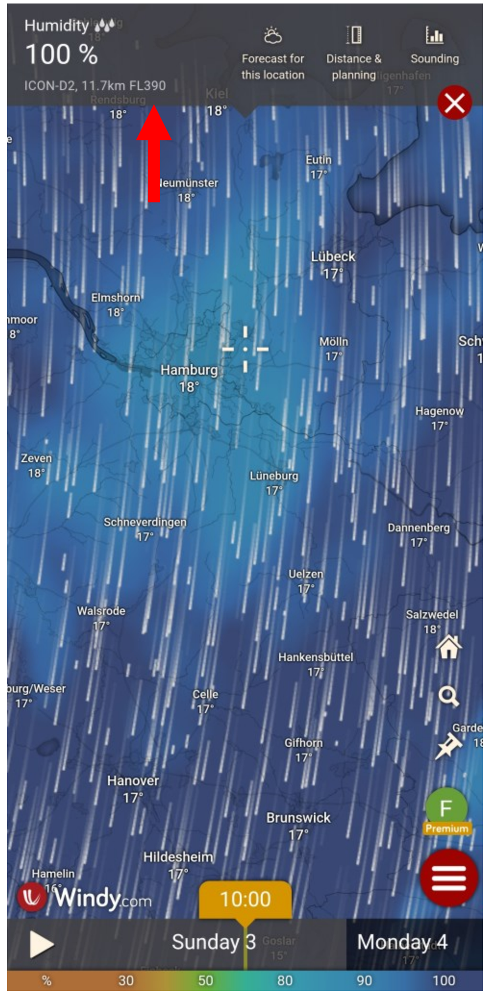




EGGW
-
EYKA

Relative Humidity





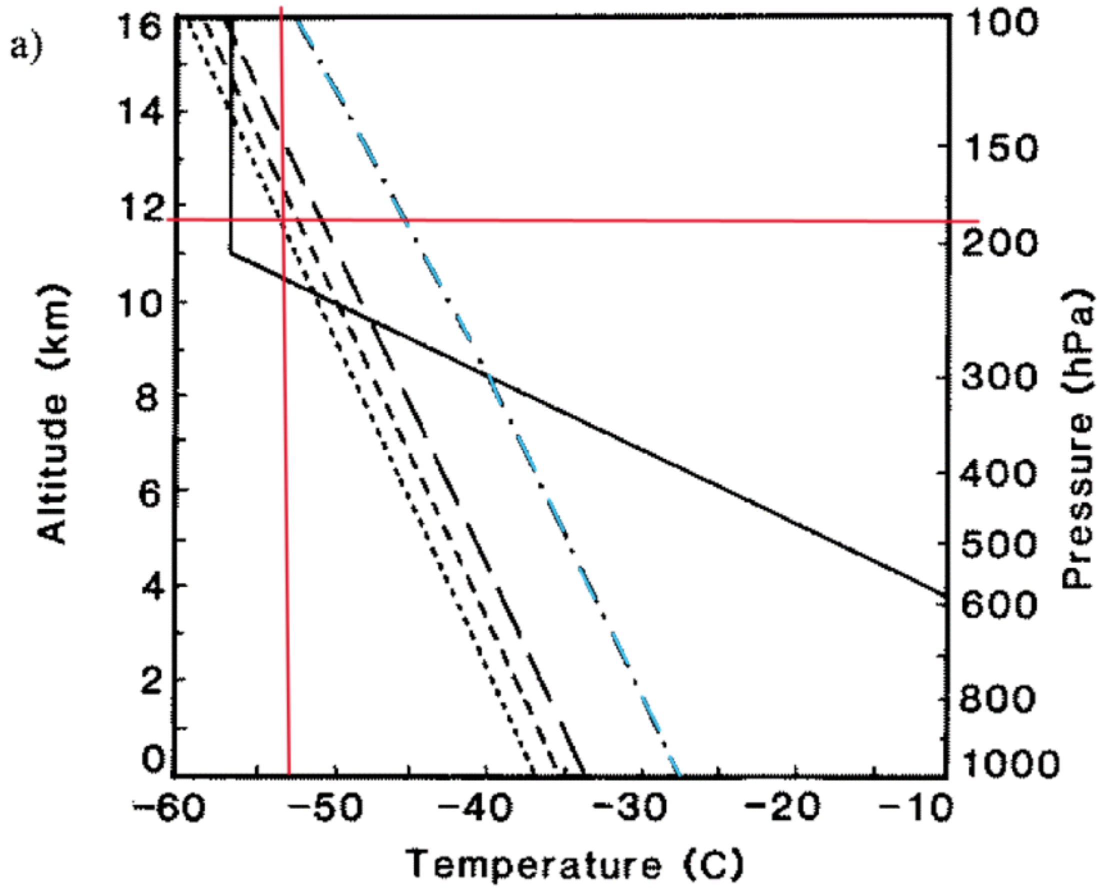
Relative humidity at FL340: 100%
Relative humidity at FL390: 100%

Interpolated relative humidity at FL370: 100% (trivial here).

Aircraft Data

Obtained in the project with: https://flightradar24.com
Free data: https://globe.adsbexchange.com

Evaluation of the Schmidt-Appleman Diagram



The red cross is far left of the blue line (100% relative humidity).

A contrail is expected to form.

Definition of the 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**.

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

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.

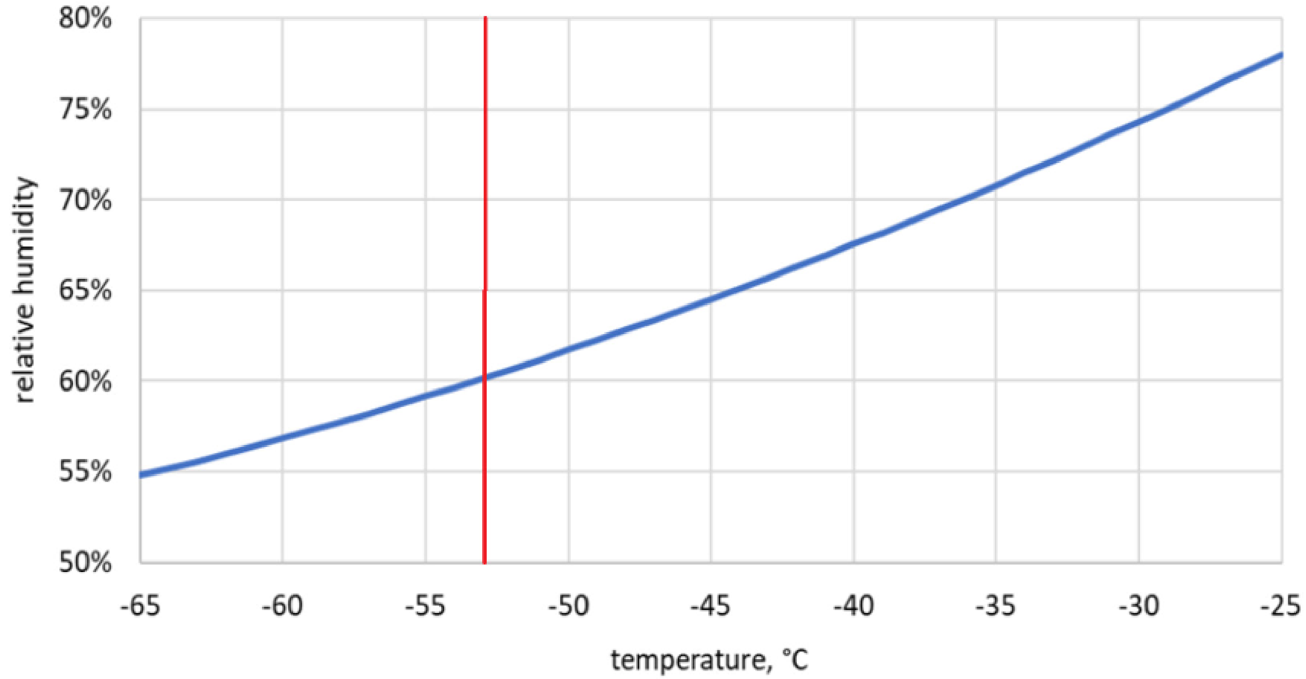
This project starts with this hypothesis:

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

The persistence factor, *R* is the same as the **relative humidity with respect to ice**, RH_i .

RH_i > 100% is called **supersaturation**.

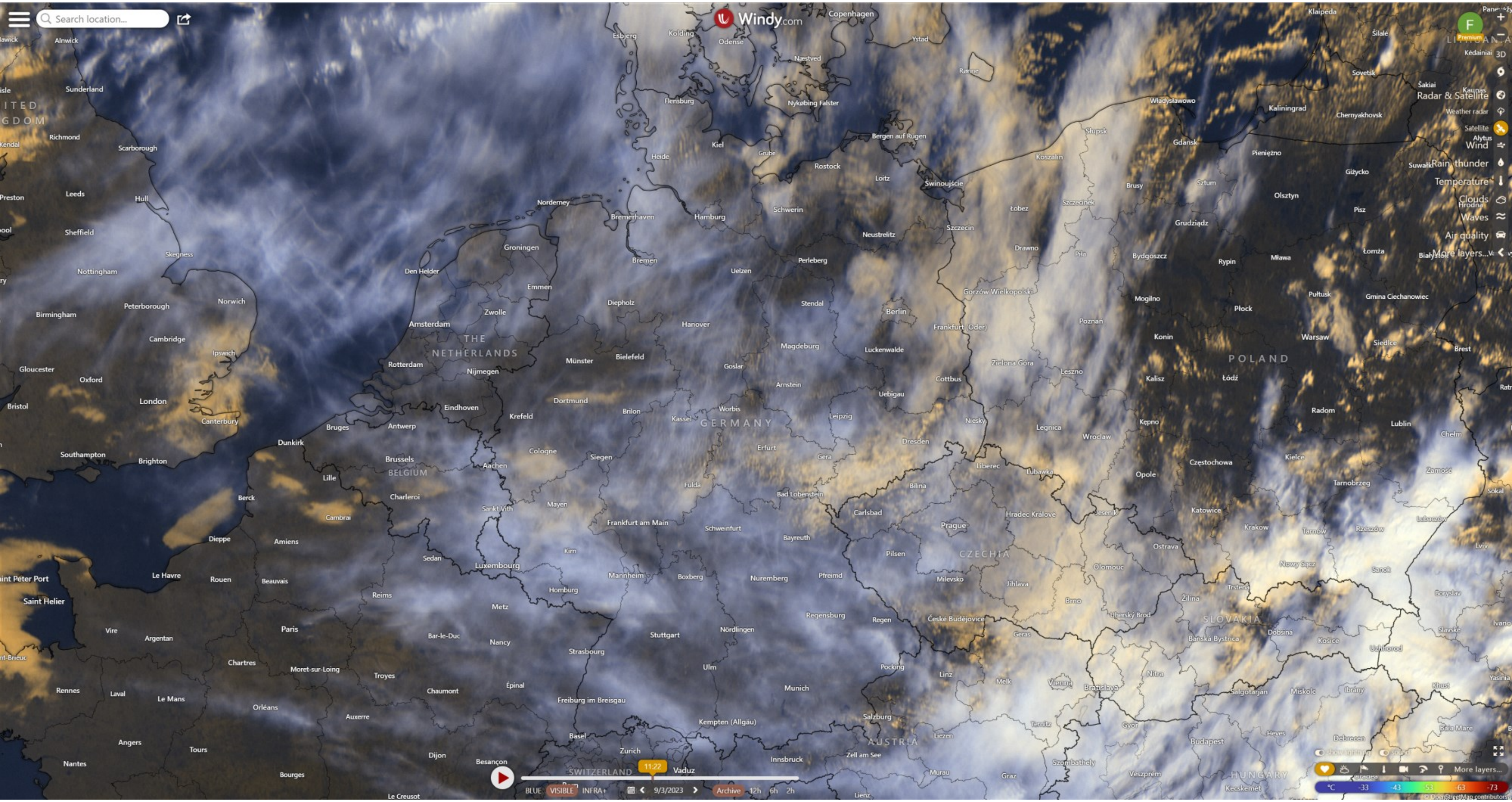
Evaluation of the Schmidt-Appleman Criterion



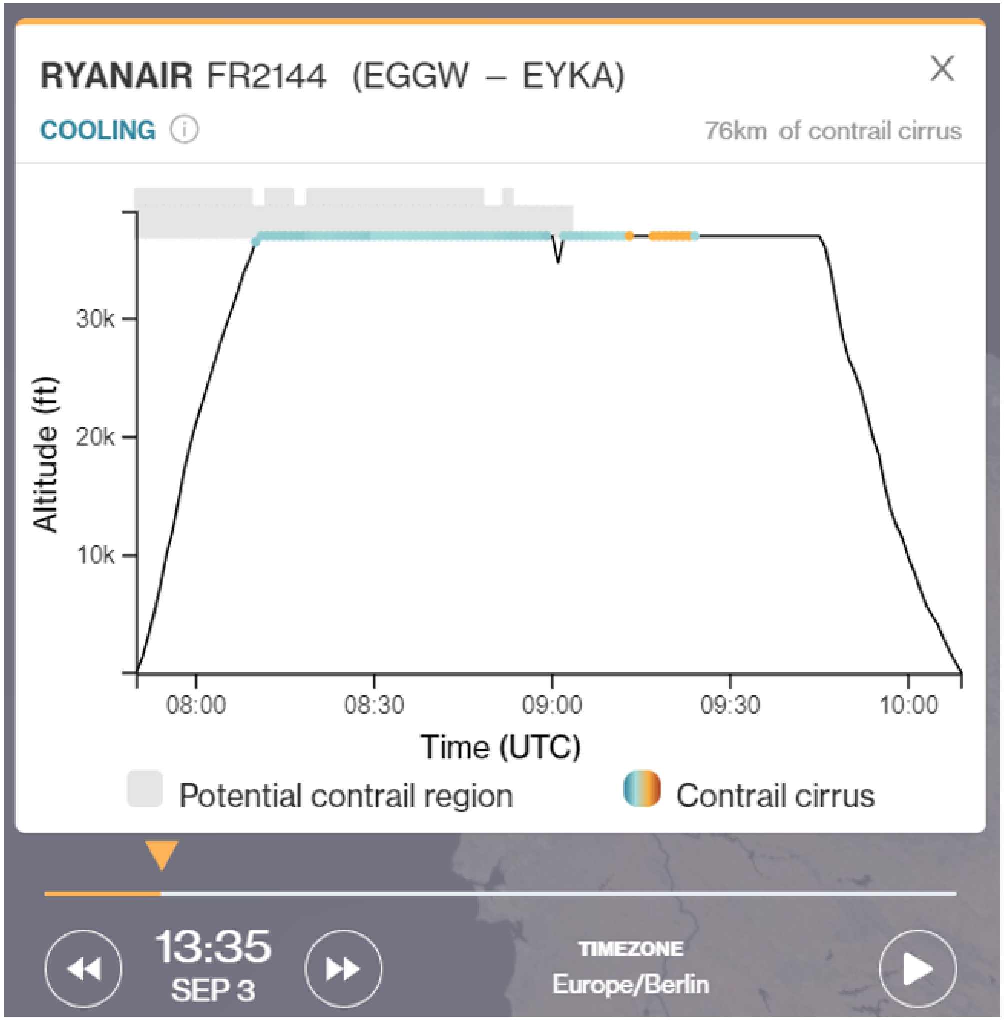
Minimum relative humidity for given temperature for persistent contrails to form.
If above the blue line persistent contrails are expected to form. Here
***R* = 100% / 60.2% = 1.66 => persistent contrail (survival longer than 5 min.)**

Weather Observation, Satellite Image

https://windy.com



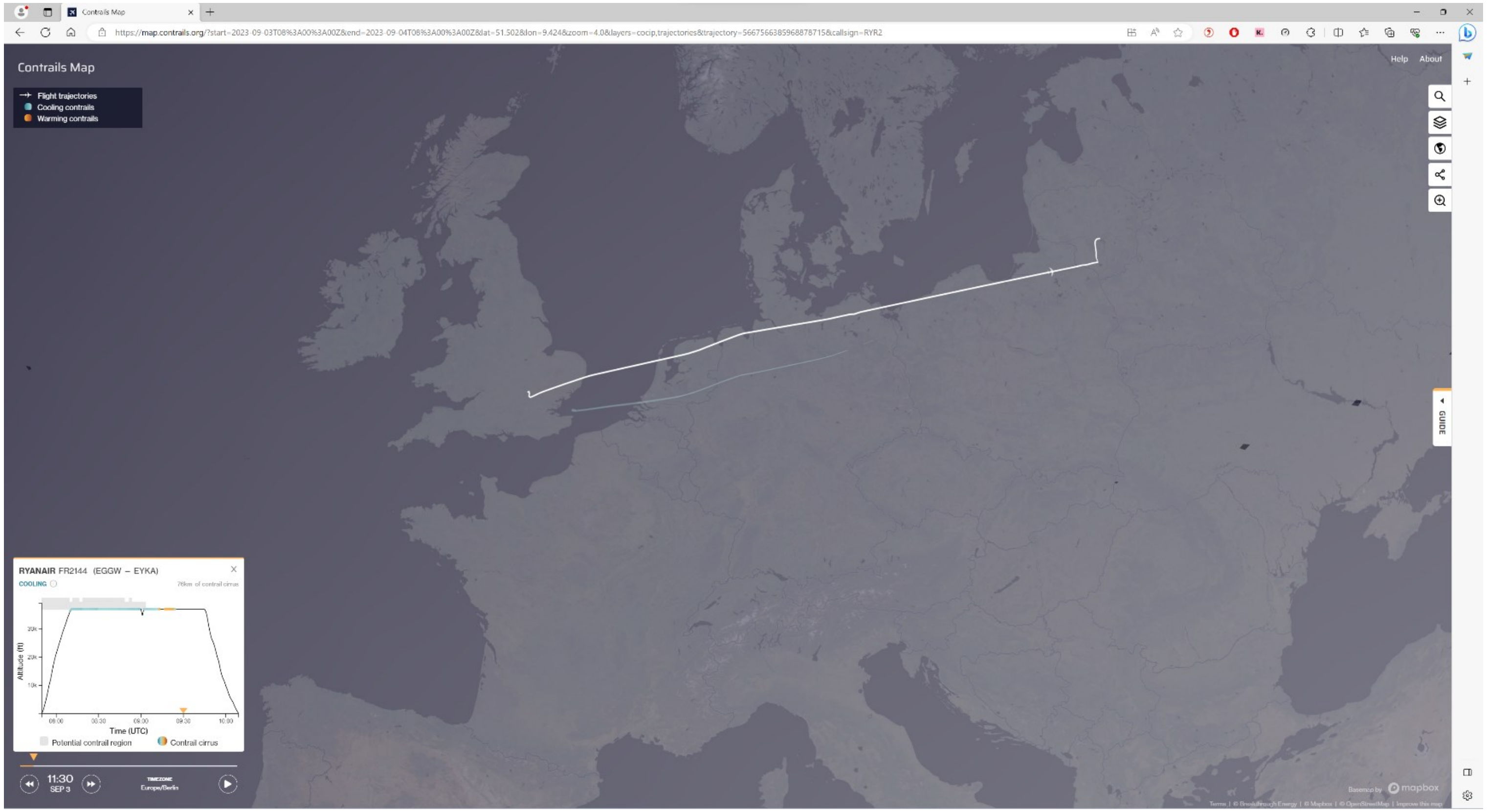
The Flight on contrails.org



AT 10:53 (08:53 UTC), the flight is passing just at the lower edge of a region with Potential Contrail Coverage (PCC).

At this time of the day (daytime) and the sky only partially covered with clouds, the **contrail is cooling**.

The Flight on contrails.org

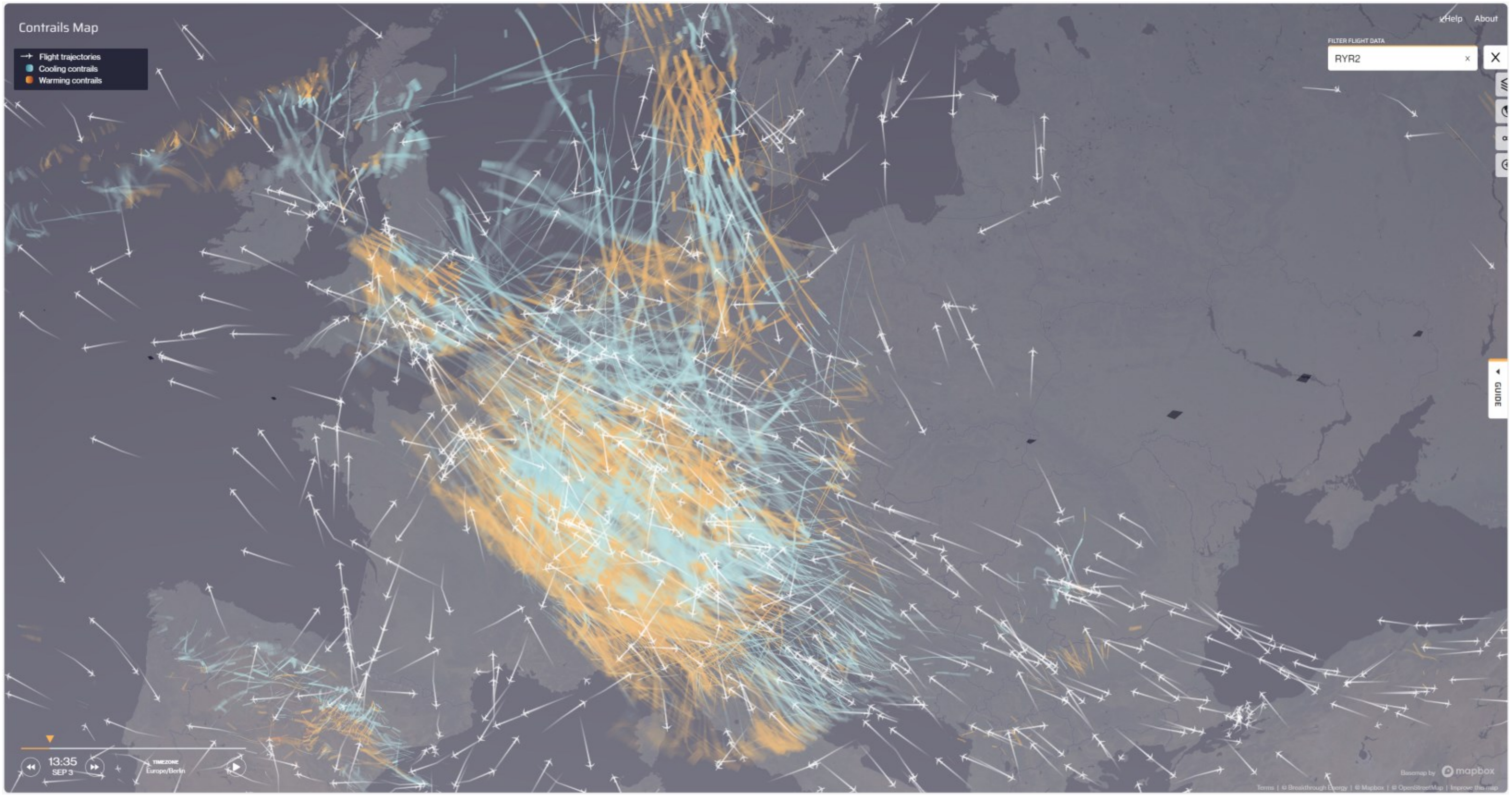


09:30 UTC: In a wind from the north (356°, 108 kt) the cooling contrail (blue) is drifting to the south.

The Flight on contrails.org

11:35 UTC: The contrail has drifted further south.

All Flights on contrails.org at 2023-09-03



11:35 UTC: All flights covered by contrails.org at this day and time. Some contrails are warming, some are cooling.

Observation & Prediction – Summary of 6 Flight

Prediction and Observation of Contrails

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

(orange)	Wrong categorization due to Geometrical Altitude (GPS Altitude) instead of Barometric Altitud
(green)	Correct categorization with Barometric Altitude.

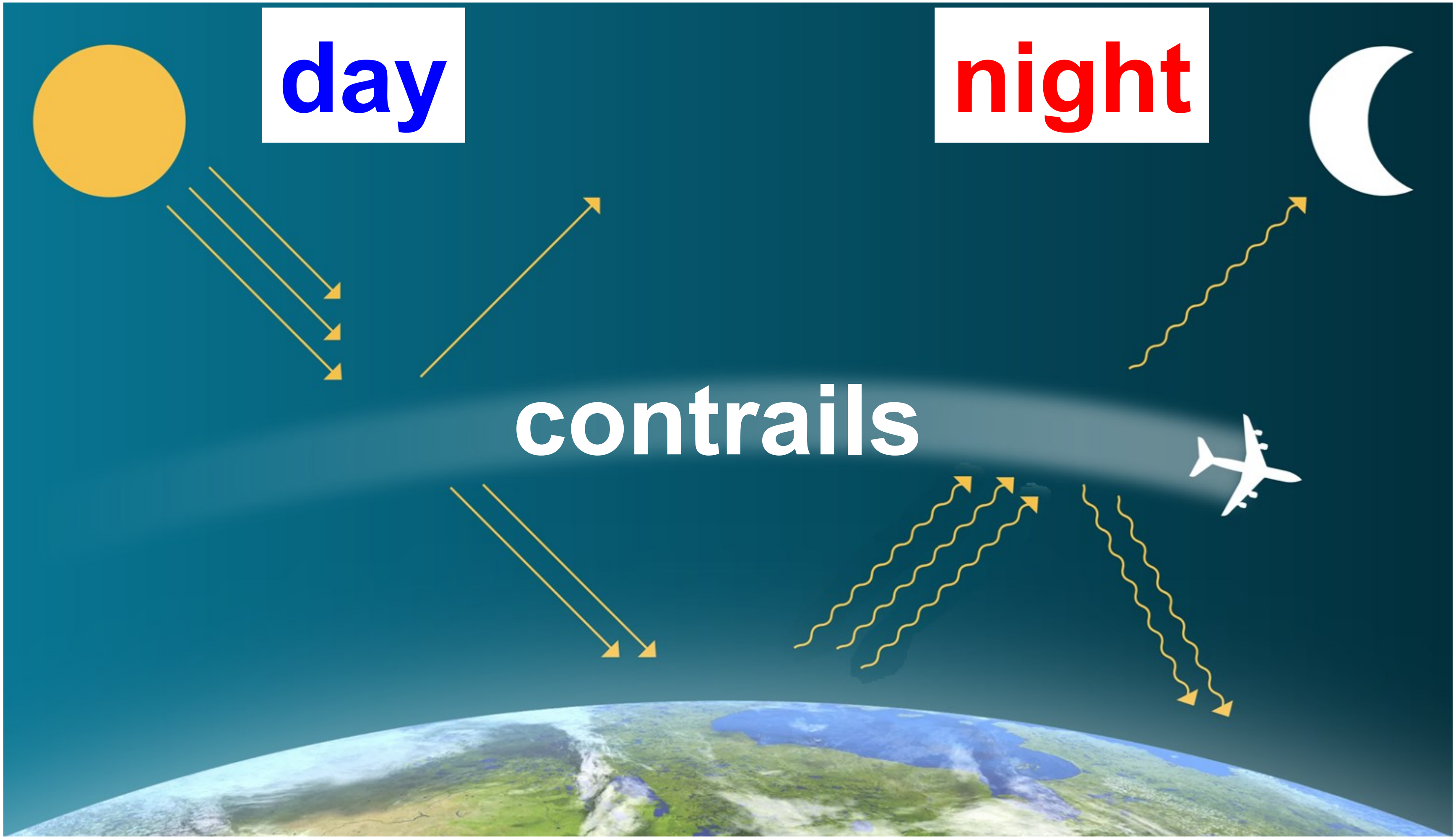
Definition

	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

All 6 flight were classified correctly based on the Persistence Factor, *R*

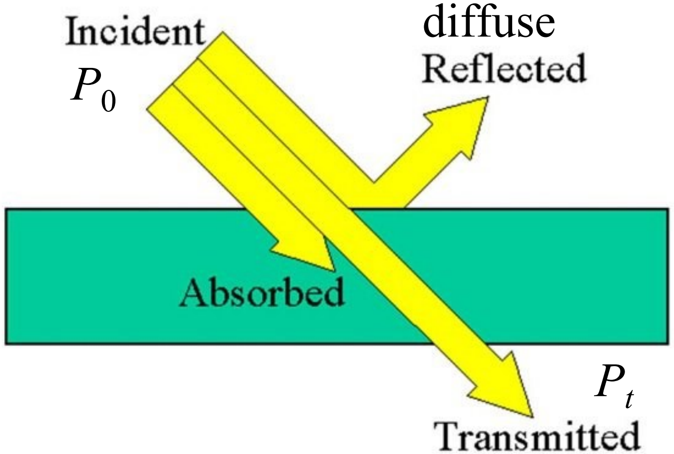
Contrail
Avoidance

Cooling (Day) versus Warming (Night) Contrails



Radiation & Clouds

https://www.quora.com/What-is-the-difference-between-transmitted-light-and-reflected-light



$$T = \frac{P_t}{P_0} \qquad A = \frac{P_a}{P_0} \qquad R = \frac{P_r}{P_0}$$

transmittance, *T*
absorption, *A*
remission, *R*
(diffuse reflection, scatter)
extinction, *E*

$$T + A + R = 1$$

$$E = A + R$$

$$T = 1 - E$$

$$T = \frac{P_t}{P_0} = e^{-\tau}$$

P_t and P_0 in W/m²

$$\tau = \int_0^l a(x)\mathrm{d}x$$

optical depth, τ

$$\tau = a \cdot l$$

length, *l*

$$a = C \cdot \sigma$$

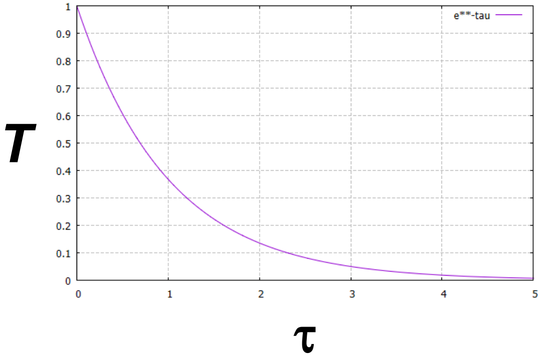
attenuation or extinction coefficient, *a* in 1/m

$$C = \frac{n}{V}$$

number density, *C* in 1/m³

$$\sigma$$

cross section, σ in m²



Radiation & Clouds

$$T = \frac{P_t}{P_0} = e^{-\tau}$$

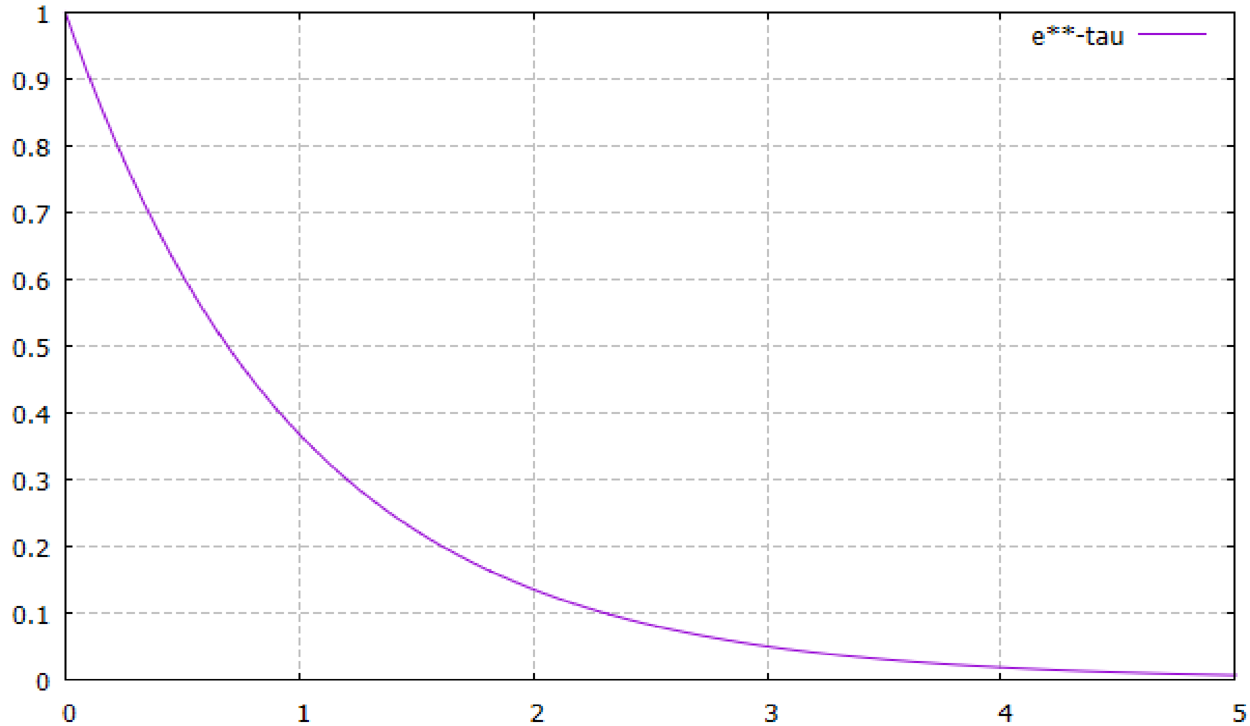
$$\tau = a \cdot l$$

$$a = C \cdot \sigma$$

length, *l*

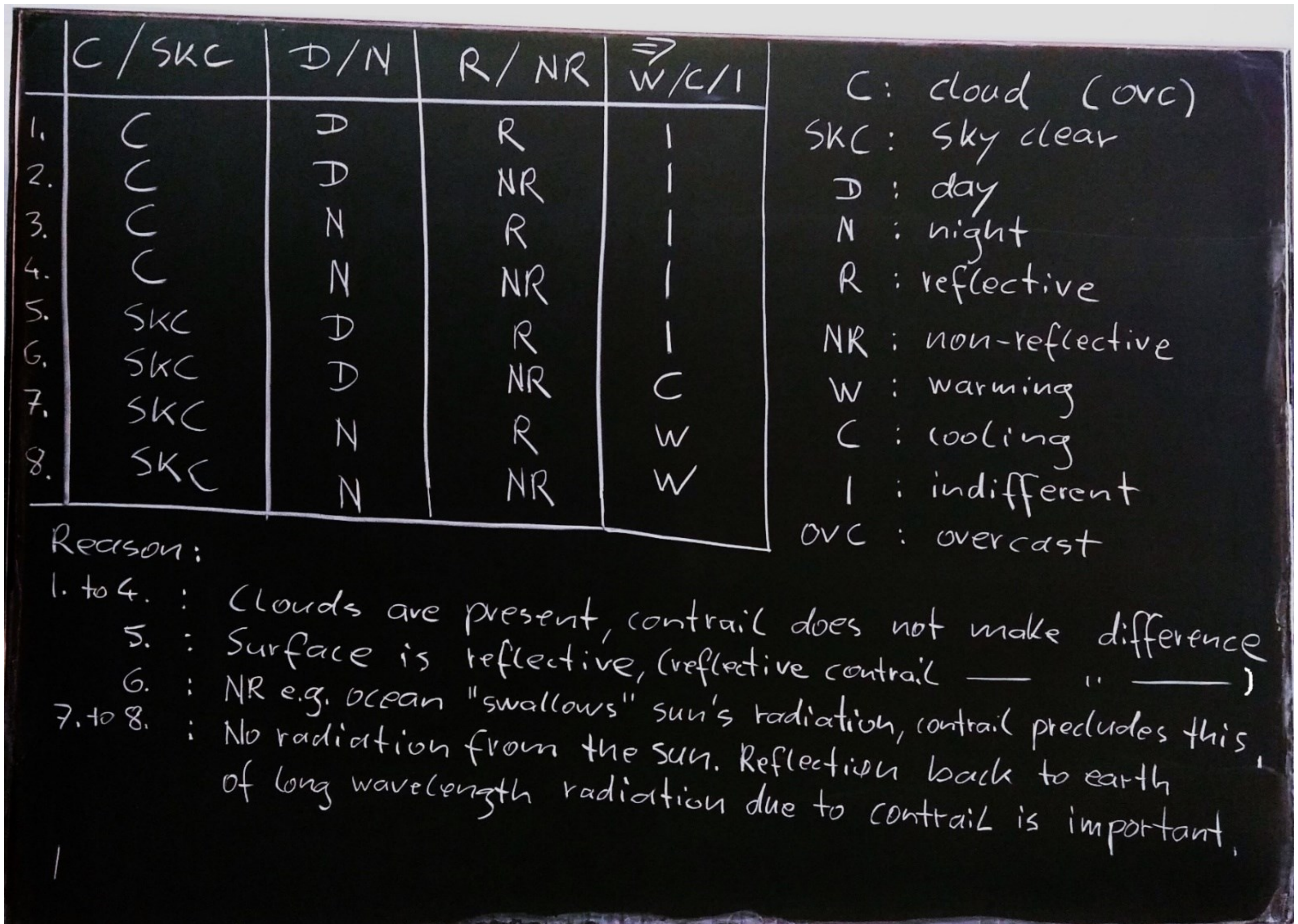
attenuation or extinction coefficient, *a* in 1/m

T

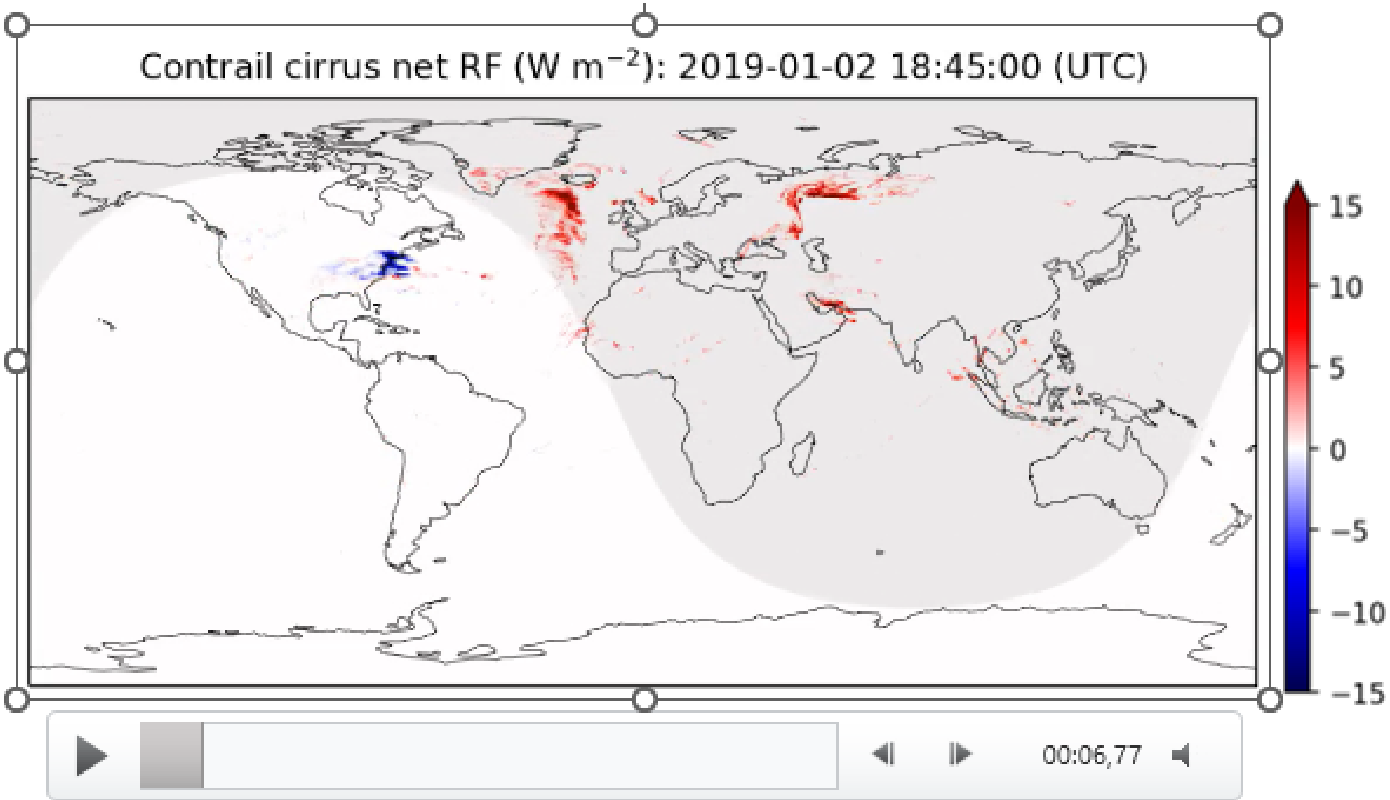


τ ≈ *l* (length through cloud)

Systematic of Cooling and Warming Contrails



Prediction of Regions with Contrails and Their Energy Forcing



One moment in time from a video showing radiative forcing, RF of contrails in W/m². During the night, all contrails are warming. During the day, some contrails are cooling.

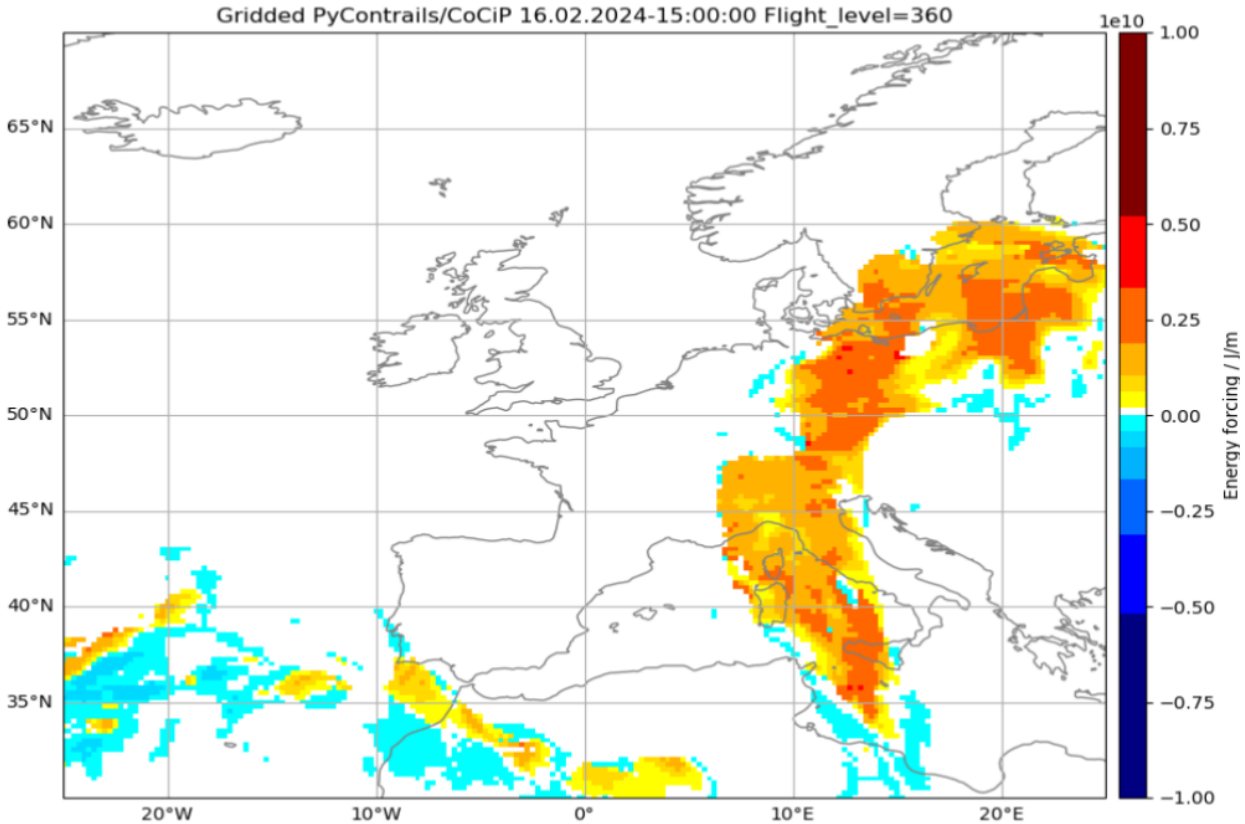
Teoh, Stettler, Imperial College; Shapiro, Breakthrough Energies; Schumann, Voigt, DLR

https://py.contrails.org (open source)

HAW HAMBURG

Prediction of Regions with Contrails and Their Energy Forcing

16.2.2024, FL 360, hourly prediction



One moment in time from a video showing the development of energy forcing of contrails in J/m.

Kirschler, DLR

Contrail
Management

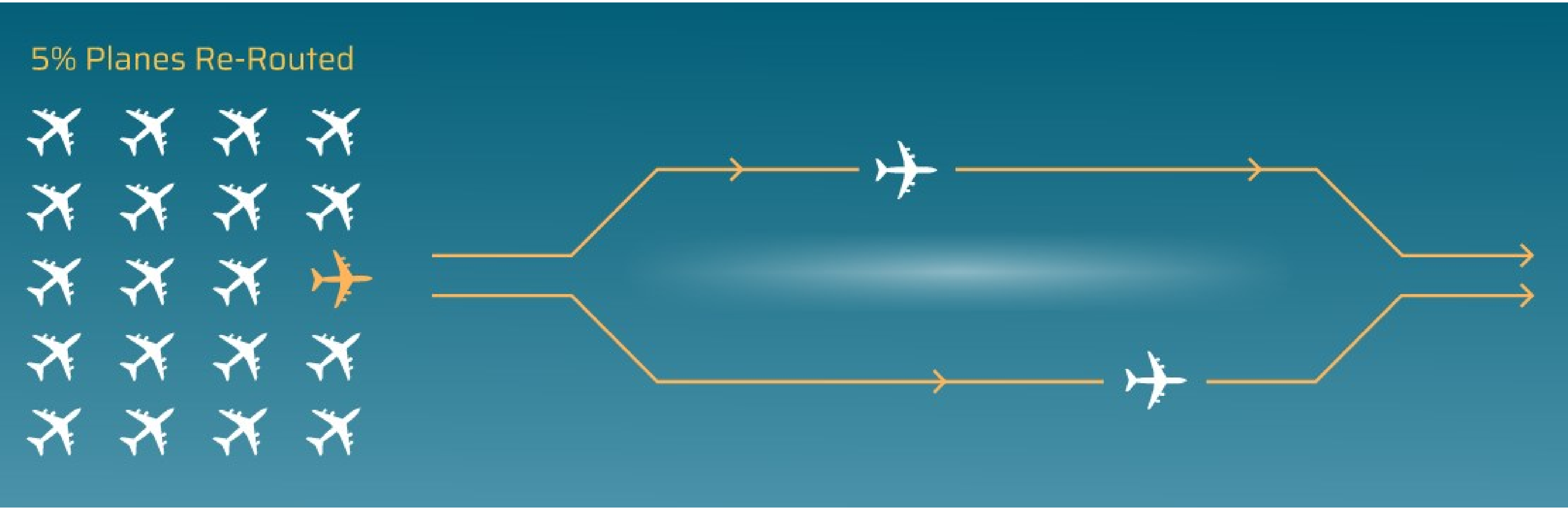
https://contrails.org

Re-route 5% of flights

...avoid 80% of warming

5%	Number of planes slightly redirected to avoid making most harmful contrails
80%	Portion of contrail climate warming avoided by re-routing 5% of planes
<$0.5	Average cost of avoiding warming equivalent to one tonne of CO_2
Days	Time it takes to get the full cooling effect of avoiding contrails

https://contrails.org/science



The best available data indicates a kind of “super-Pareto principle” at play, where tweaking only a few flight paths would eliminate almost all of contrails-induced warming. In practice, this means that just 1 in 20 flights would need to fly over, under, or around areas of the sky predicted to produce harmful contrails.

Better yet properly implemented, these adjustments would be cheap: Our studies show a fleet-average cost of roughly $5.00 per flight, or less than $0.50 per tonne of CO2 equivalent warming avoided.

https://map.contrails.org

See How It Works

Explore the contrail map

Our contrail map shows you how contrail-induced cirrus clouds are warming the planet. Learn whether your recent flight created harmful contrails, see how small changes to flight paths can prevent contrails, and more.

START EXPLORING »

https://map.contrails.org

An Initiative of:

Bill Gates
FOUNDER, BREAKTHROUGH ENERGY

Breakthrough Energy

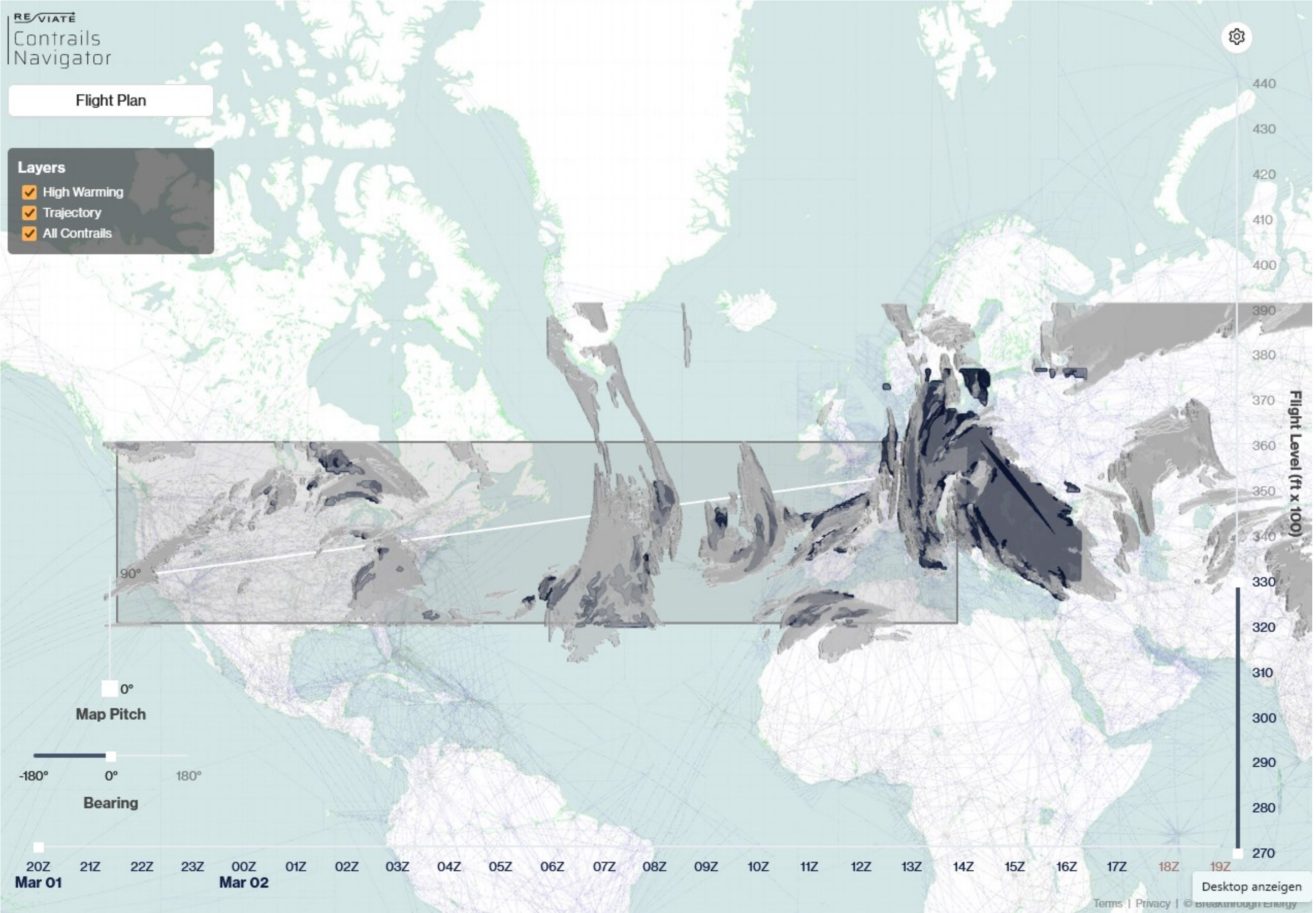
REVIATE
BY BREAKTHROUGH ENERGY

https://contrails.org
https://www.breakthroughenergy.org

Our Mission

Our mission is to **accelerate the transition of contrail research into actionable climate solutions.**

Flight Planning with https://forecast.contrails.org



Here:

All contrails are shown in FL270 to FL330.

Free on request.

Flight Planning with https://forecast.contrails.org

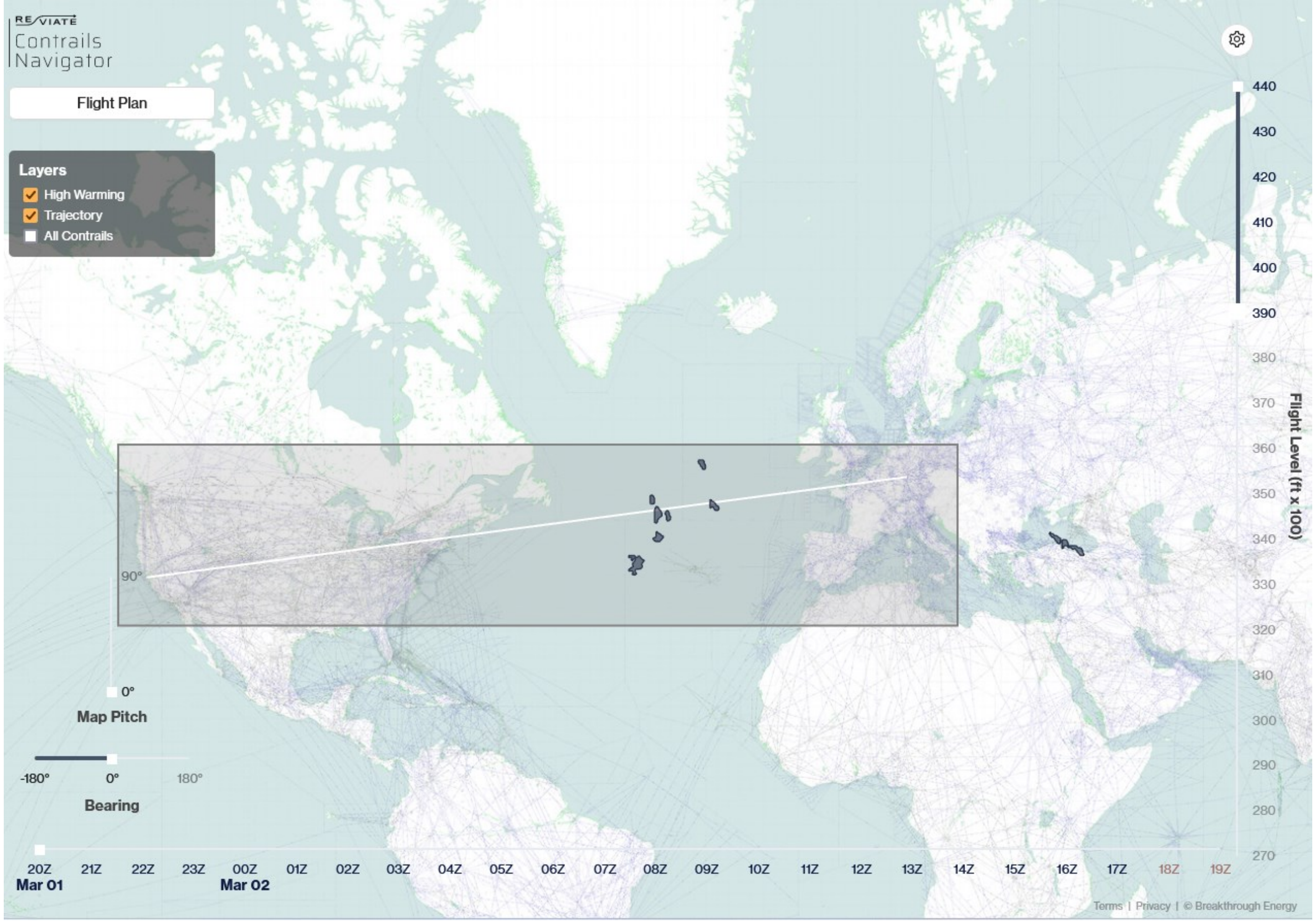
Here:
Only highly warming contrails are shown in FL270 to FL440.

Flight Planning with https://forecast.contrails.org

Here:

Only highly warming contrails are shown in FL330 to FL440.

Flight Planning with https://forecast.contrails.org

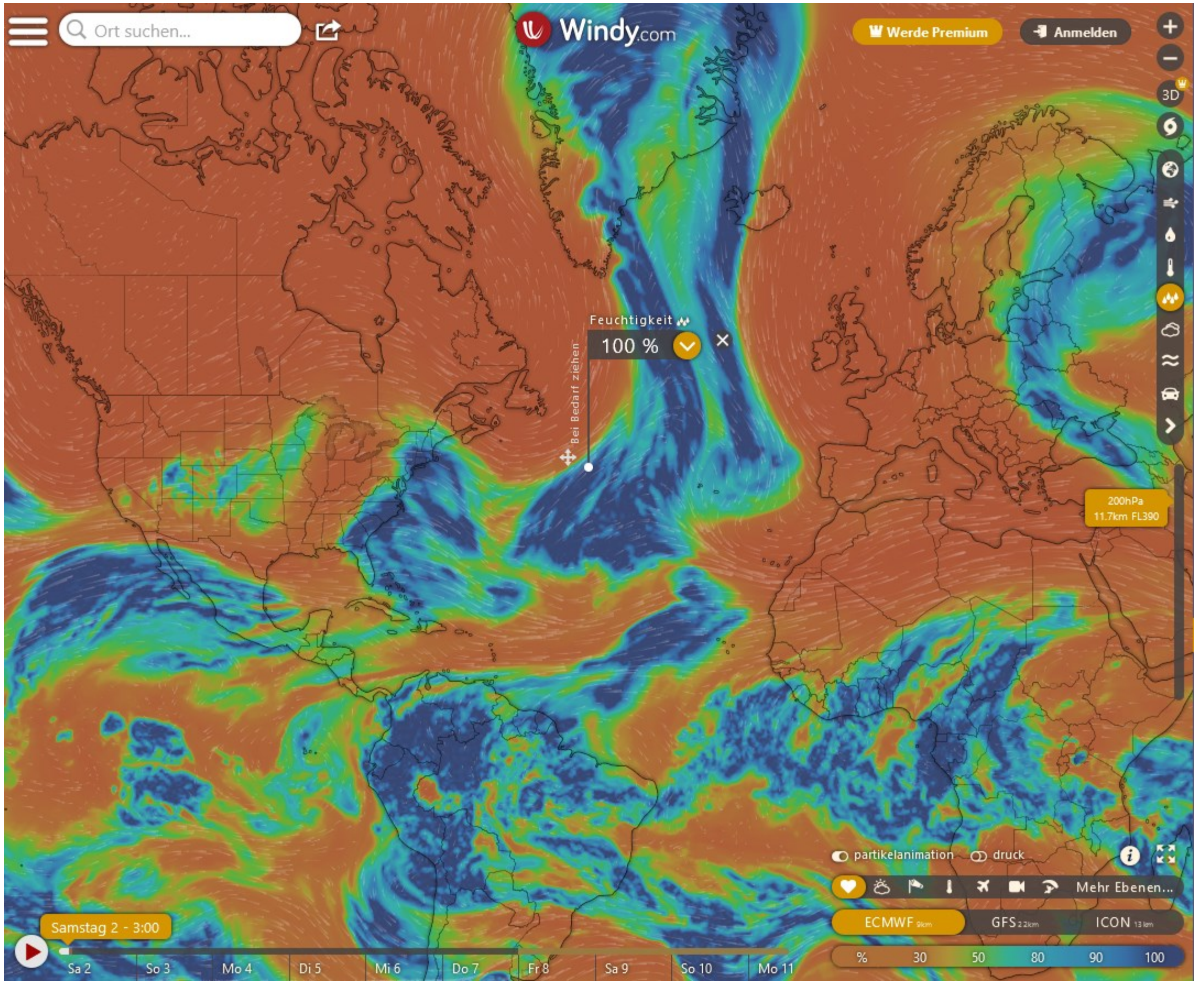


Here:

Only highly warming contrails are shown in FL390 to FL440.

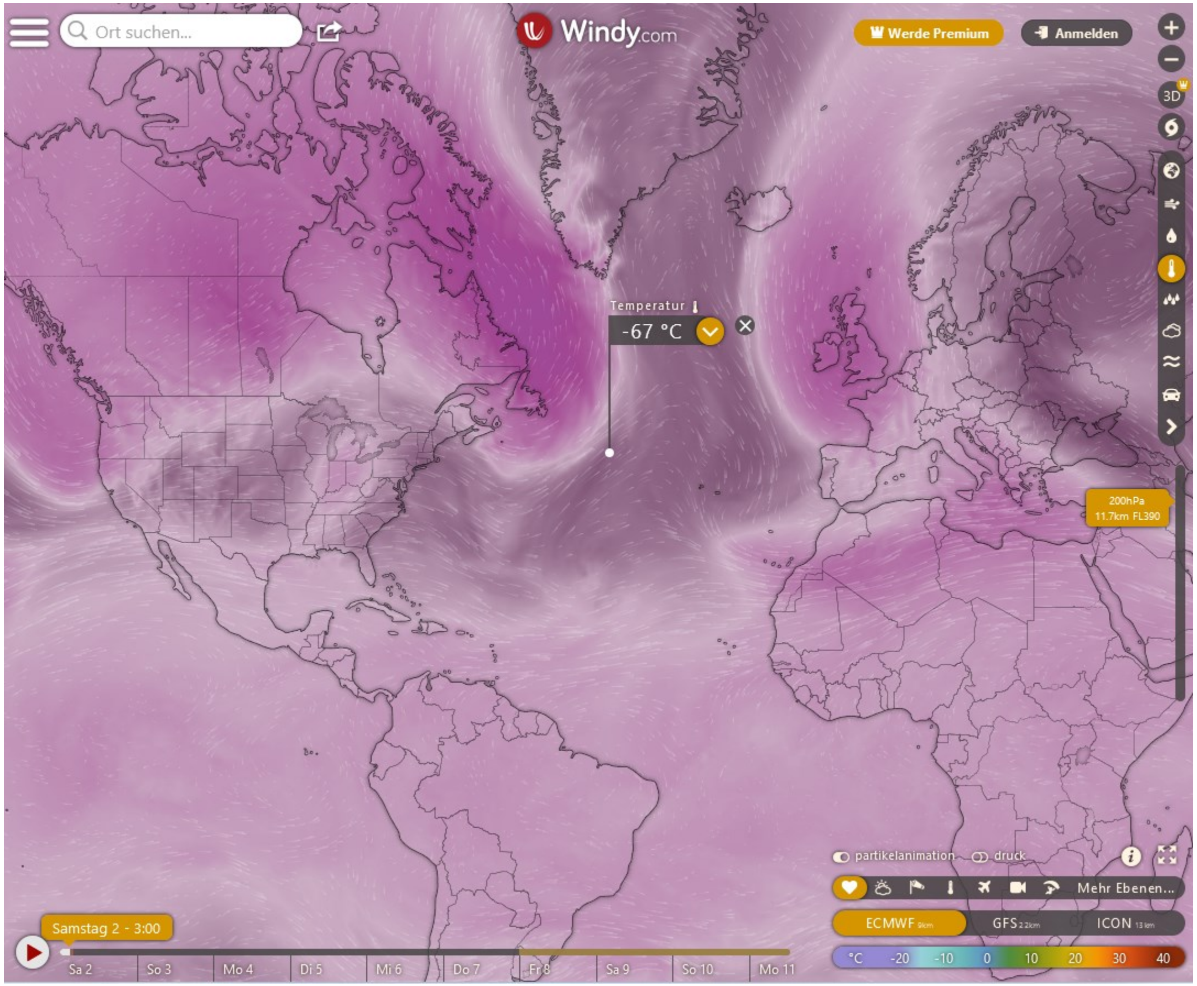
A business jet using these high flight levels would not need to be rerouted for contrail avoidance.

Flight Planning with https://www.windy.com



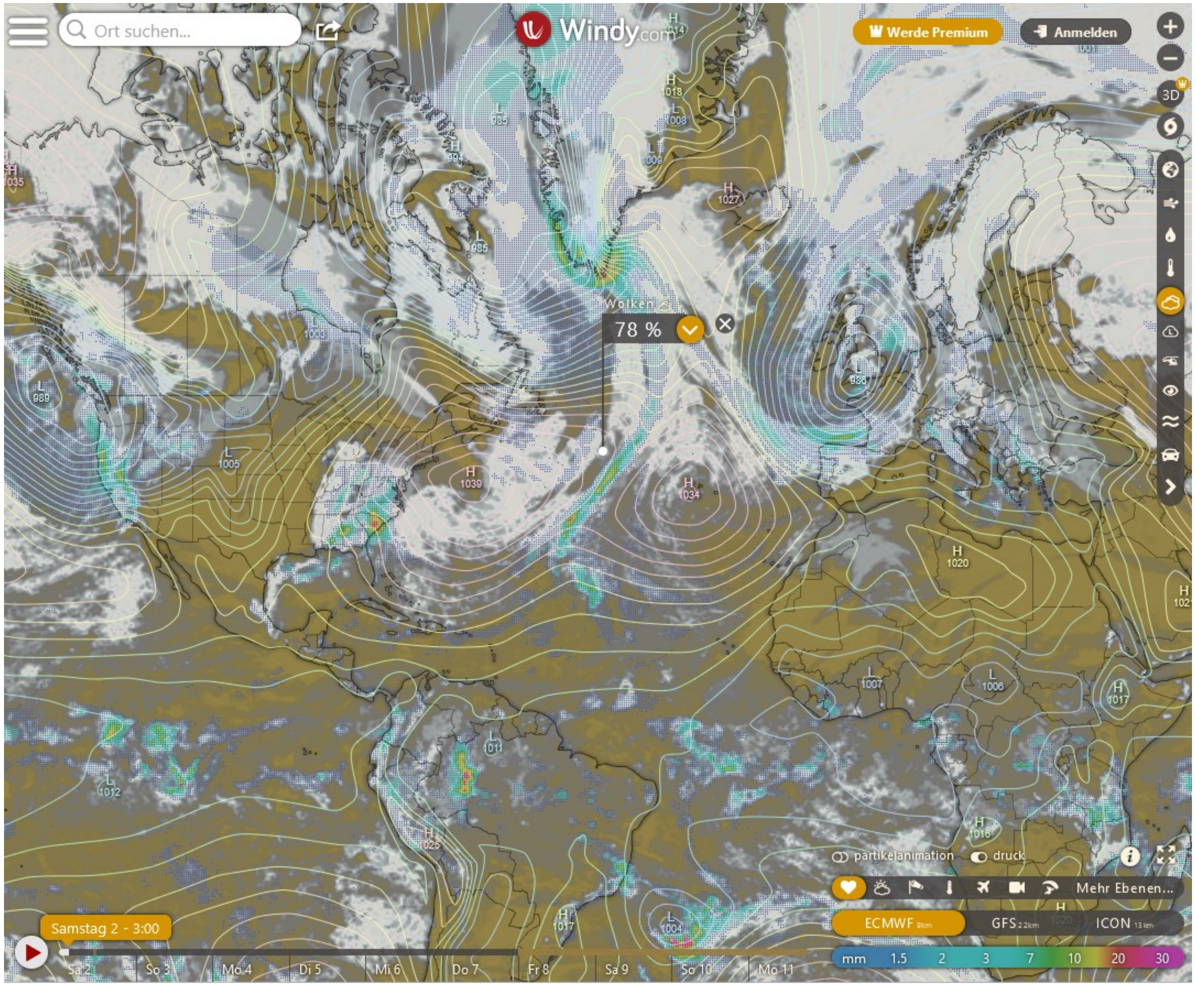
Relative humidity. Data from ECMWF and 7 other weather models. Forecast 5 days ahead. Vertical resolution is rather course: FL 100, 140, 180, 240, 300, 340, 390, and 450.

Flight Planning with https://www.windy.com



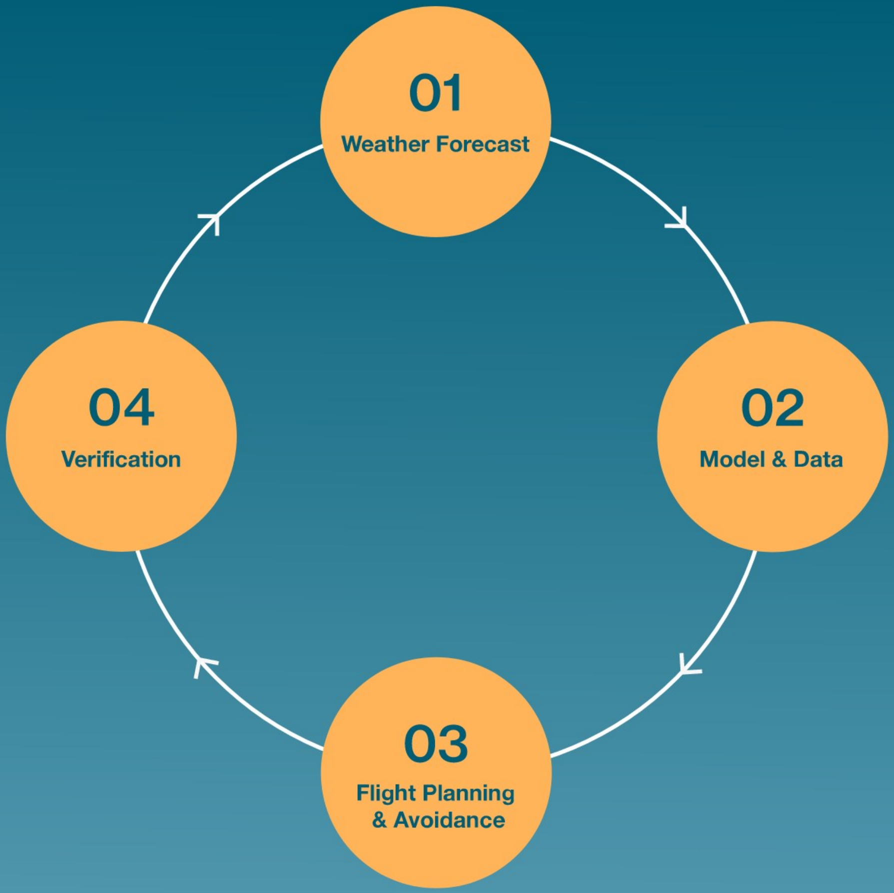
Temperature. Data from ECMWF and 5 other weather models. Forecast 5 days ahead. Vertical resolution is rather course: FL 100, 140, 180, 240, 300, 340, 390, and 450.

Flight Planning with https://www.windy.com



Clouds. Data from ECMWF and 7 other weather models. Forecast 5 days ahead. No vertical information. Cloud cover from brown (0%), via grey to white (100%). Precipitation (dots) from blue to purple according to scale.

https://contrails.org



- **Forecast Input**
  Weather forecasts, satellite images, flight locations, and other data are fed into contrail forecast models
- **Modeling**
  Models determine where harmful contrails are likely to occur and compare these predictions with observations
- **Flight Planning**
  Flight planners calculate the fastest route with the lowest fuel consumption accounting for contrail impact in their flight plan
- **Verification**
  Ground-, air-, and satellite observations verify contrail avoidance and feed back into forecasting models to improve accuracy

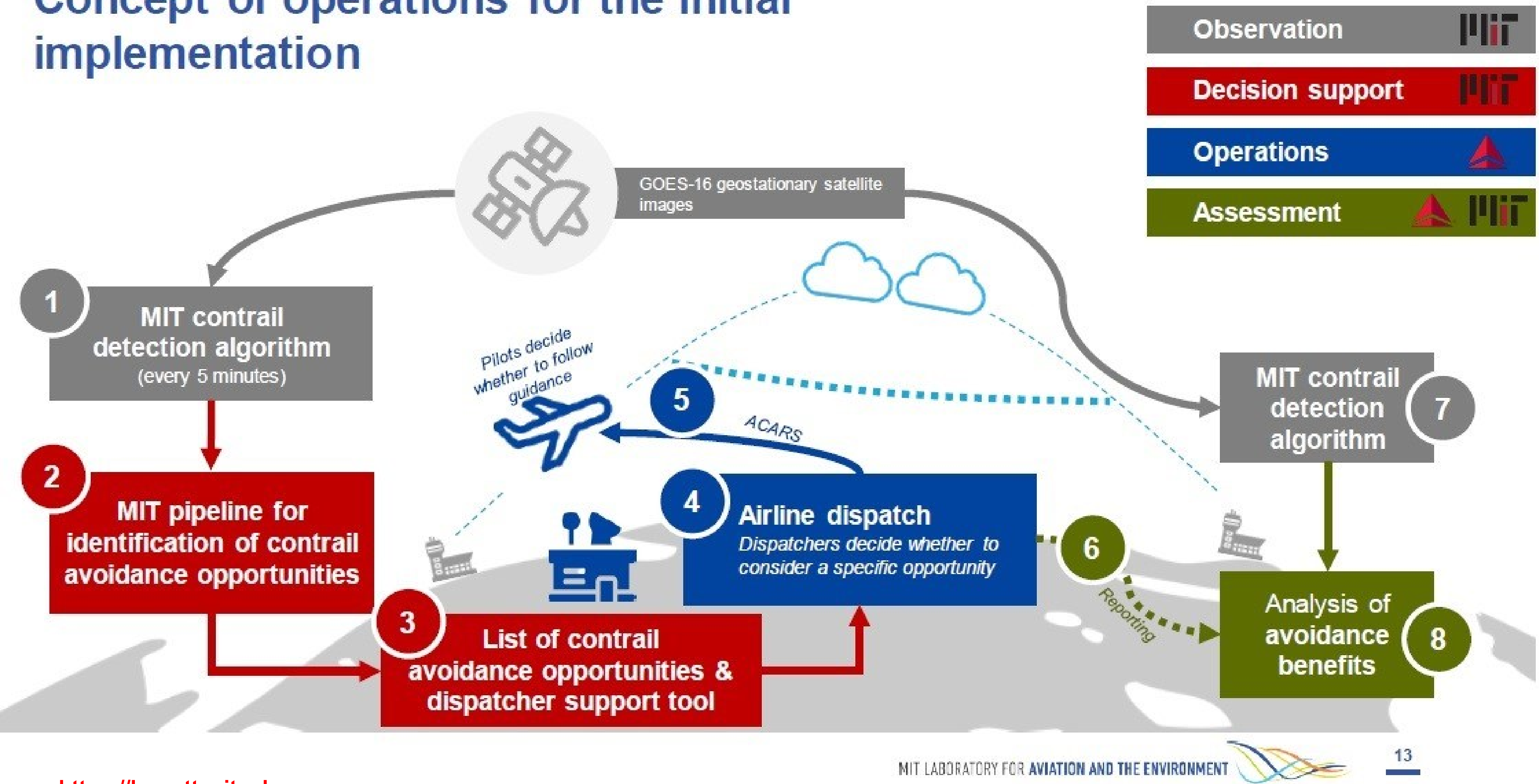
Tactical versus Strategic Contrail Avoidance

Tactical avoidance		Strategic avoidance
Adjust flight trajectory en-route to avoid contrails as they are observed	*Long-term vision:* **Convergence of concepts:**	Flight trajectories are planned to avoid expected contrails along the route
Based on contrail "nowcast"	• Strategic elements to support fuel burn planning	Based on contrail forecast
• Issue real-time guidance • Restrict avoidance to maneuvers within fuel burn limits • ATC responsiveness	• Tactical elements to maximize precision of guidance	• Reliable forecast of PCC regions • Minimal deviation flightplan vs. flown trajectory • ATC clearance

https://barrett.mit.edu
https://lae.mit.edu
https://www.eurocontrol.int/sites/default/files/2023-12/2023-11-07-contrails-conference-session-003-barrett-observational-contrail-avoidance.pdf
https://www.eurocontrol.int/event/sustainable-skies-conference-contrails-focus

MIT LABORATORY FOR AVIATION AND THE ENVIRONMENT

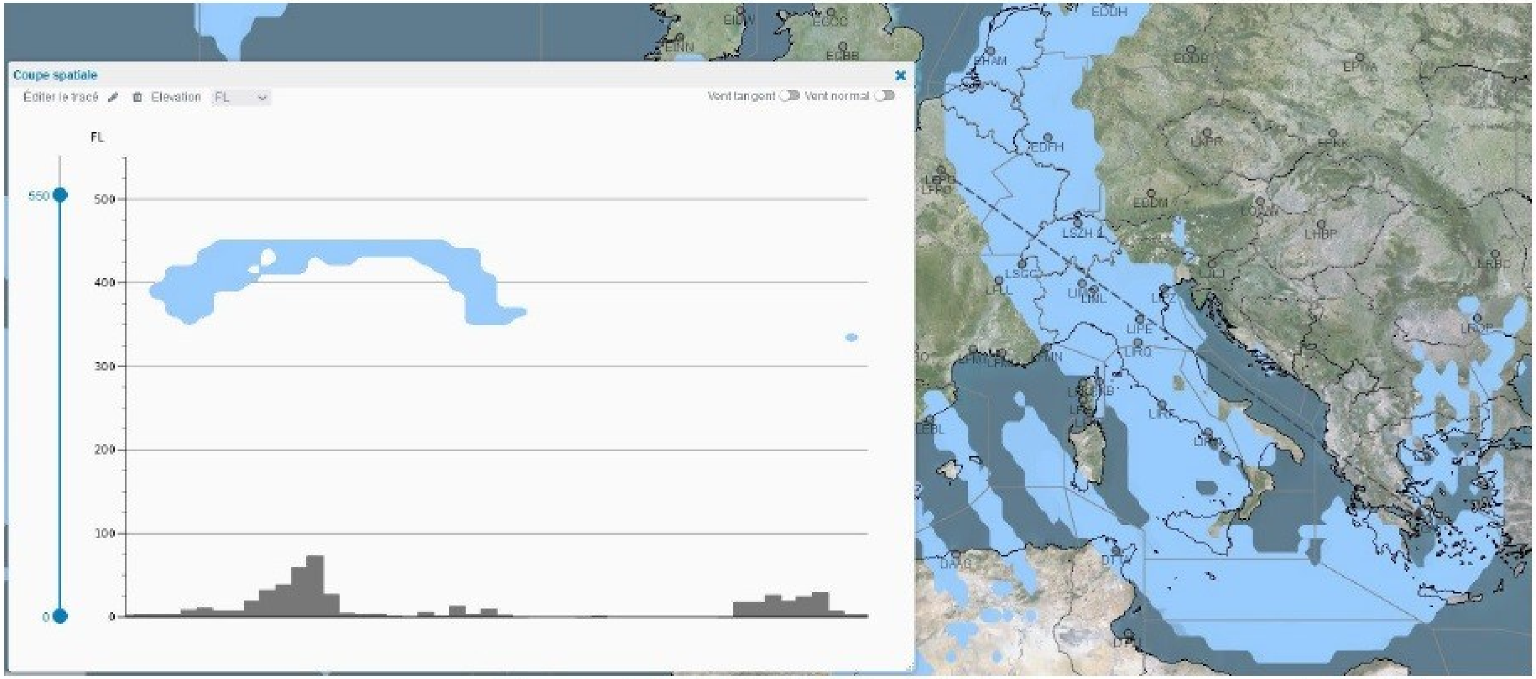
Concept of operations for the initial implementation



https://barrett.mit.edu
https://lae.mit.edu
https://www.eurocontrol.int/sites/default/files/2023-12/2023-11-07-contrails-conference-session-003-barrett-observational-contrail-avoidance.pdf

Meteo France: Cross Section along Flight with ISSR (Blue)

WIMCOT - Demonstration



Forecast for 04/09/2023 at 10UTC
From 03/09/2023 12UTC
Cross section from Paris to Athens

Risk area

RÉPUBLIQUE FRANÇAISE

METEO FRANCE

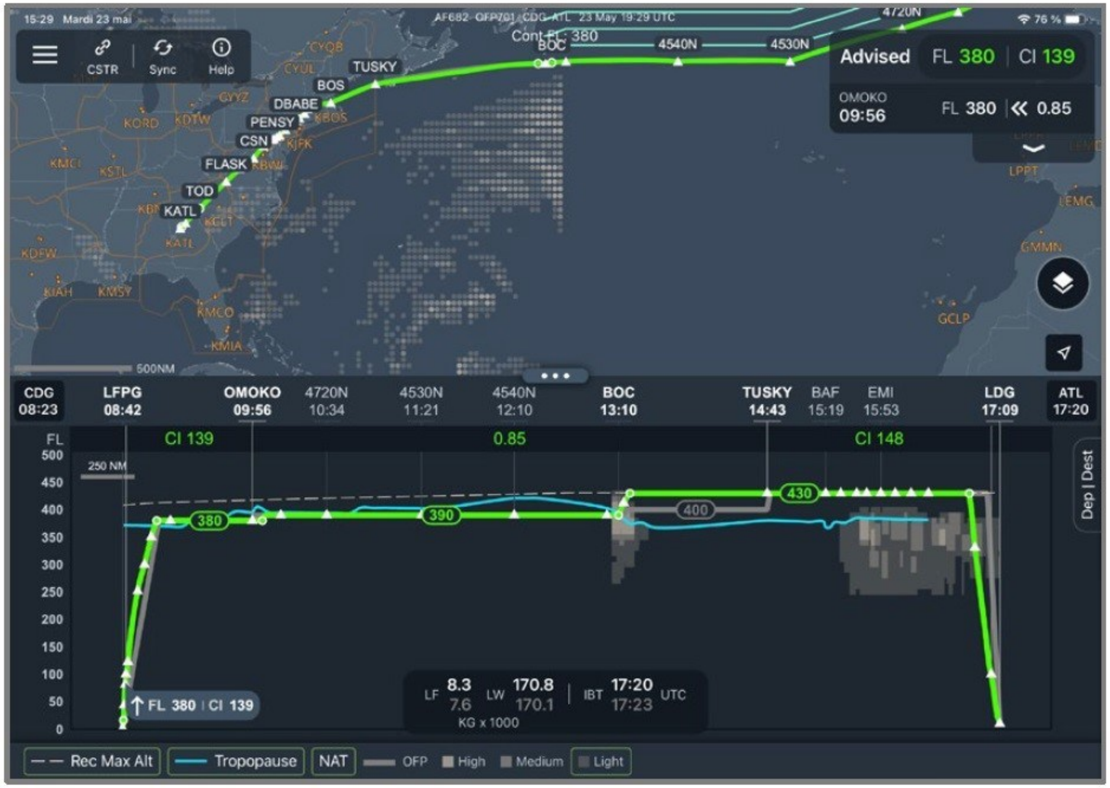
This is only a demo for research.

https://www.eurocontrol.int/sites/default/files/2023-11/2023-11-07-contrails-conference-session-004-curat-pechaut-prediction-contrail-formation-observation-process.pdf

Pace, Germany

https://pace.txtgroup.com

SHARE CONTRAILS RISK AREAS WITH PILOTS

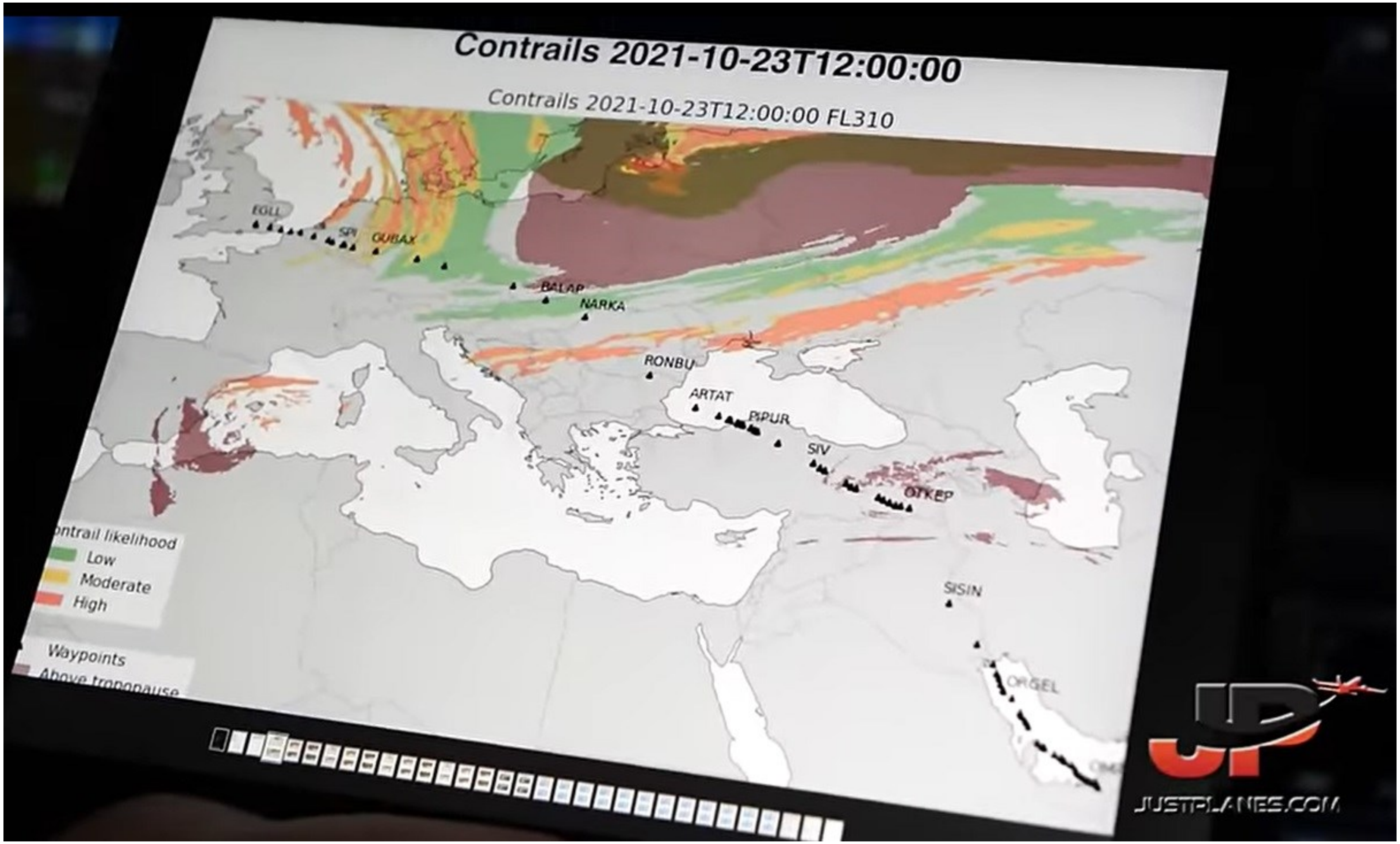


This is only a demo for research.

Pacelab FPO•SR combines lateral optimization capabilities with vertical flight profile optimization. Integration of weather (wind, turbulence) and ATC restrictions. Collaborative crew-dispatch decision-making. No contrail management. Electronic Flight Bag (EFB) for crew.

SATAVIA, UK and Etihad

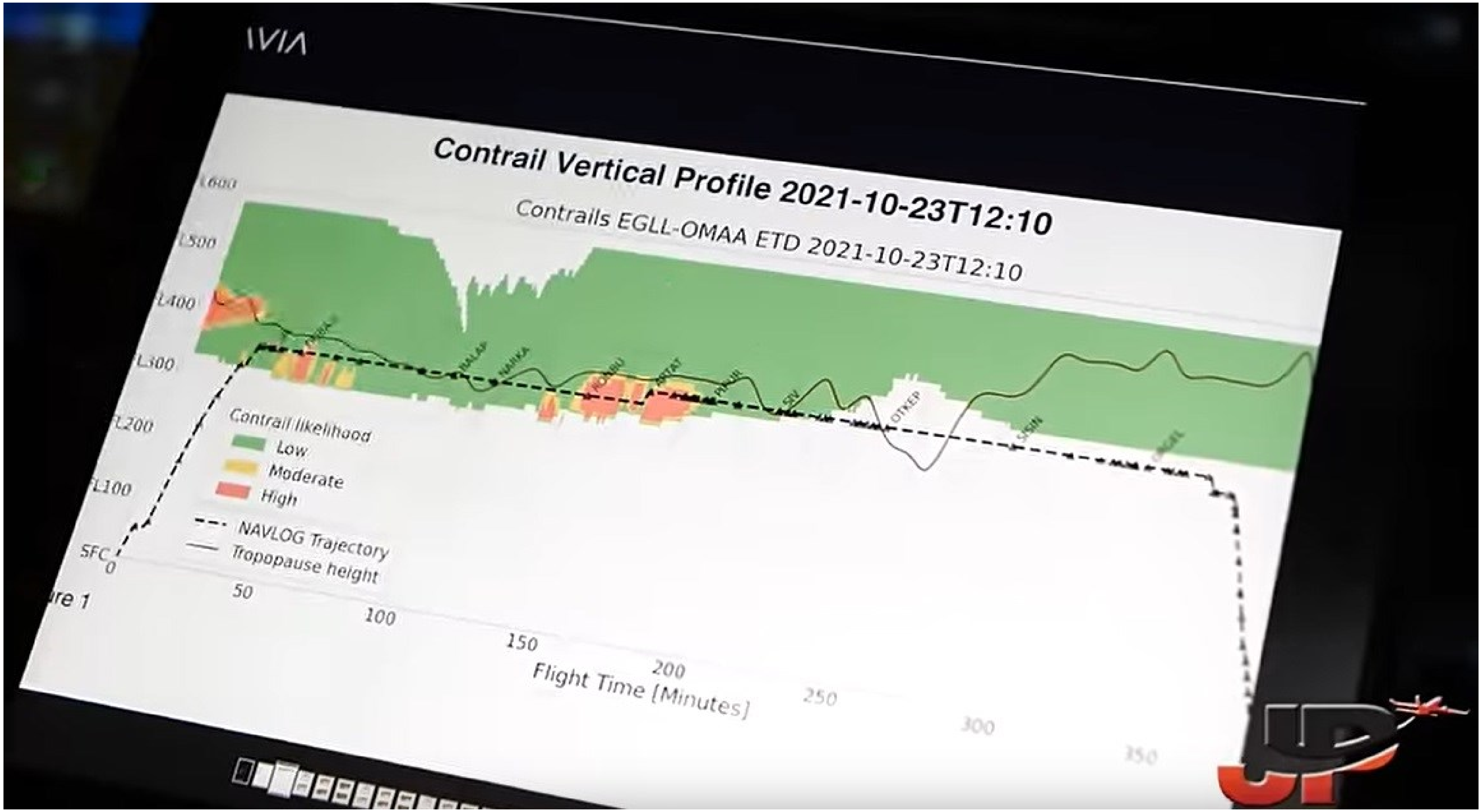
https://satavia.com



https://youtu.be/r5tH2BsyMpE

SATAVIA, UK and Etihad

https://satavia.com



https://youtu.be/r5tH2BsyMpE

SATAVIA, UK

https://satavia.com

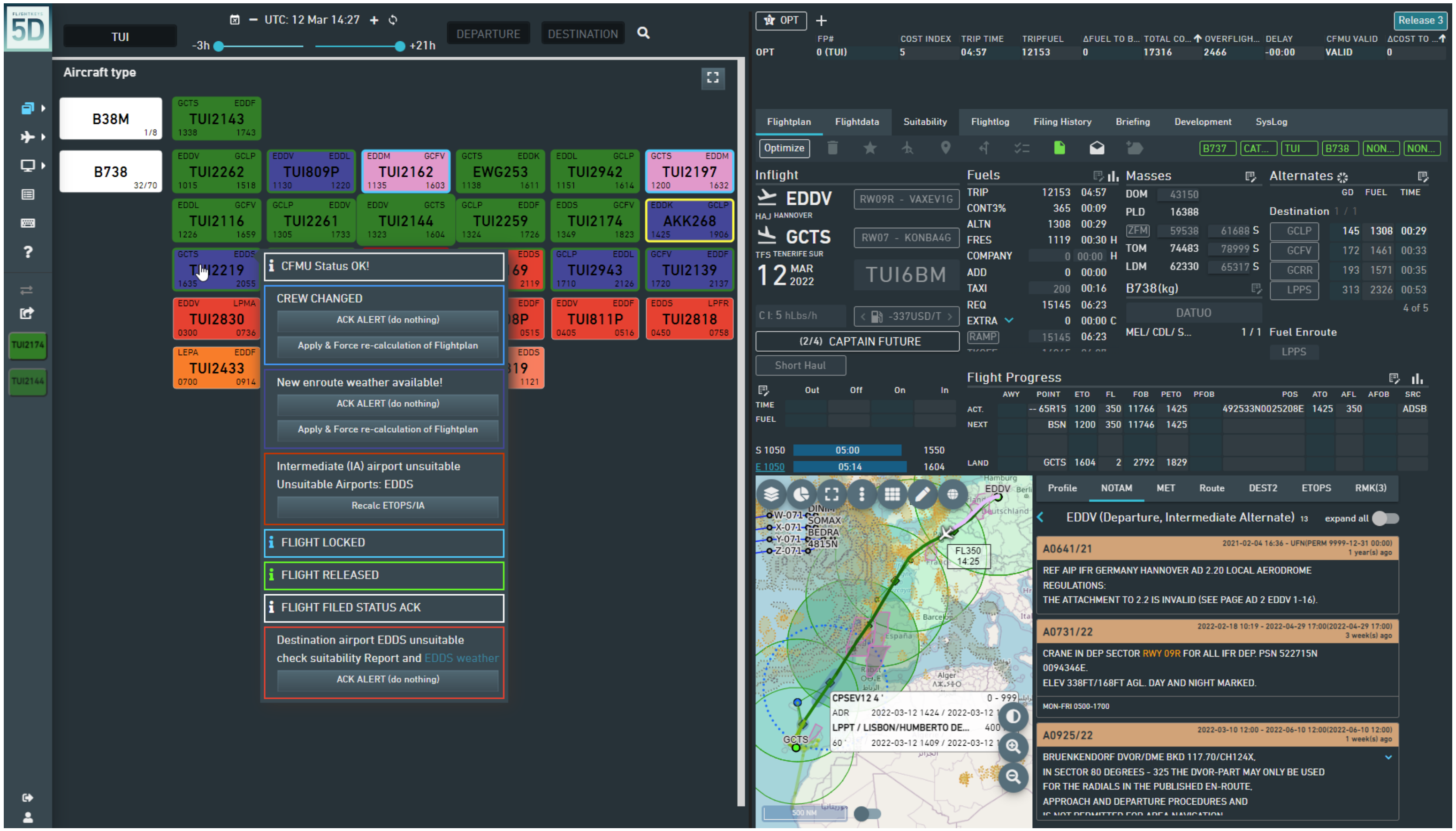
SATAVIA CEO, Dr. Adam Durant: "As a software solution incorporating the excellent and decades-mature atmospheric science available to us, contrail management provides the airline sector with an immediate and tangible option to reduce the climate impact of flying. With the incentive provided by Gold Standard Certified Mitigation Outcome Units (CMOUs), **aviation could reduce its non-CO2 impact by perhaps 50% before 2030**. All we need is a willingness to adopt this approach, which importantly doesn't require any changes to regulation and **could be deployed at scale today**."

https://perma.cc/4RFA-EETB
https://perma.cc/XS5G-PU4Q
https://perma.cc/EX8H-YRUP
https://perma.cc/229N-LWSS

DECISIONX :NETZERO
SATAVIA

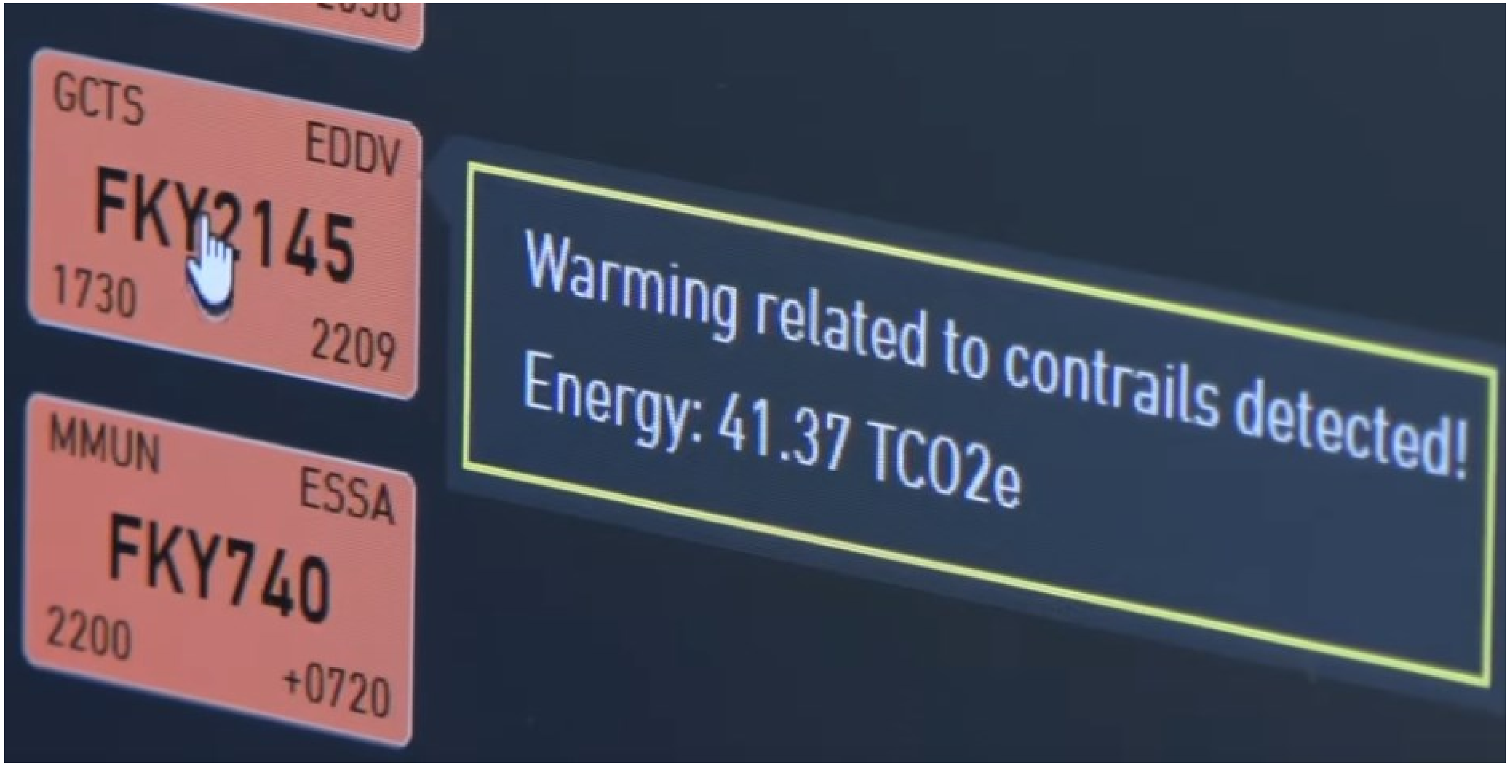
FlightKeys

https://www.flightkeys.com



FlightKeys flight planning system "5D".

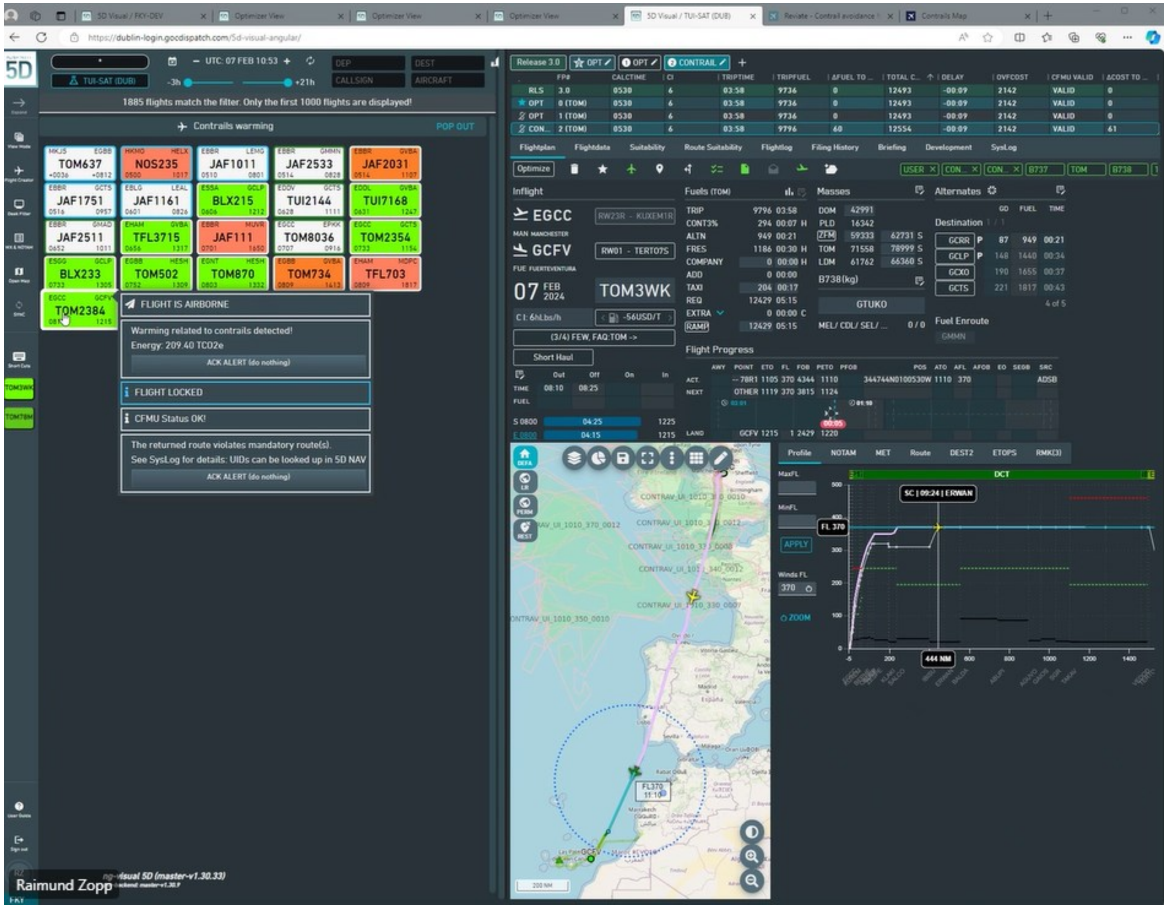
FlightKeys



FlightKeys flight planning system "5D" with new features for contrail avoidance.

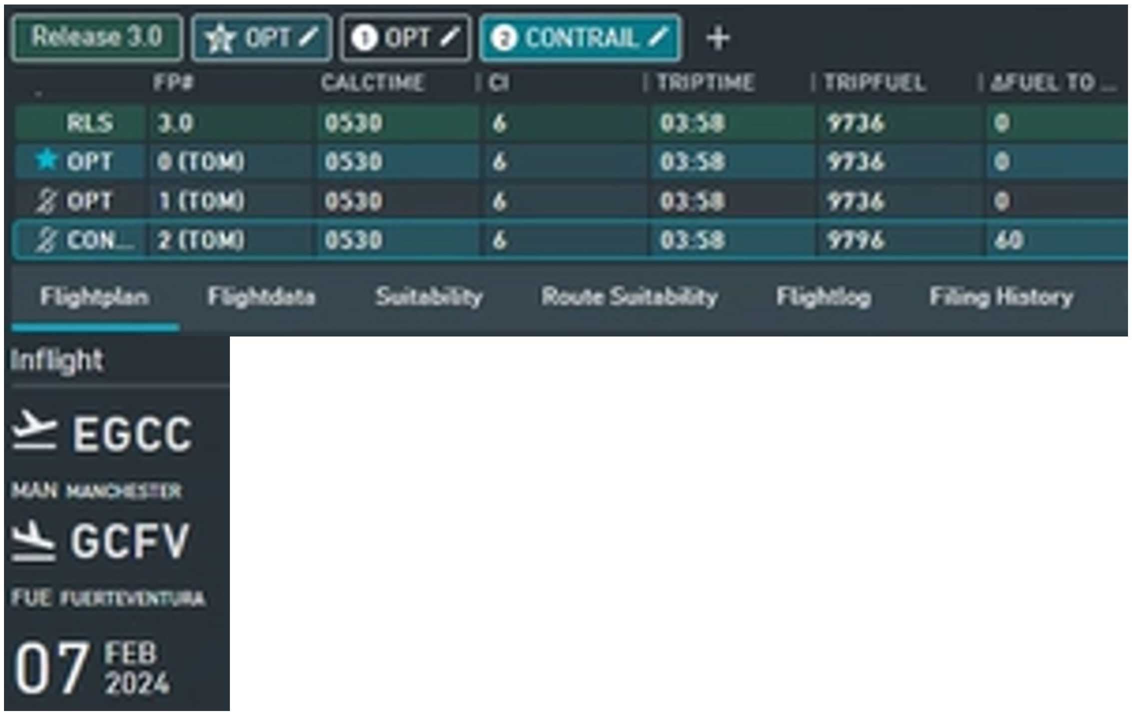
https://youtu.be/HYJawLmiLS8

FlightKeys



FlightKeys flight planning system "5D" with contrail avoidance.

FlightKeys



Compared to the optimum flight plan, the contrail avoidance flight plan requires 60 kg more fuel (plus 0.6%). On average, contrail avoidance requires 0.11% more fuel (calculated by FlightKeys).

FlightKeys

FlightKeys flight planning system "5D" with new features for contrail avoidance. ISSRs are indicated in white. Lateral and vertical avoidance of ISSRs is possible.

https://youtu.be/HYJawLmiLS8

FlightKeys

FlightKeys flight planning system "5D" with new features for contrail avoidance.

Lateral avoidance on the map (left).

The vertical flight profile (right).

https://youtu.be/HYJawLmiLS8

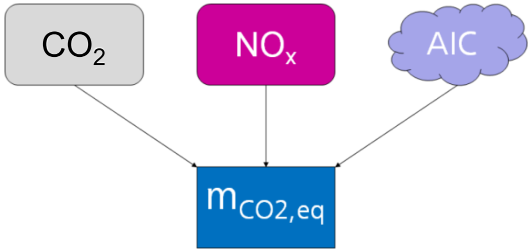
FlightKeys

https://youtu.be/HYJawLmiLS8

Use of the Electronic Flight Bag (EFB) on a tablet in an Airbus A320 cockpit.

The EFB helps the pilot to make inflight adjustments to the flight (tactical contrail avoidance) if Air Traffic Control (ATC) allows.

Aviation and the Climate



Contrail Management

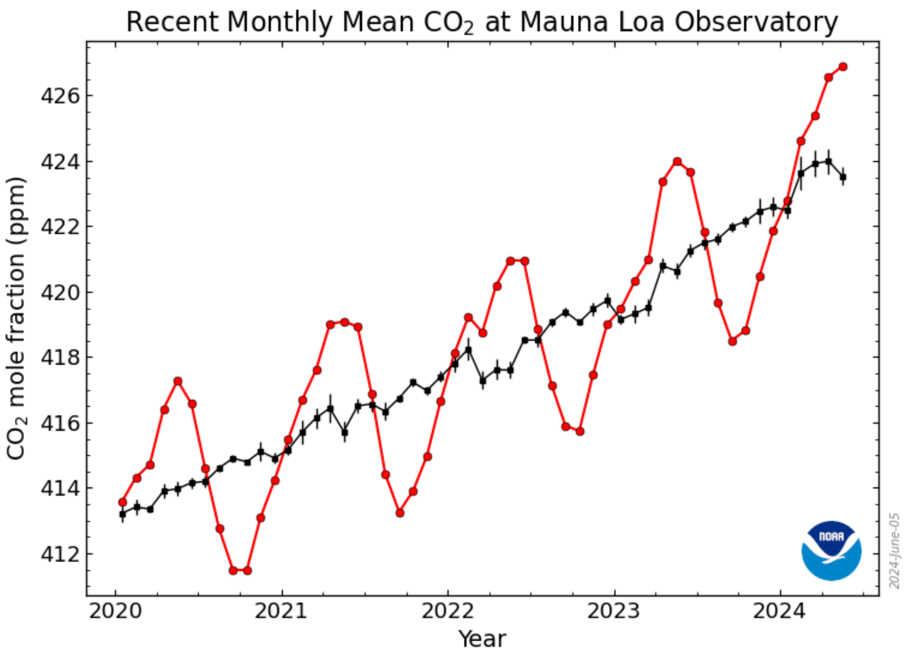
Now !

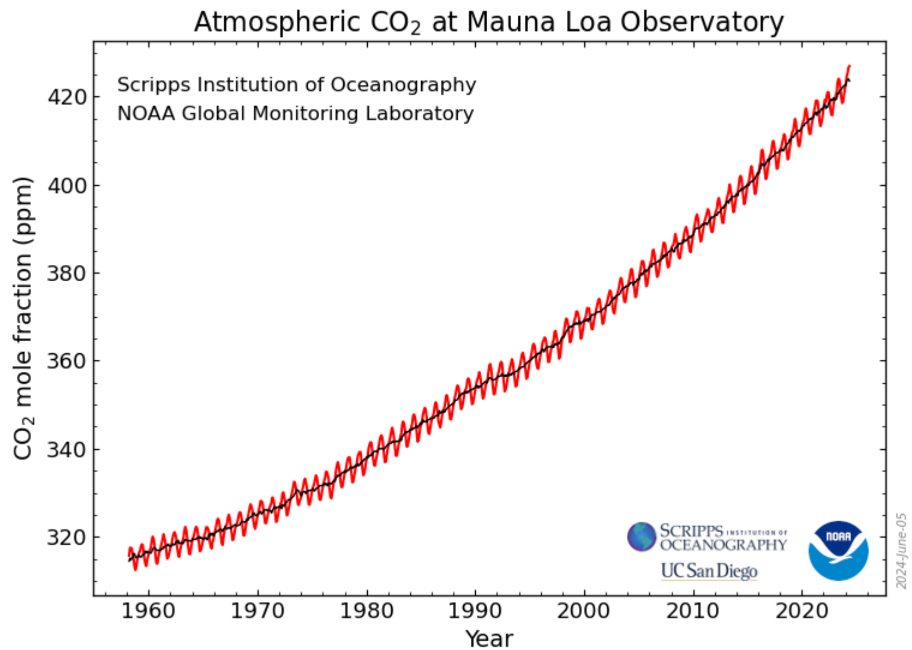
Why ?

Latest CO2 Data

Mauna Loa, Hawaii

May 2024: 426.90 ppm
May 2023: 424.00 ppm
Last updated: Jun 05, 2024

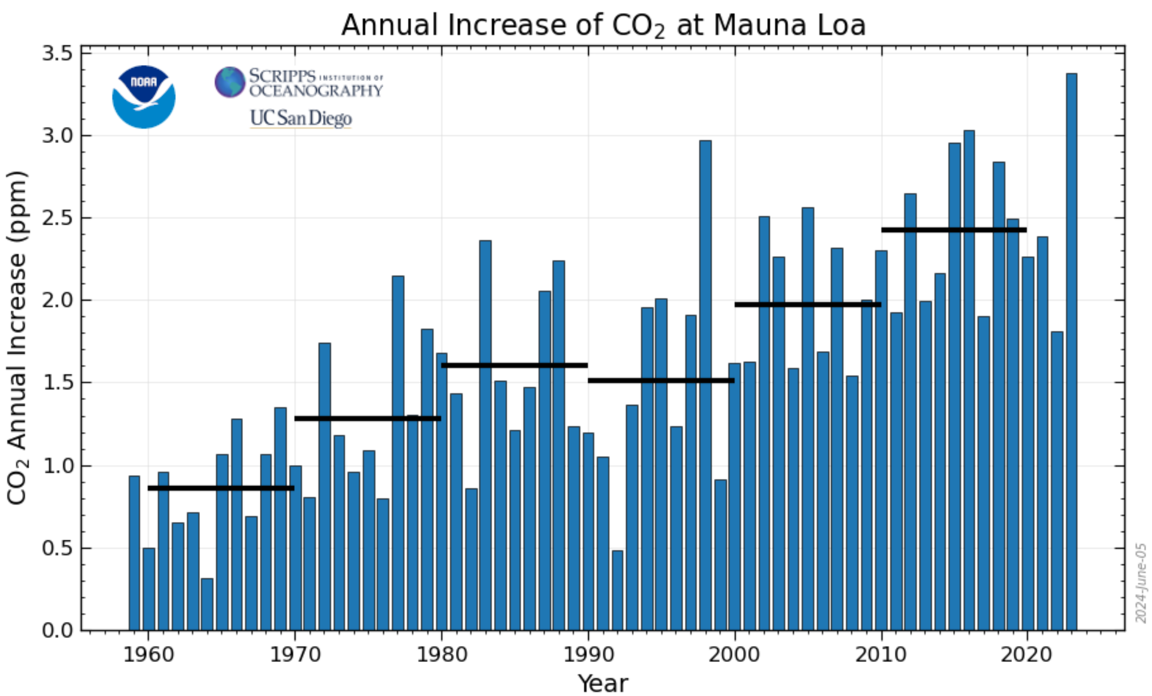




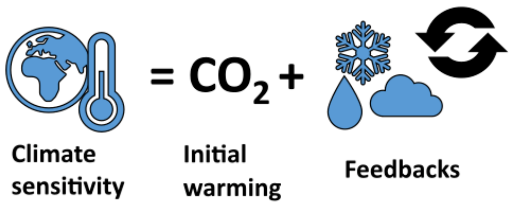
https://gml.noaa.gov/ccgg/trends

Base: Pre-industrial (1850-1900), 280 ppm, temperature change: 0 °C

Latest CO2 Data and Climate Sensitivity



2.5 ppm/year



Climate sensitivity is a key measure in climate science and describes how much Earth's surface will warm for a doubling in the atmospheric carbon dioxide (CO2) concentration. In other words, due to an increase from 280 ppm to 560 ppm (plus 280 ppm).

3 °C (+/- 1.5)°C / 280 ppm

3.0 °C / 280 ppm = 0.0107 °C/ppm

≈ **0.01 °C/ppm**

https://en.wikipedia.org/wiki/Climate_sensitivity

Latest Temperature Data

2023: Copernicus – Europe's eyes on Earth | Climate Change Service

Tracking breaches of the 1.5°C global warming threshold

https://climate.copernicus.eu/tracking-breaches-150c-global-warming-threshold

2.5 ppm/year

May 2024:	426.90 ppm
May 2023:	424.00 ppm

Last updated: Jun 05, 2024

Calculating the climate sensitivity from 424 ppm – 280 ppm = 144 ppm:

1.5 °C / 144 ppm = 0.01042 °C/ppm

Additional 0.5 °C need 144 ppm/3 = 48 ppm. Hence:

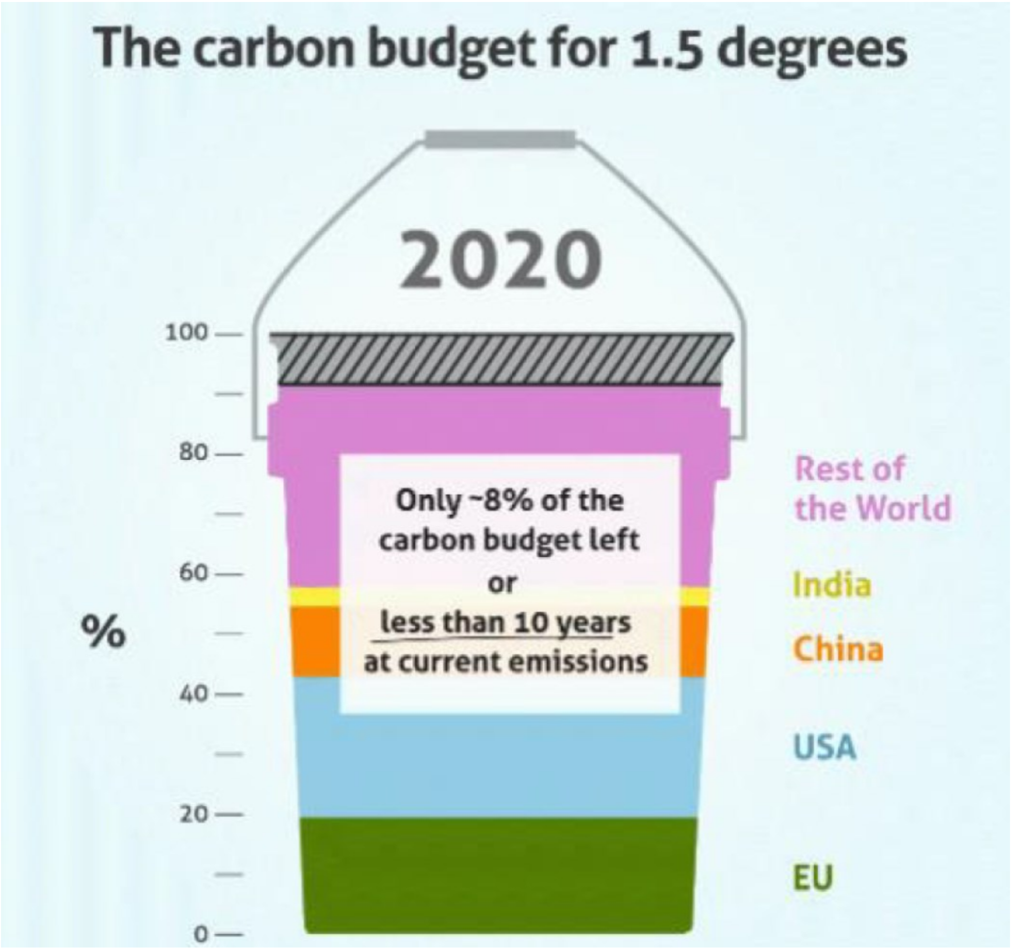
2.0 °C threshold after further 48 ppm or after 48/2.5 years = 19 years

2023 + 19 => 2.0 °C threshold reached in 2042

1 ppm CO2 in the atmosphere is equivalent to 17.3 Gt of CO2 emissions

COOK, John [Skeptical Science], 2024. Comparing CO2 emissions to CO2 levels. Archived at: https://perma.cc/ZFM7-ZUE5

Forecast in 2020 – Way Off



"less than 10 years" left
was finally
"3 years" left,
because
1.5 °C threshold
was already reached in 2023

Stanford University and others:
https://youtu.be/aD0EgwohZwg

Dubai Flooding, 15^{th} to 17^{th} April 2024

https://nilepost.co.ug/asia/196130/dubai-airport-chaos-as-uae-and-oman-reel-from-rare-flooding

Dubai Flooding, 15th to 17th April 2024

https://airport.online/dubai-airport/en/last-update-dubai-airport-flooding https://en.wikipedia.org/wiki/2024_United_Arab_Emirates_floods

But: If we would stop flying today,
the reef will get destroyed for other reasons.

Safe Landing:
https://doi.org/10.5281/zenodo.7901353

Goal of Industry:

Later !

Airbus, 2020: "Zero-Emission" Hybrid-Hydrogen Passenger Aircraft

https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html
Archived at: https://perma.cc/HJ6L-3HUB

"At Airbus, we have the ambition to develop the world's first zero-emission commercial aircraft by 2035."
(2020-09-21)

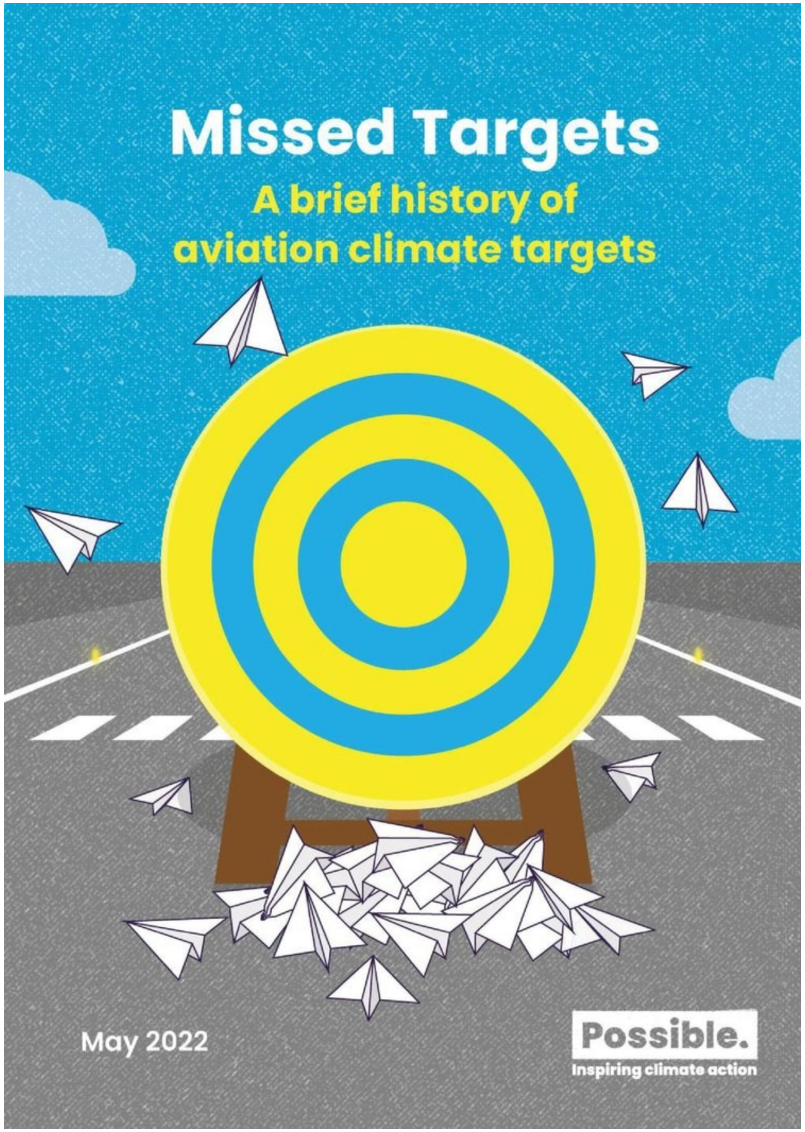
Airbus, 2023/2024: No Hydrogen Flight Demonstrator Launched

Introducing #ZEROe, 2020-09-21, https://youtu.be/525YtyRi_Vc. Left to right: Jean-Brice Dumont (Executive Vice President Engineering, Airbus), Glenn Llewelyn (Vice President Head of Zero Emission Aircraft, Airbus), Grazia Vittadini (Chief Technology Officer, Airbus. Left Airbus in April 2021).

Airbus, 2024: Zero-Emission Aircraft with Fuel Cell by 2035 (???)

"It has been three years since we revealed an aircraft concept 100% powered by hydrogen fuel cells. Since then, we have adhered to our initial timeline and made tremendous progress. The recent success of powering on the iron pod system at 1.2 megawatts is a crucial step towards our goal of putting a hydrogen-powered aircraft in the skies by 2035." Glenn Llewellyn, Vice President of ZEROe Aircraft at Airbus (16 January 2024)

https://web.archive.org/web/20240116140238/https://www.airbus.com/en/newsroom/stories/2024-01-first-zeroe-engine-fuel-cell-successfully-powers-on



"This report assessed every public climate target which the international aviation industry set itself since 2000.

We found that all but one of over 50 separate climate targets has either been missed, abandoned or simply forgotten about.

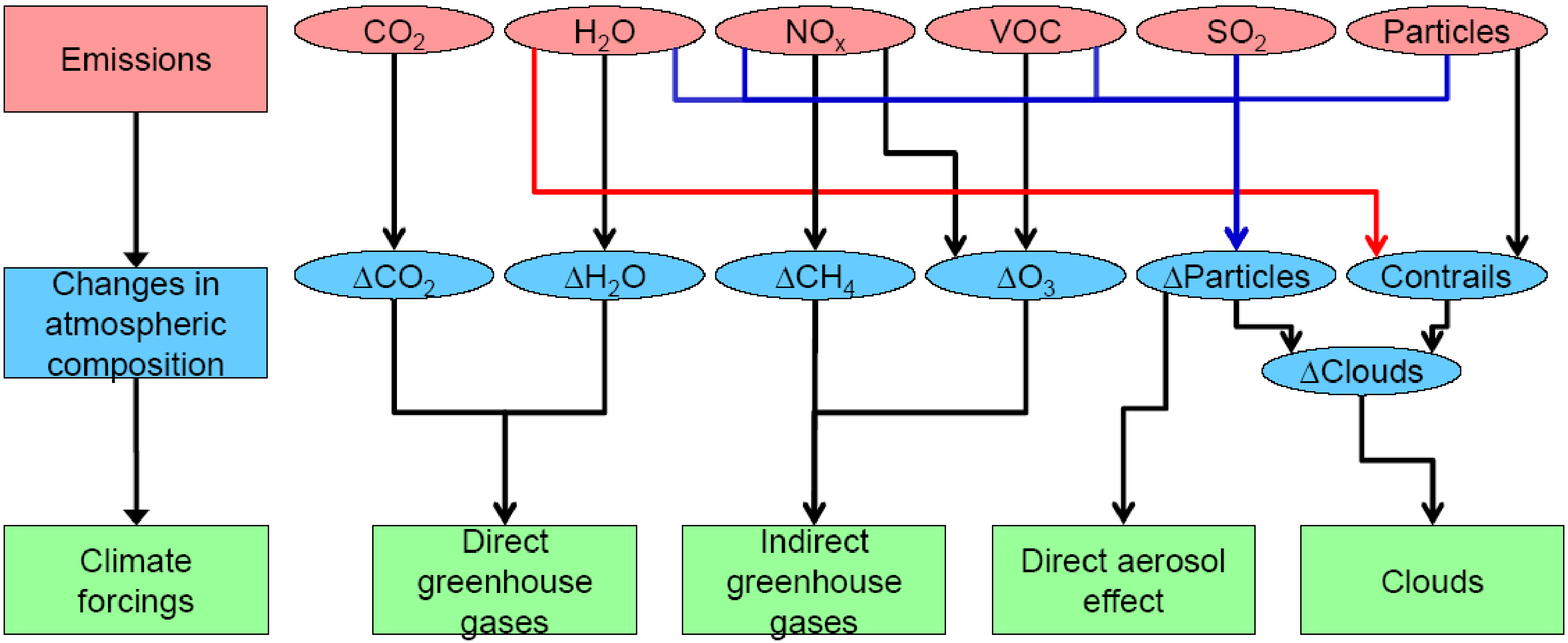
Overall, the industry's attempts to regulate its emissions and set its own targets suffered from a combination of unclear definitions, shifting goalposts, inconsistent reporting, a complete lack of public accountability and, in some cases, [goals] being quietly dropped altogether."

URL: https://www.wearepossible.org/our-reports-1/missed-target-a-brief-history-of-aviation-climate-targets

Archived: https://perma.cc/4SYC-UL93

Global Warming due to Aviation

Aviation Emissions and Climate Impact

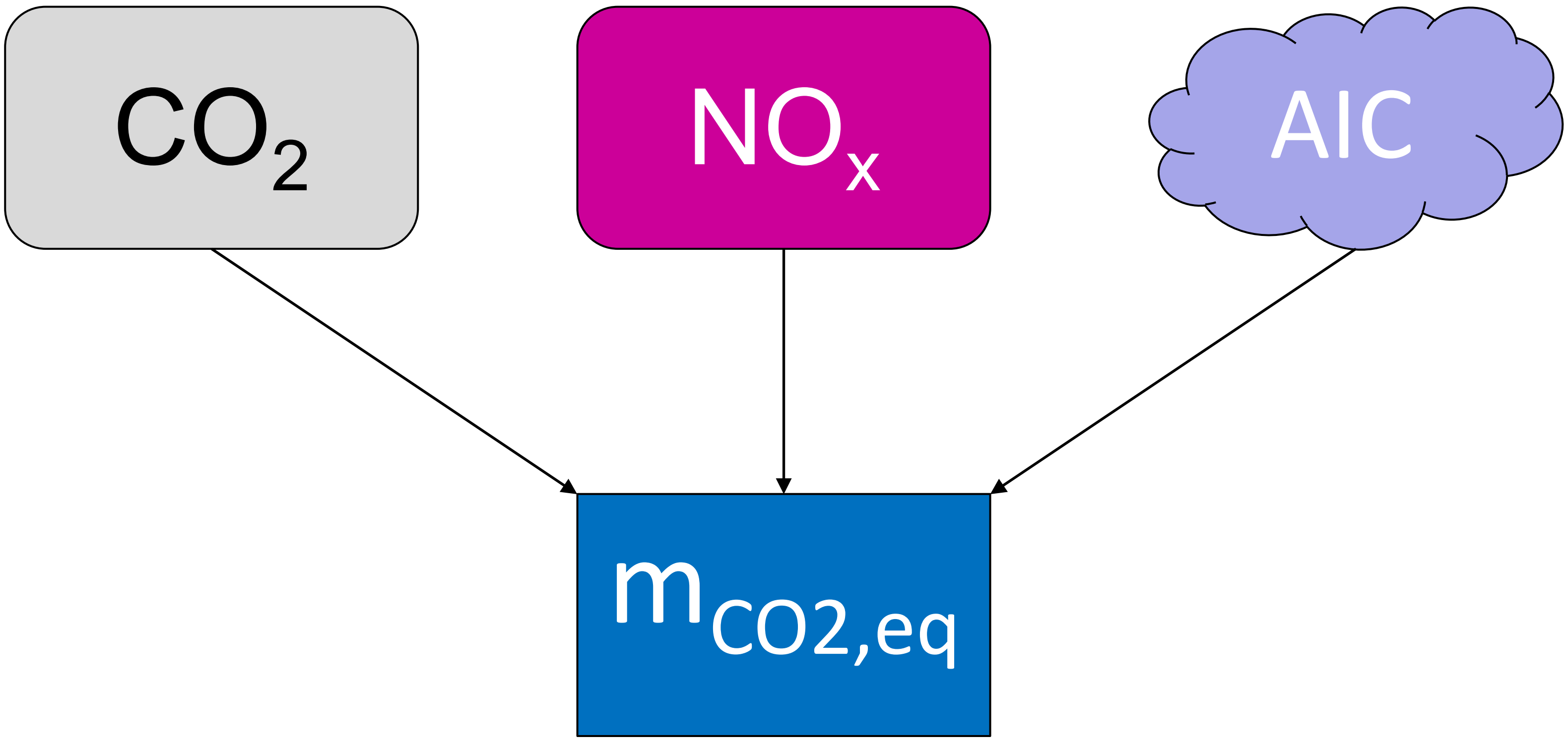


CO2: Long term influence

Non-CO2: Short term influence (immediate mitigation is possible)

RAPP, Markus, 2019. Perspektive: Wasserstoff & Hybride. Meeting: "Emissionsfreies Fliegen-wie weit ist der Weg?", Berlin, 13.11.2019

Global Warming – Measured in Equivalent CO_2 Mass



CAERS, Brecht, SCHOLZ, Dieter, 2020. *Conditions for Passenger Aircraft Minimum Fuel Consumption, Direct Operating Costs and Environmental Impact*. German Aerospace Congress 2020 (DLRK 2020), Online, 01.-03.09.2020.
Available from: https://doi.org/10.5281/zenodo.4068135

Calculating Altitude-Dependent Equivalent CO2 Mass

$$m_{CO2,eq} = \frac{EI_{CO_2} \cdot f_{NM}}{n_{seat,typical}} \cdot CF_{midpoint,CO_2} + \frac{EI_{NO_x} \cdot f_{NM}}{n_{seat,typical}} \cdot CF_{midpoint,NO_x} + \frac{R_{NM} \cdot f_{NM}}{R_{NM} \cdot f_{NM,ref} \cdot n_{seat,typical}} \cdot CF_{midpoint,AIC}$$

$$f_{NM,ref} = 4.74 \text{ kg/km}$$

MATTAUSCH 2024

Sustained Global Temperature Potential, SGTP (similar to GWP):

$$CF_{midpoint\ ,NOx}(h) = \frac{SGTP_{O_{3S},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,S}(h) + \frac{SGTP_{O_{3L},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,L}(h) + \frac{SGTP_{CH_4,100}}{SGTP_{CO_2,100}} \cdot s_{CH_4}(h)$$

$$CF_{midpoint,AIC}(h) = \frac{SGTP_{contrails\ ,100}}{SGTP_{CO_2,100}} \cdot s_{contrails}(h) + \frac{SGTP_{cirrus\ ,100}}{SGTP_{CO_2,100}} \cdot s_{cirrus}(h)$$

Species	Emission Index, EI (kg/kg fuel)
CO_2	3,15
H_2O	1,23
SO_2	$2{,}00 \cdot 10^{-4}$
Soot	$4{,}00 \cdot 10^{-5}$
NOx	$1.45 \cdot 10^{-2}$ (typical value)

$$s_{O_3,L}(h) = s_{CH_4}(h)$$

$$s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h)$$

SCHWARTZ 2009, JOHANNING 2014

Species	$SGTP_{i,100}$
CO_2 (K/kg CO_2)	$3{,}58 \cdot 10^{-14}$
Short O_3 (K/kg NO_x)	$7{,}97 \cdot 10^{-12}$
Long O_3 (K/NO_x)	$-9{,}14 \cdot 10^{-13}$
CH_4 (K/kg NO_x)	$-3{,}90 \cdot 10^{-12}$
Contrails (K/NM)	$2{,}54 \cdot 10^{-13}$
Contrails (K/km)	$1{,}37 \cdot 10^{-13}$
Cirrus (K/NM)	$7{,}63 \cdot 10^{-13}$
Cirrus (K/km)	$4{,}12 \cdot 10^{-13}$

EI emission index
f_{NM} fuel consumption per NM or km
R_{NM} range in NM or km
CF characterization factor

Cirrus/Contrails = 3.0

water vapor not considered

AIC aviation-induced cloudiness

Contrail Radiative Forcing (CRF) as a Function of Fuel Flow (ff)

JEßBERGER, Philipp, et al. Aircraft type influence on contrail properties. Atmospheric Chemistry and Physics, 2013, 13. Jg., Nr. 23, S. 11965-11984. Available from: https://doi.org/10.5194/acp-13-11965-2013

Contrail Radiative Forcing (CRF) as a Function of Fuel Flow (ff)

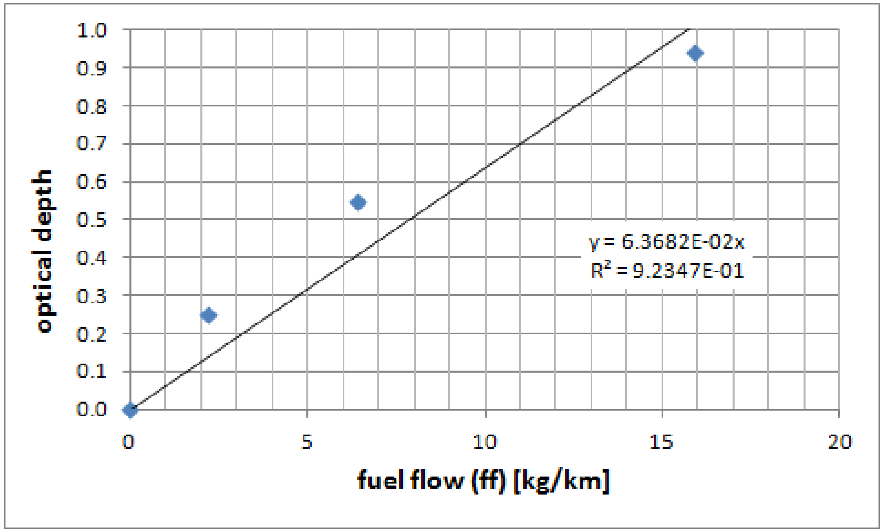
Aircraft	A319-111	A340-311	A380-841
Encounter time	09:14–09:27	08:45–08:48	12:14–12:29
Contrail altitude (km)	10.5–10.7	10.5–10.7	10.3–10.7
Latitude	52.91° N	53.35° N	52.37° N
Longitude	8.06° E	8.94° E	9.66° E
Pressure p (hPa)	241	242	241
Temperature T (K)	217	217	218
T_C (K)	223.5	223.6	223.6
Brunt–Väisälä frequency	0.0170	0.0126	0.0132
NO_y (nmol mol^{-1})	4.3	4.4	6.7
EI_{NO_x} (g kg^{-1})	8.7	11.6	19.7
RHI (%)	91	94	92
Contrail age (s)	105–118	80–90	102–115
Fuel flow (Mg engine^{-1} h^{-1})	0.9	1.3	3.6
Fuel flow rate (kg km^{-1})	2.2	6.4	15.9
Aircraft engine	CFM56-5B6/P	CFM56-5C2	Trent 970-84
Mach	0.76	0.737	0.85
Fuel sulphur content (mg kg^{-1})	1155	940	–
Aircraft weight (Mg)	47	150	508
Wingspan (m)	34.09	60.30	79.81

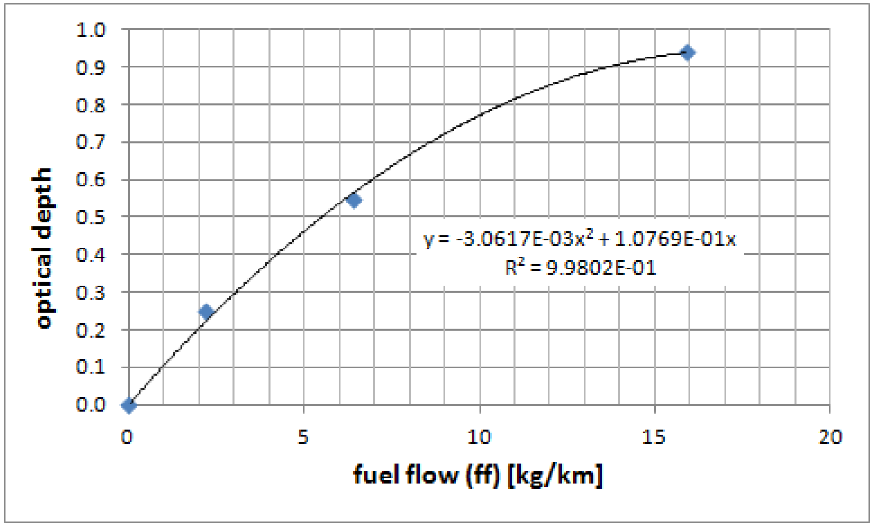
τ		ff	τ / ff [km/kg]	aircraft
0.25	/	2.2	= 0.114	A319
0.55	/	6.4	= 0.0859	A340
0.94	/	15.9	= 0.059	A380

JEßBERGER, Philipp, et al. Aircraft type influence on contrail properties. Atmospheric Chemistry and Physics, 2013, 13. Jg., Nr. 23, S. 11965-11984. Available from: https://doi.org/10.5194/acp-13-11965-2013

Aircraft	n_{ice} (cm^{-3})	D_{eff} (µm)	Projected surface area A (µm^2 cm^{-3})	IWC (mg m^{-3})	Extinction (km^{-1})	Vertical extension (m)	Optical depth τ
A319	162±18	5.2(±1.5)	$0.93(\pm0.14)\times10^3$	4.1(±1.0)	2.1(±0.3)	120	0.25
A340	164±0.11	5.8(±1.7)	$1.12(\pm0.17)\times10^3$	4.0(±1.0)	2.5(±0.4)	220	0.55
A380	235±10	5.9(±1.7)	$1.45(\pm0.22)\times10^3$	5.2(±1.3)	3.2(±0.5)	290	0.94

Contrail Radiative Forcing (CRF) as a Function of Fuel Flow (ff)





The quadratic regression (right) fits amazingly well. However, from the small number of aircraft tested, no such general law may be derived.

The climate model by SCHWARTZ 2009, which calculates AIC effects only based on contrail length (flight distance) was extended to include fuel burn (in kg/km) into the equation. Fuel burn enters optical depth linearly!

SCHWARTZ, Emily, KROO, Ilan M., 2009. *Aircraft Design: Trading Cost and Climate Impact*. 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, 05.01.-08.01.2009, Orlando, Florida, AIAA 2009, No.1261. Available from: https://doi.org/10.2514/6.2009-1261

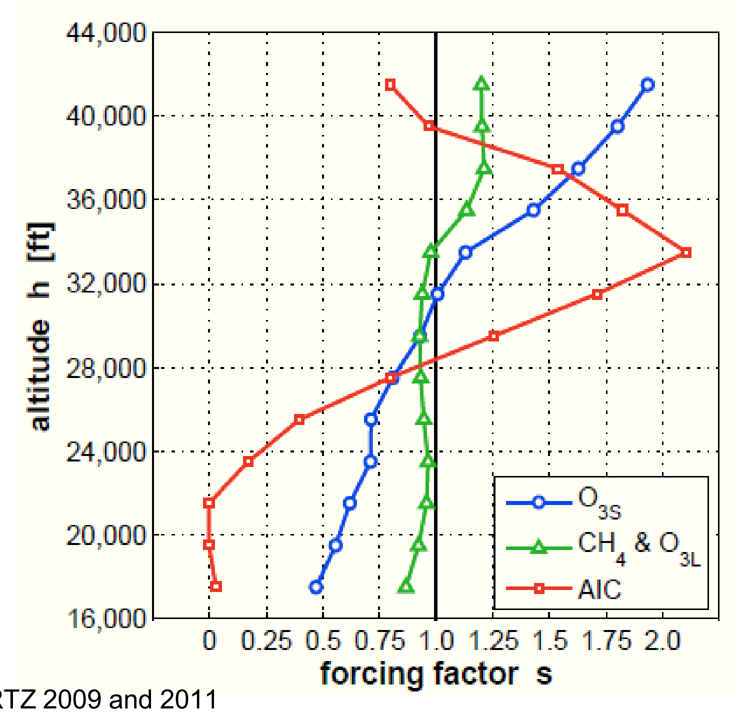
JOHANNING, Andreas, SCHOLZ, Dieter, 2014. *Adapting Life Cycle Impact Assessment Methods for Application in Aircraft Design*. German Aerospace Congress 2014 (DLRK 2014), Augsburg, 16.-18.09.2014. Available from: https://nbn-resolving.org/urn:nbn:de:101:1-201507202456. Download: http://Airport2030.ProfScholz.de

Calculating Altitude-Dependent Equivalent CO2 Mass

E.g.: $$CF_{midpoint,AIC}(h) = \frac{SGTP_{contrails,100}}{SGTP_{CO_2,100}} \cdot s_{contrails}(h) + \frac{SGTP_{cirrus,100}}{SGTP_{CO_2,100}} \cdot s_{cirrus}(h)$$

$$s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h)$$

Forcing Factor *s* = f(*h*)

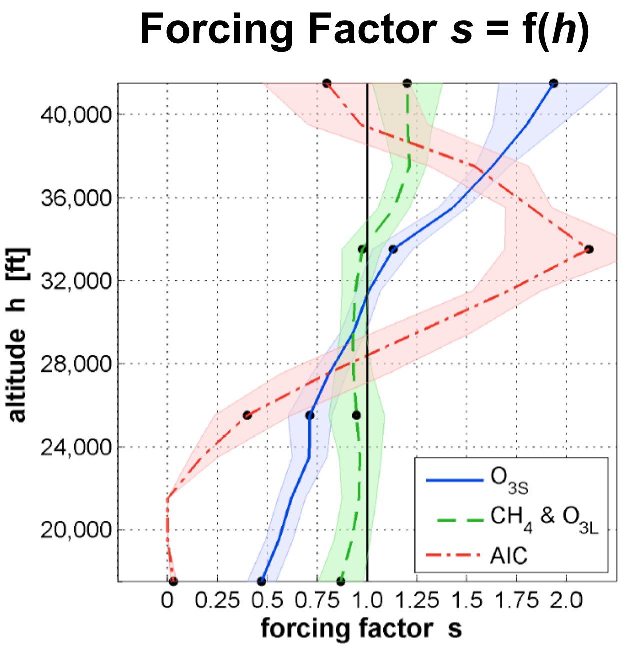


SCHWARTZ 2009 and 2011

- The curves go along with the ICAO Standard Atmosphere (ISA) applicable for average lattitudes. With a first approximation, the curves could be adapted to other lattitudes by stretching and shrinking them proportionally to the altitude of the tropopause.
- The curves from SVENSSON 2004 (Fig. 1) show similar shapes. However, the importance of AIC is not yet as distinct.

SVENSSON, Fredrik, HASSELROT, Anders, MOLDANOVA, Jana, 2004. Reduced Environmental Impact by Lowered Cruise Altitude for Liquid Hydrogen-Fuelled Aircraft. In: *Aerospace Science and Technology*, Vol. 8 (2004), Nr. 4, pp. 307–320. Available from: https://doi.org/10.1016/j.ast.2004.02.004

Calculating Altitude-Dependent Equivalent CO2 Mass



Forcing factors (lines) with **66% likelihood ranges** (shaded areas). Altitudes with forcing factors based on radiative forcing data with independent probability distributions. (SCHWARTZ 2011)

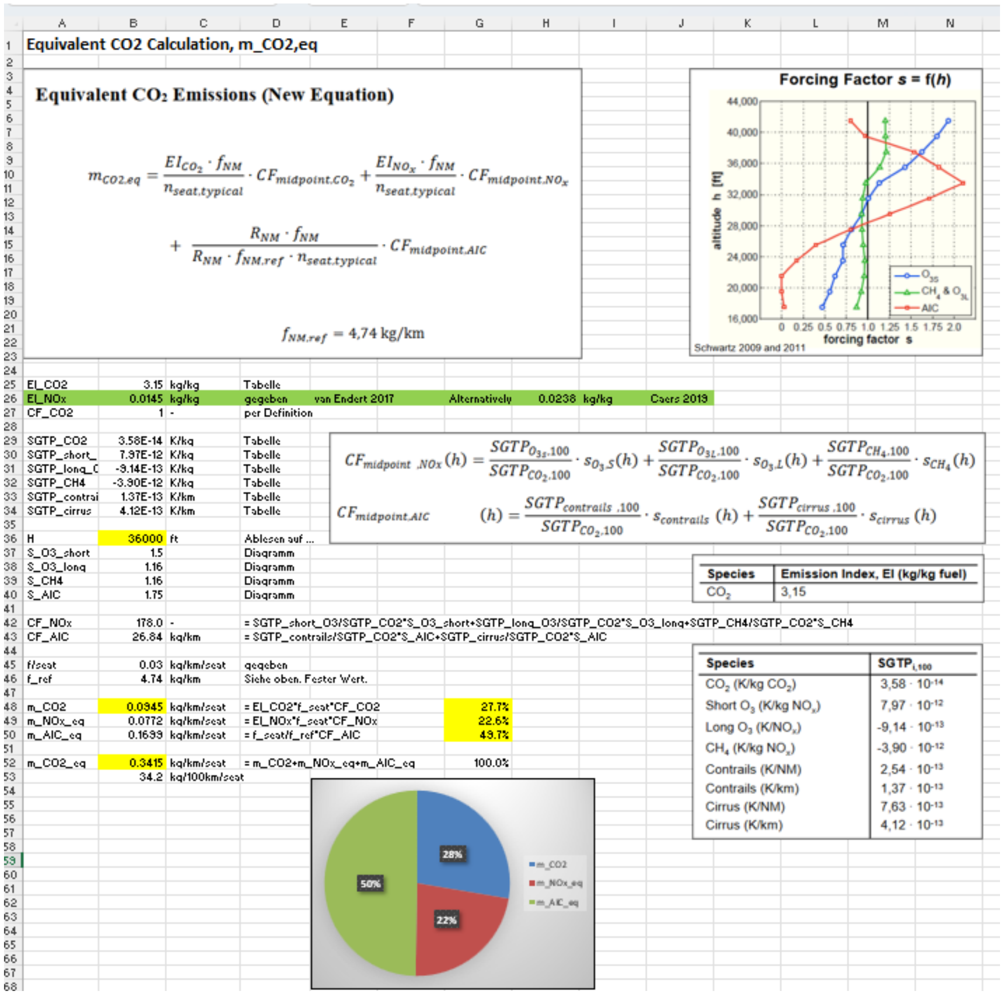
Based on KÖHLER 2008 and RÄDEL 2008.

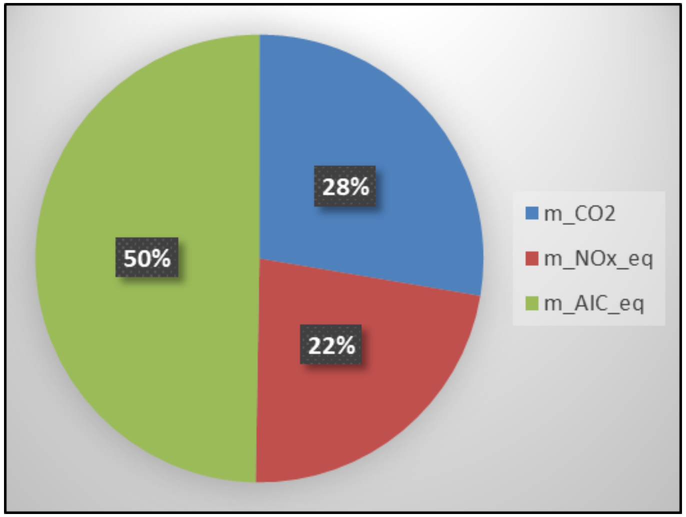
SCHWARTZ DALLARA, Emily, 2011. *Aircraft Design for Reduced Climate Impact*. Dissertation. Stanford University. Available from: http://purl.stanford.edu/yf499mg3300

KÖHLER, Marcus O., RÄDEL, Gaby, DESSENS, Olivier, SHINE, Keith P., ROGERS, Helen L., WILD, Oliver, PYLE, John A., 2008. Impact of Perturbations to Nitrogen Oxide Emissions From Global Aviation. In: Journal of Geophysical Research, 113. Available from: https://doi.org/10.1029/2007JD009140

RÄDEL, Gaby, SHINE, Keith P., 2008. Radiative Forcing by Persistent Contrails and Its Dependence on Cruise Altitudes. In: Journal of Geophysical Research, 113. Available from: https://doi.org/10.1029/2007JD009117

Calculating Altitude-Dependent Equivalent CO2 Mass with Excel





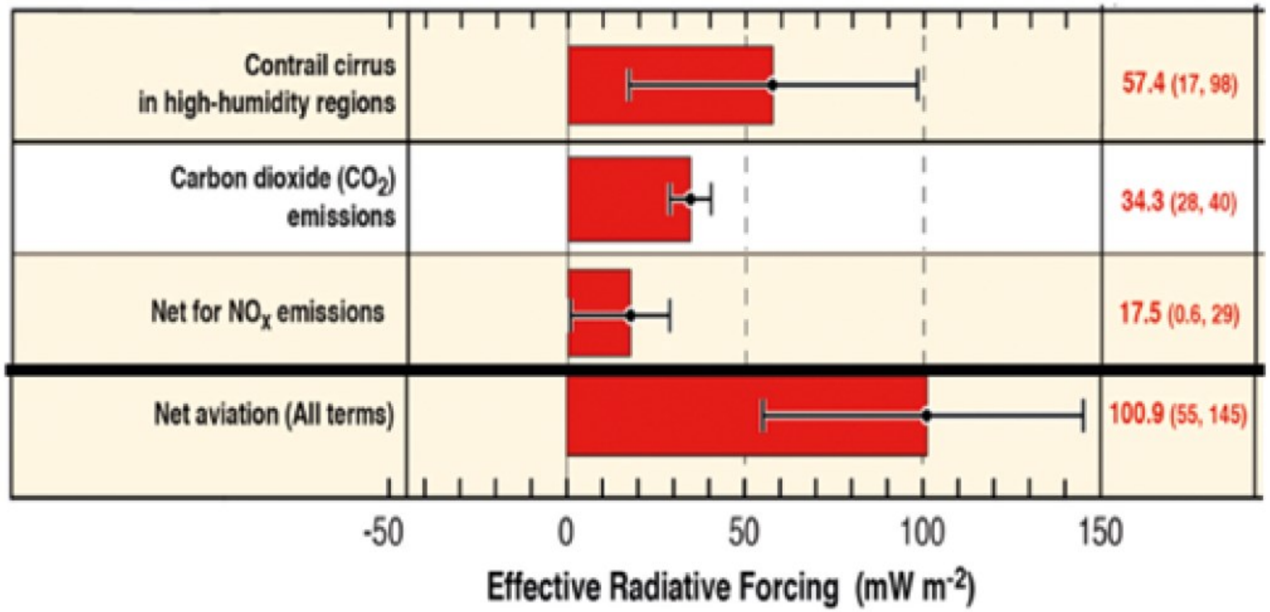
EI_NOx = 0.0145 kg/kg

h = 36000 ft

Standard split of CO2,eq:

1/6 = 1/6 = 16.7% from NOx
2/6 = 1/3 = 33.3% from CO2
3/6 = 1/2 = 50.0% from AIC

Relative Contributions to Global Warming

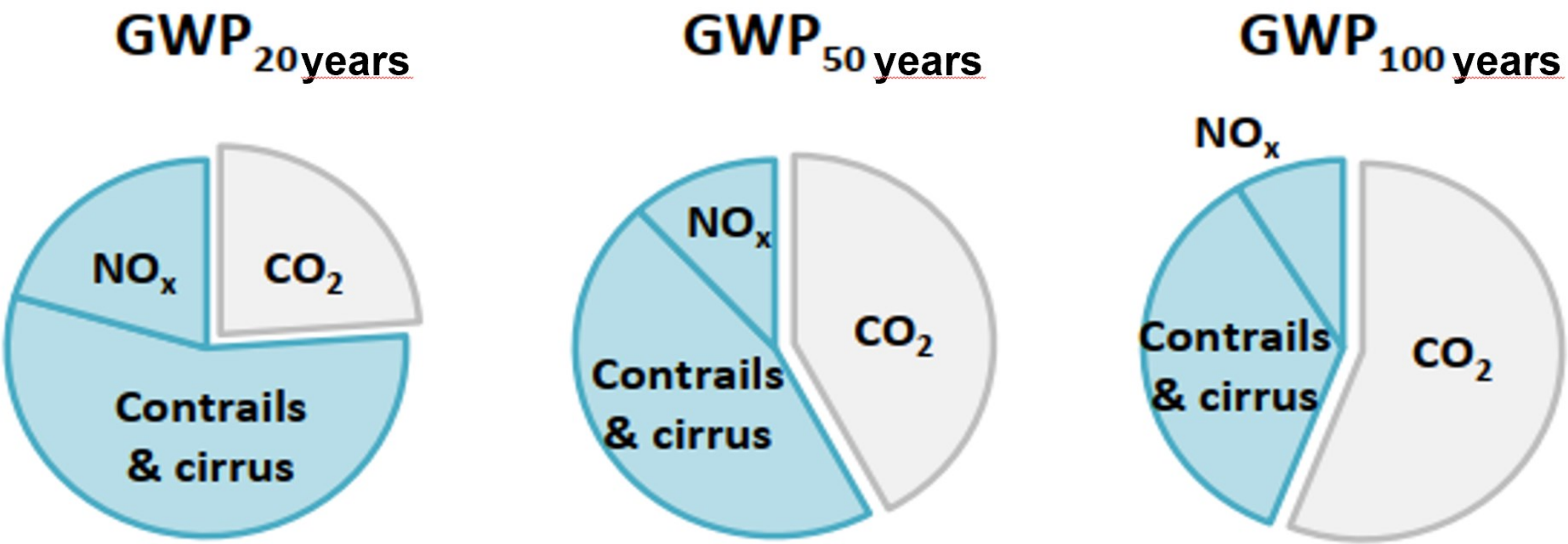


LEE, D.S., et al., 2020. The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018. In: Atmospheric Environment, vol. 211 (2021), art. 17834. Available from: https://doi.org/10.1016/j.atmosenv.2020.117834

This can be compared to equivalent CO2 at peak AIC ("33548 ft") according to the model by SCHWARTZ 2009 due to

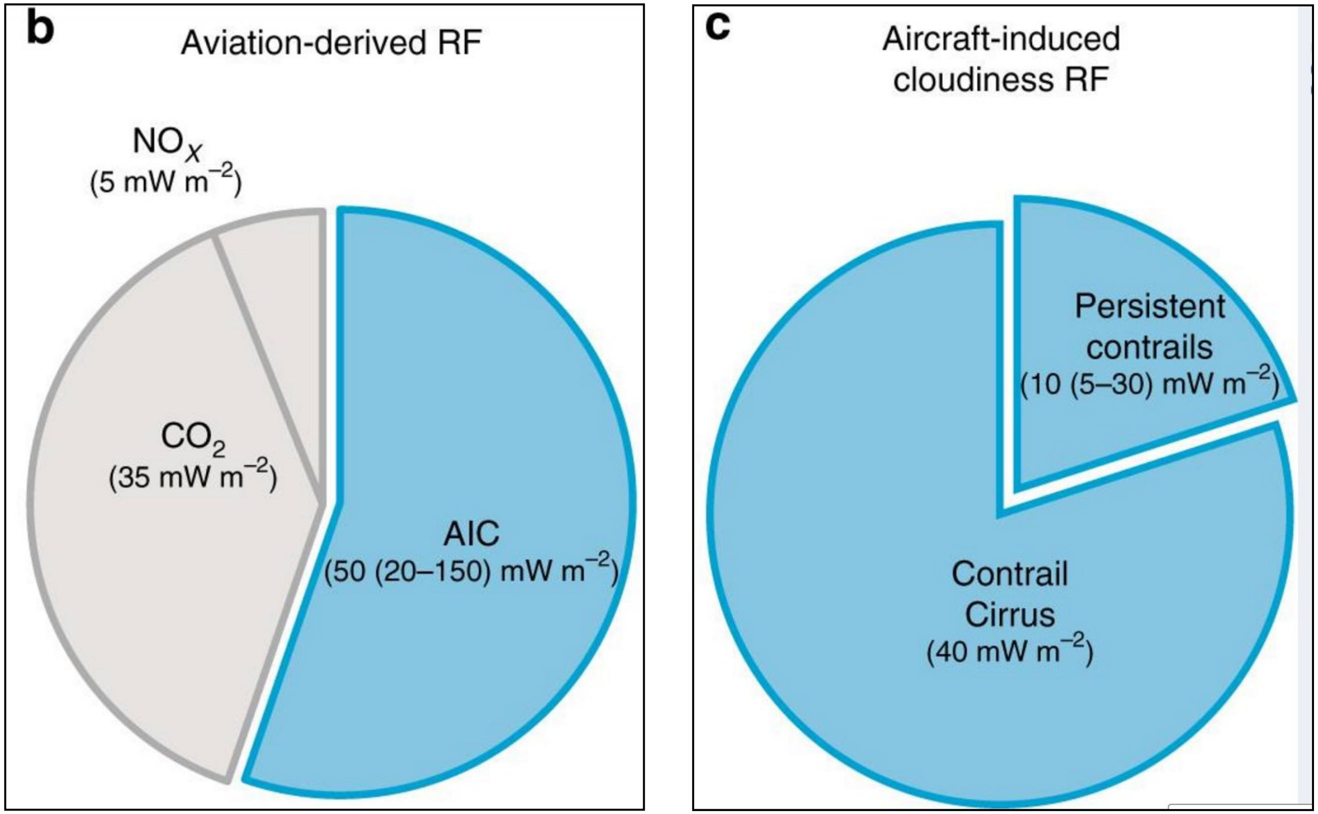
- 54.7% AIC
- 23.6% CO2
- 21.7% NOX

Aviation-Induced Cloudiness (AIC) – Share Depends on Integration Time



LEEMÜLLER, 2022. Climate Optimized Flight Routes – The Path from Research to Operations. Hamburg Aerospace Lecture Series (DGLR, RAeS, VDI, ZAL, HAW Hamburg), Hamburg, Germany, 2022-11-24. Zenodo. https://doi.org/10.5281/zenodo.7396325

Aviation-Induced Cloudiness: Contrail Cirrus & Persistent Contrails

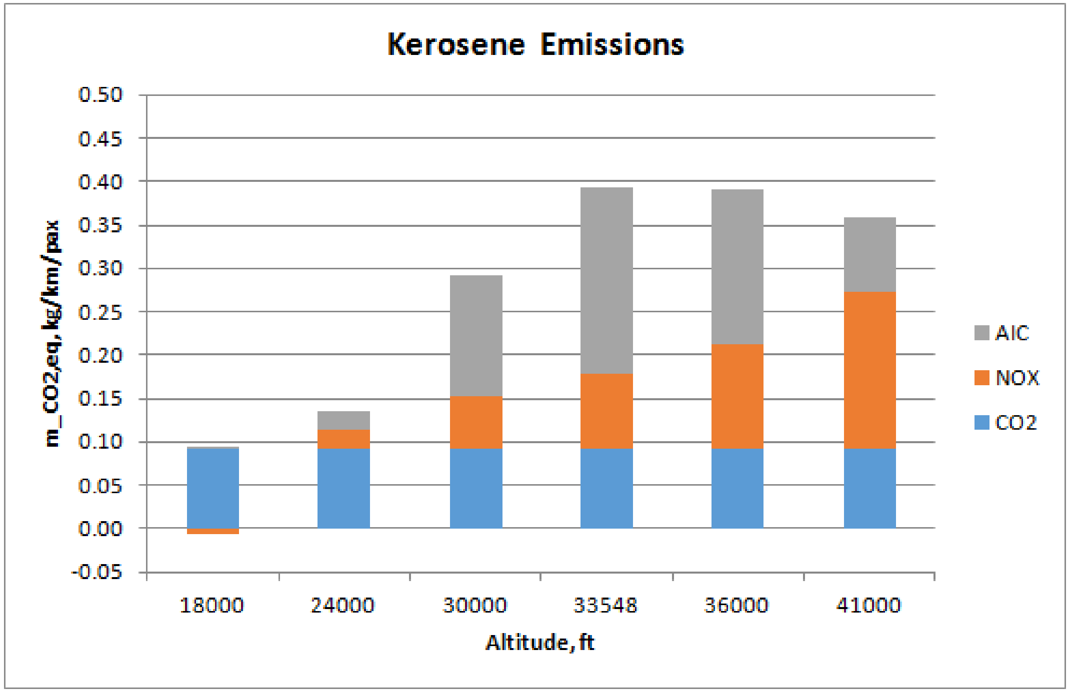


Cirrus/Contrails = 4.0

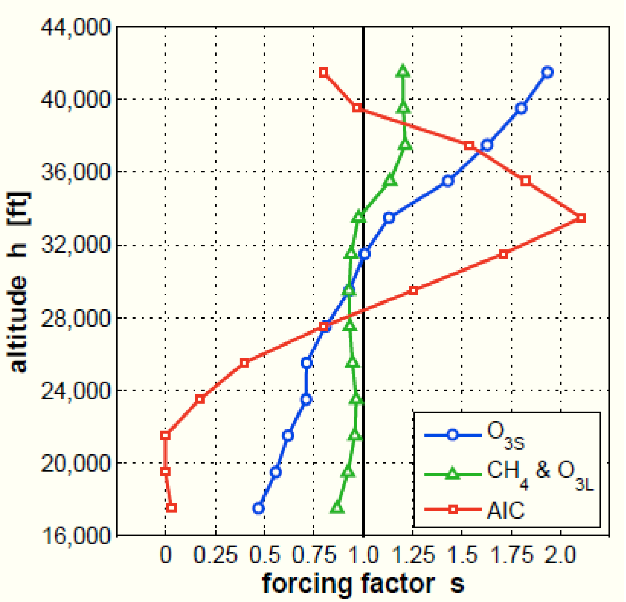
(b) Aviation forcing components, of which aviation-induced cloudiness (AIC) account for more than half.
(c) Breakdown of AIC radiative forcing into contrail cirrus and persistent contrails.

KÄRCHER, Bernd, 2018. Formation and Radiative Forcing of Contrail Cirrus. In: *Nature Communications*, vol. 9, art. 1824. Available from: https://doi.org/10.1038/s41467-018-04068-0

Calculating Altitude-Dependent Equivalent CO2 Mass



https://doi.org/10.7910/DVN/DLJUUK



SCHWARTZ 2009 and 2011

- At **41000 ft**, AIC is low. Equivalent CO2 is now dominated by NOx.
- Equivalent CO2 mass peaks at **"peak AIC" (33548 ft)** due to contrails and contrail cirrus.
- At lower altitudes (**24000 ft**) very little equivalent CO2 is produced. NOx effects and AIC are low. CO2 dominates.
- At very low altitudes (**18000 ft**) the forcing factor for CH4 and O3L is getting so large that it dominates the forcing factor of the warming O3S. NOx is now **slightly cooling**.

New Technologies & Fuels

Calculating Maximum Range for Battery–Electric Flight: Range too Short!

$$e_{bat} = \frac{E_{bat}}{m_{bat}} \qquad L = W = m_{MTO}\, g \qquad E = \frac{L}{D} \qquad D = \frac{m_{MTO}\, g}{E}$$

$$P_D = D\,V = \frac{m_{MTO}\, g}{E} V = P_T = P_{bat}\, \eta_{prop}\, \eta_{elec} \qquad V = \frac{R}{t}$$

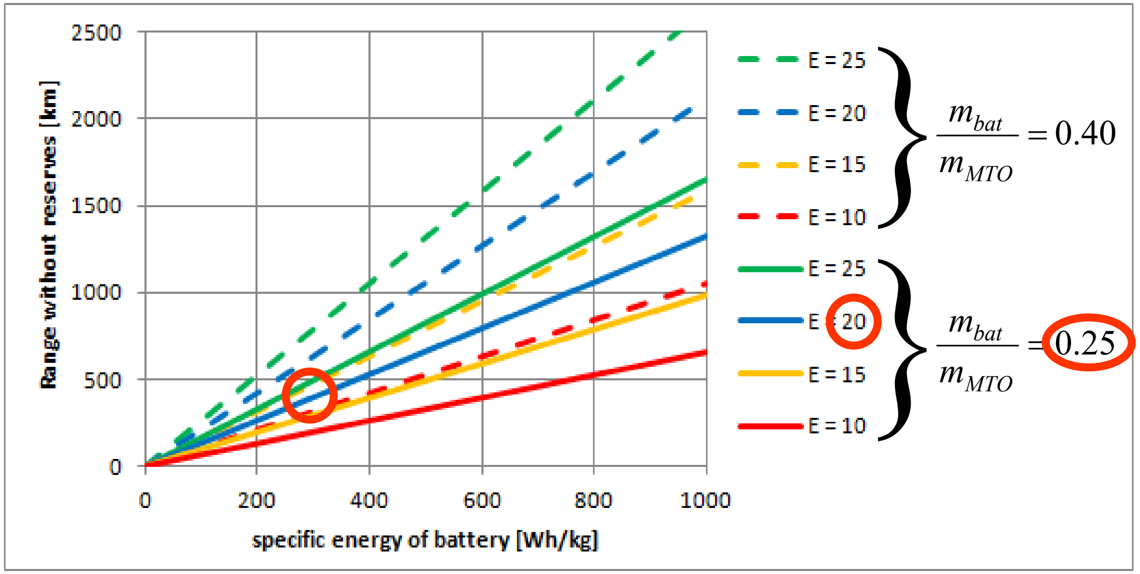
$$P_{bat} = \frac{E_{bat}}{t} = m_{bat}\, e_{bat} \frac{V}{R}$$

$$m_{bat}\, e_{bat} \frac{V}{R} \eta_{elec}\, \eta_{prop} = \frac{m_{MTO}\, g}{E} V$$

$$\boxed{R = \frac{m_{bat}}{m_{MTO}} \frac{1}{g} e_{bat}\, \eta_{elec}\, \eta_{prop}\, E}$$

$$\eta_{elec} = 0.9; \qquad \eta_{prop} = 0.8$$

e_{bat} : specific energy
E_{bat} : energy in battery
E : glide ratio (aerodynamic efficiency)
L : lift
D : drag
W : weight
V : flight speed
R : range
t : time
g : earth acceleration
P : power
η : efficiency (prop : propeller)



○ : realistic parameters

Question:

The EU is calling for 70% Sustainable Aviation Fuel (SAF) by 2050 (a blend of 70% SAF and 30% kerosene). Let's assume SAFs "produce around 80 percent less CO2" (Airbus).

a) To what percentage are CO2 emissions left?

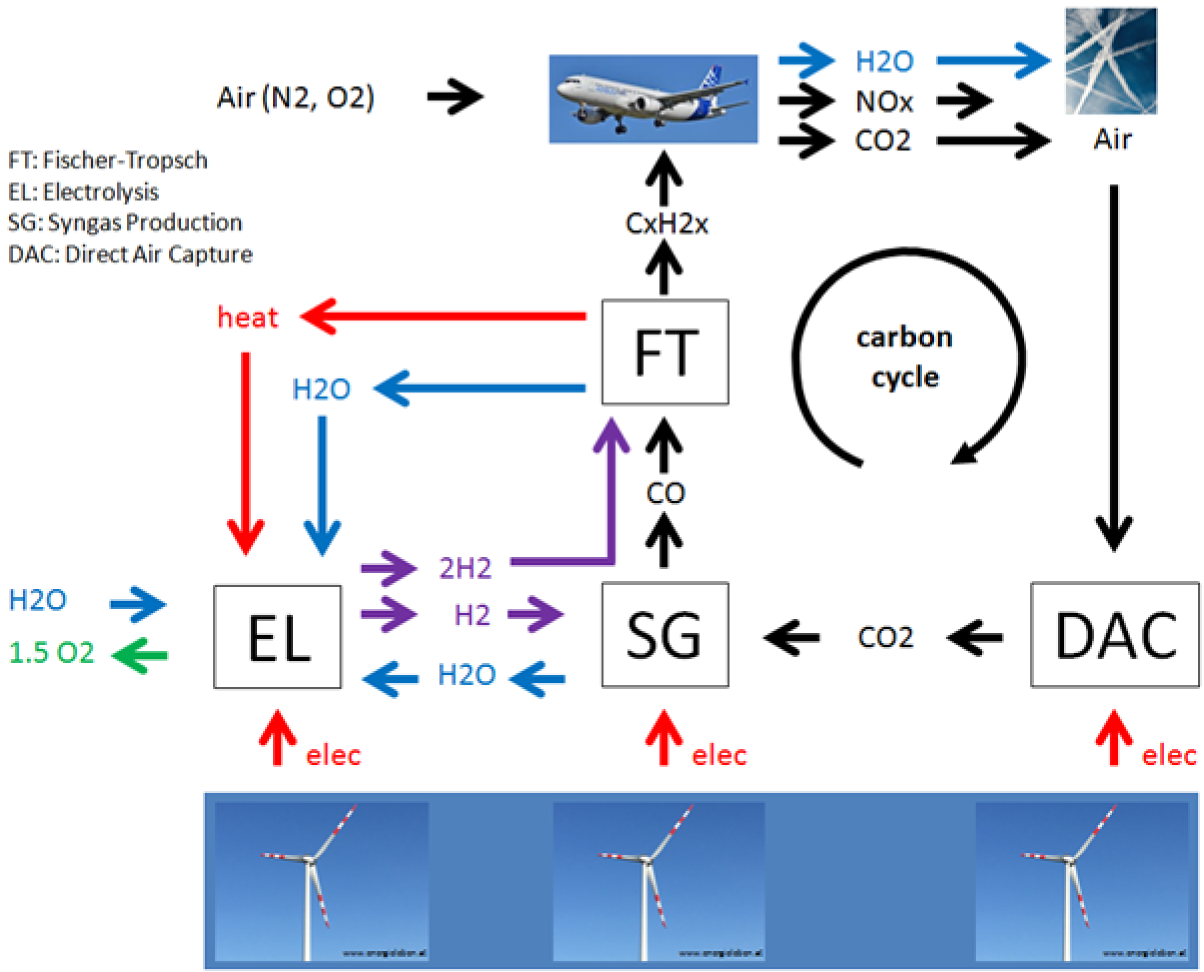
b) It is estimated that aviation will have grown by a factor of 2.9 by 2050. Based on this: How much more CO2 will be emitted in 2050 compared to today?

Answer:

a) The 70% SAF are 35% from biofuel (CO2-efficiency 80%) hence as good as 0.8 · 35% = 28%. The other 35% are from e-fuel, which may be considered to have a CO2-efficiency of 100%. Together SAF is as good as 63%. The fuel in the tank is producing CO2 as 37% of the kerosene before.

b) Due to traffic growth, the 37% become 37% · 2.9 = 107%. This means CO2 emission in 2050 are increased(!) by about 7% compared to today (despite the ambitious introduction of SAF).

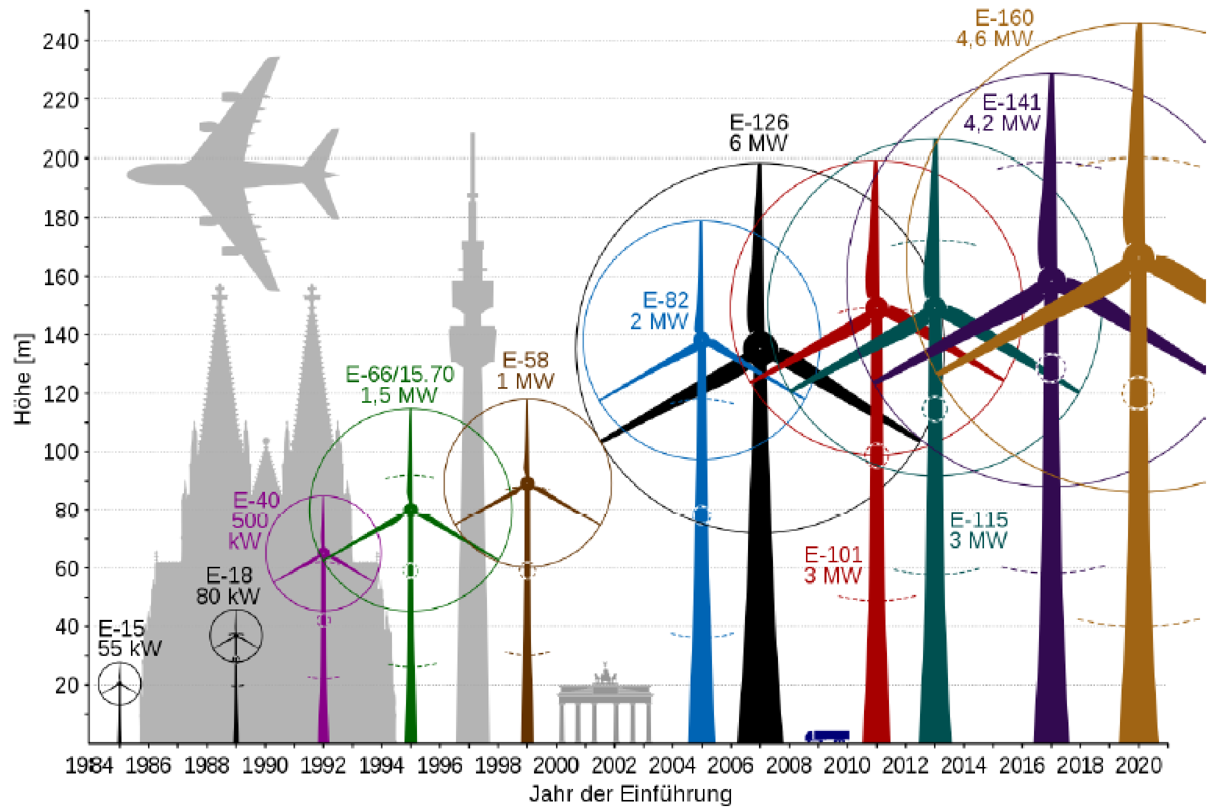
The Carbon Cycle of Sustainable Aviation Fuel (SAF, E-Fuel)



- **SAF need DAC (Direct Air Capure) to compensate for CO2 ("cabon cycle")**
- **In addition: SAF and BioFuel need more DAC to compensate for the global warming effect due to**
  - **NOX and**
  - **H2O (AIC)**

Production of synthetic kerosene (e-fuel) with power-to-liquid (PtL). Taking CO2 from the air (Direct Air Capture, DAC) enables a carbon cycle.

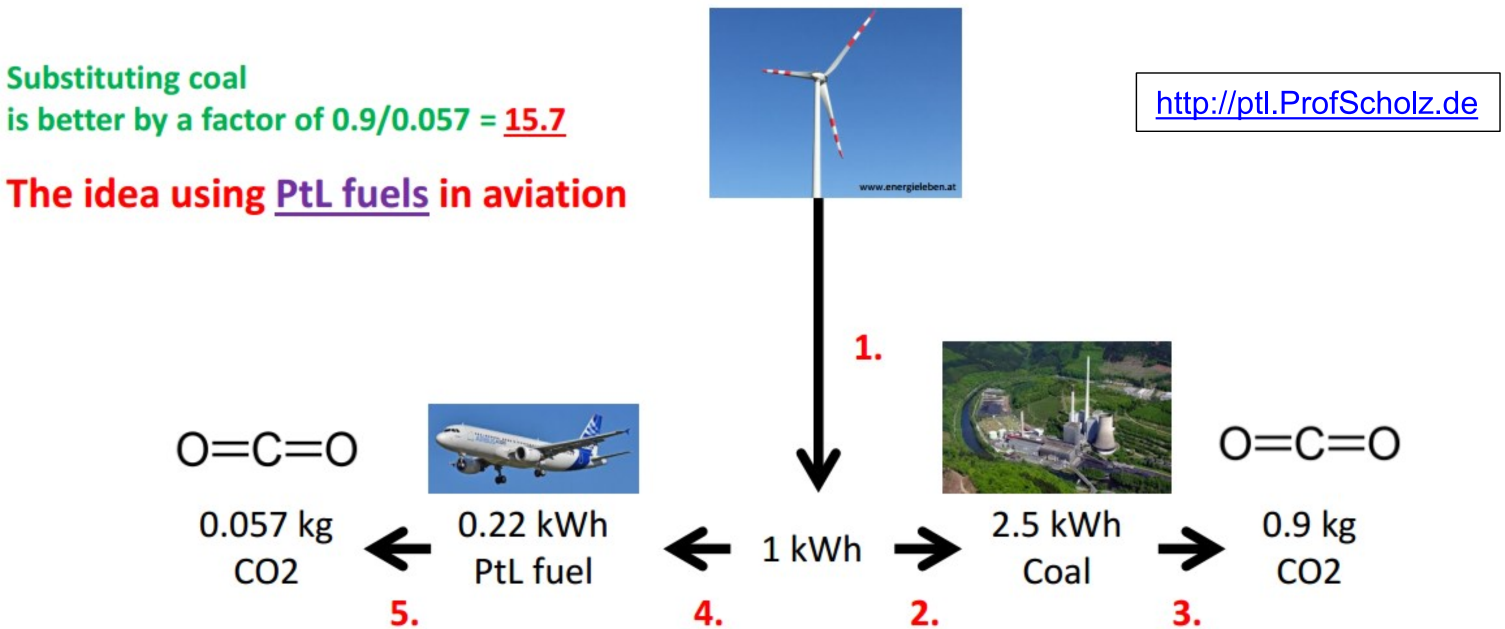
Refueling One A350 Once per Day with SAF (E-Fuel): 53 of the Larges Wind Power Plants (4.6 MW each) Are Needed!



Airbus A350-900
Tank Volume: 138 m³
Fuel Mass:110.4 t (800 kg/m³)
Energy: 4747.2 GJ (43 MJ/kg)
One E-160 per day: 89.4 GJ SAF
(Capacity Factor: 0.5, η_{PTL} = 0.45)

53 E-160 required !

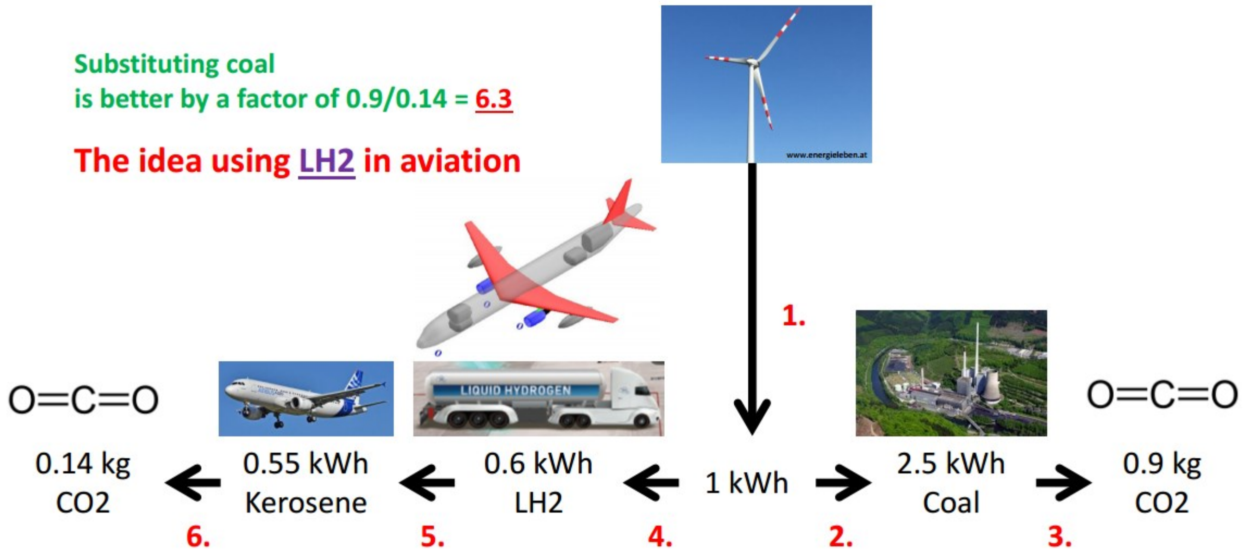
Best: Use Renewable Energy to Replace Coal Power Plants



1.) 1 kWh of renewable energy ...
2.) ... can replace 2.5 kWh lignite in coal-fired power plants (efficiency 40%);
3.) This corresponds to 0.9 kg of CO2 (0.36 kg of CO2 for 1 kWh of energy from lignite *).
4.) ... converted into Sustainable Aviation Fuel (SAF) only 0.22 kWh remain (efficiency: 70% electrolysis, 32% Fischer-Tropsch), 99% transport; https://perma.cc/BJJ6-5L74
5.) which save only 0.057 kg of CO2 (0.26 kg of CO2 for 1 kWh of kerosene *).
* UBA, 2016: CO2 Emission Factors for Fossil Fuels. https://bit.ly/3r8avD1

Best: Use Renewable Energy to Replace Coal Power Plants

http://ptl.ProfScholz.de



1.) 1 kWh of renewable energy ...
2.) ... can substitute 2,5 kWh of coal (lignite, brown coal) in a coal power plant (efficiency of a coal power plant: 40%) this is
3.) ... equivalent to 0.9 kg CO2 (0.36 kg CO2 for 1 kWh of energy burning lignite*)
4.) ... but if used in an aircraft it generates LH2 with energy of 0.6 kWh (efficiencies: 70% electrolysis, 83% liquefaction & transport)
5.) LH2 aircraft consume (say) 10% more energy (higher operating empty mass, more wetted area); so a kerosene aircraft needs ...
6.) only 0.55 kWh, which can be substituted. This is equivalent to 0.14 kg CO2 (0.26 kg CO2 for 1 kWh of energy burning kerosene*).
7.) Note: Not considered is that hydrogen aircraft may come with higher non-CO2 effects than kerosene aircraft.

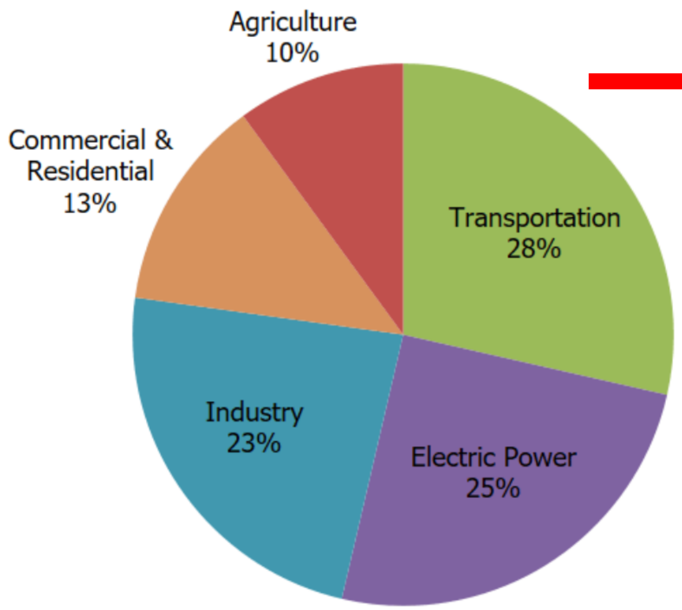
* UBA, 2016. CO2 Emission Factors for Fossil Fuels. Available from: https://bit.ly/3r8avD1

Climate & Statistics

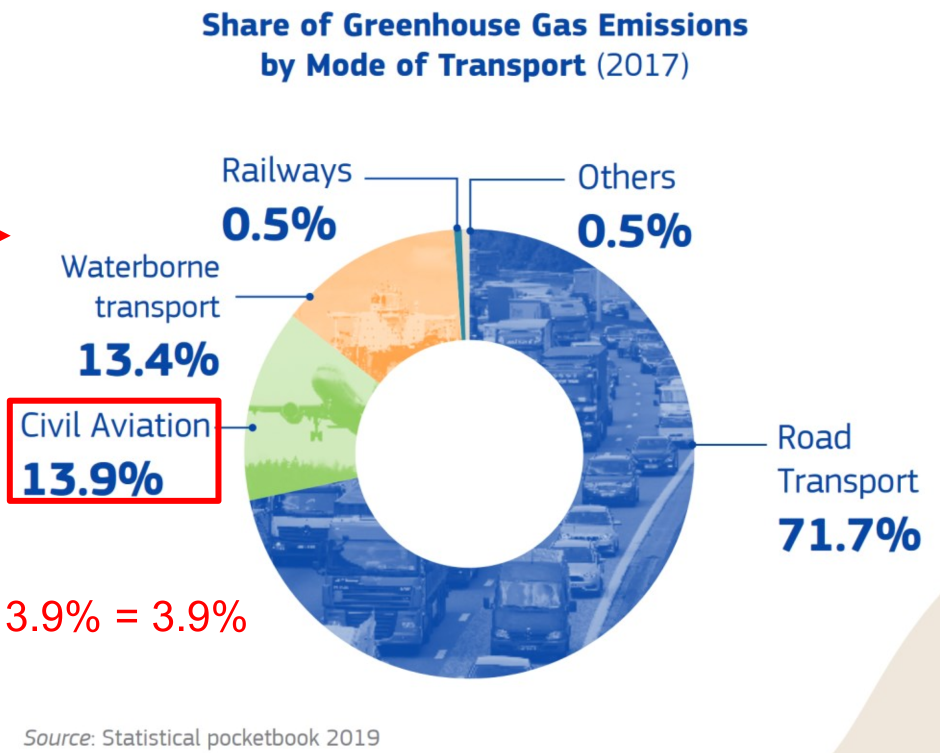
"Contribution of global aviation in 2011 was calculated to be 3.5% of the net anthropogenic Effective Radiative Forcing (ERF)."

Lee 2020, https://doi.org/10.1016/j.atmosenv.2020.117834

What is 100% ?

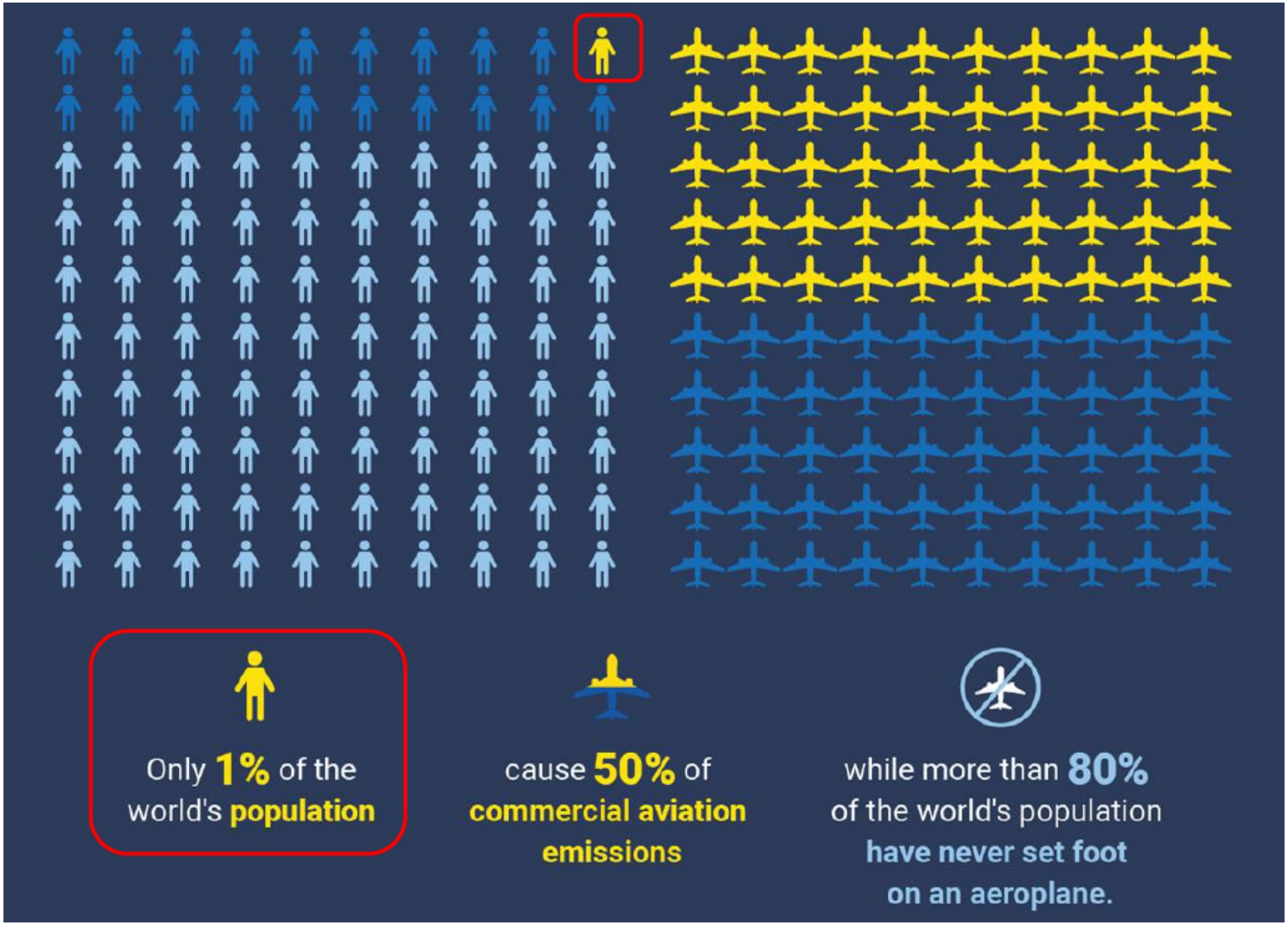


https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions



28% of 13.9% = 3.9%

https://doi.org10.2775/395792



https://stay-grounded.org/get-information

Summary

Does <u>not</u> work to Safe the World:

Alternative Fuels

Aviation Technology

Does work to some extend:

Contrail Management – Now !

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