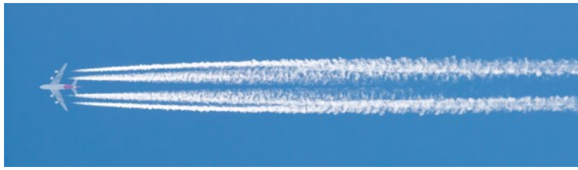
Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

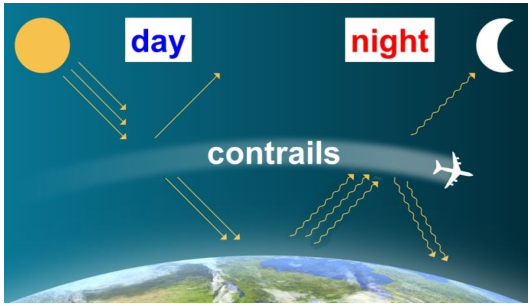
AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)



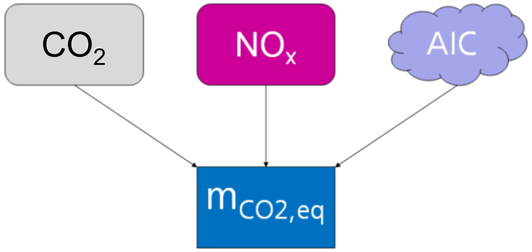
Contrail Management – From Basics to Application

Dieter Scholz

Hamburg University of Applied Sciences



DLRK 2024
DEUTSCHER LUFT- UND RAUMFAHRTKONGRESS
DGLR
30.09. – 02.10.2024 | HAMBURG



Abstract

Purpose – To show how warming persistent contrails can be predicted based on only a few physical parameters. Show the application. Present a simple equation to predict the global effect of Aviation Induced Cloudiness (AIC) considering fuel burn.

Findings – Contrail formation depends (among other parameters) on the overall efficiency of the aircraft. This efficiency does not depend on aircraft drag, but on Specific Fuel Consumption (SFC), c = c_a*V+c_b and as such on aircraft speed, V. For aircraft flying overhead, contrail persistence can be predicted. Various flight planning tools exist that help to avoid warming contrails. Global AIC is proportional to aircraft fuel burn with respect to average global aircraft fuel burn. Passengers should seek a flight with the lowest fuel burn per passenger. This not only to reduce CO2, but also to avoid contrails.

Social Implications – The International Air Transport Association (IATA) lobbies against contrail management. In contrast, this presentation provides arguments, why contrail management is simple, science based, necessary and ready to be applied.

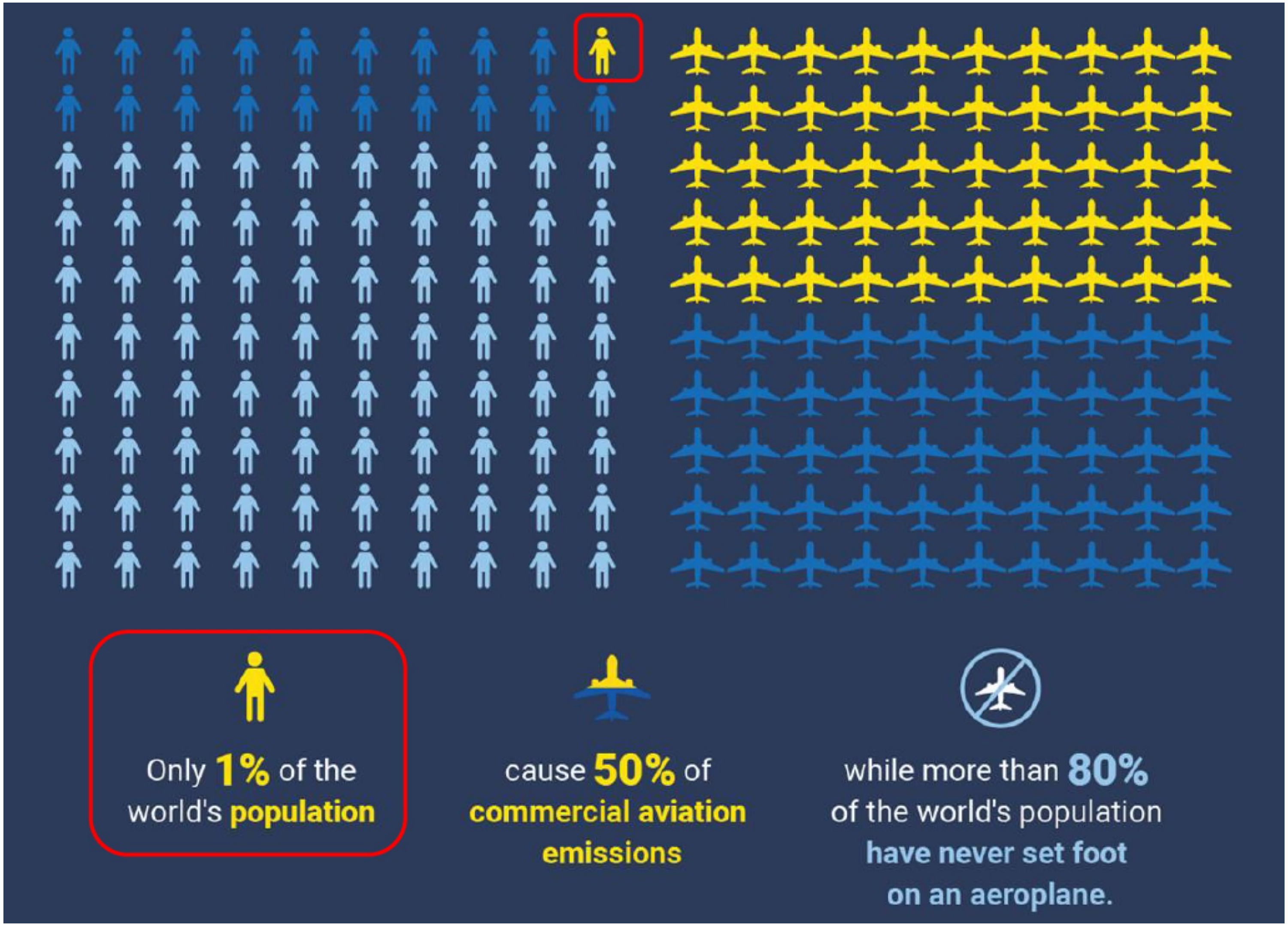
Contents

- **Motivation, Aviation & Society, Aviation Politics**

- **Contrails**
  - **Contrail Basics**
  - **Contrail Avoidance**
  - **Contrail Observation & Prediction**
  - **Contrail Management**

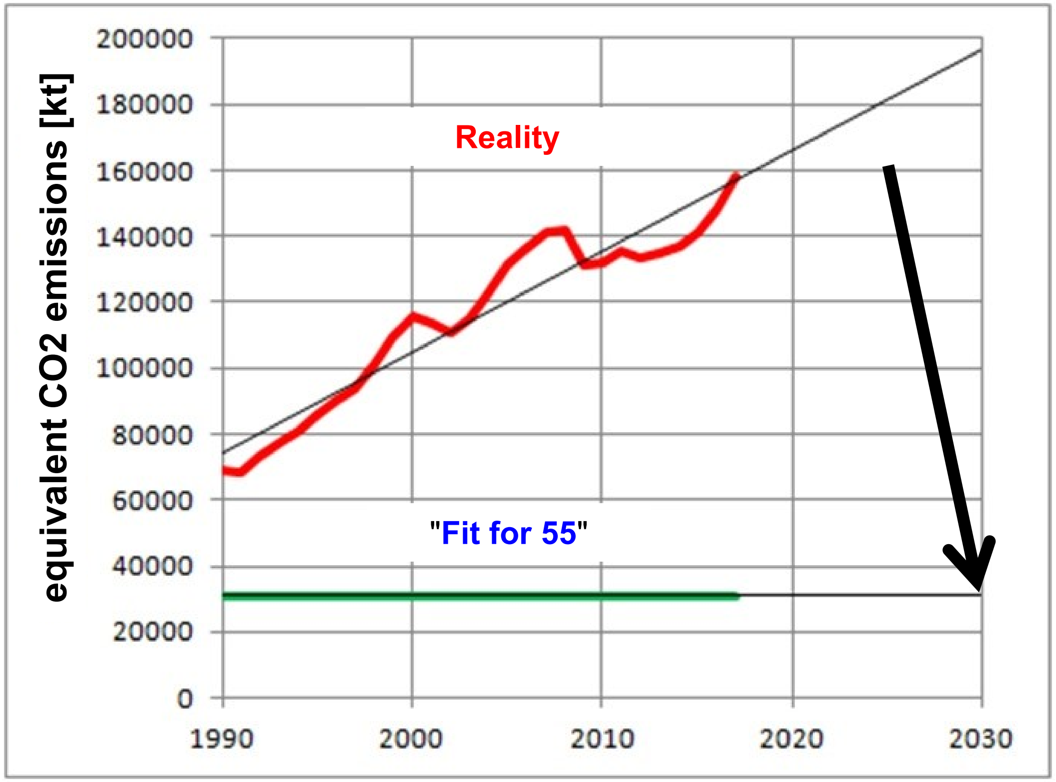
- **Equivalent CO2 Mass: The Equation for Aircraft Design & Ecolabel for Aircraft with Improved AIC Calculation**

- **Summary**



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

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.

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

Hamburg Aerospace Lecture Series
http://AeroLectures.de
http://environment.AeroLectures.de

Hamburg Aerospace Lecture Series
DGLR
HAW Hamburg
RAeS
VDI
ZAL

24.11.22	**Climate Optimized Flight Routes – The Path from Research to Operations** DOI 10.5281/zenodo.7396324	Dr. **Ralph Leemüller**, DFS Deutsche Flugsicherung GmbH	DGLR		Online with Zoom 3.4 MB Related Paper (German): 0.5 MB
03.11.22	**Wege zu weniger klimaschädlichem Luftverkehr – Politik in Deutschland** DOI 10.5281/zenodo.7325002	**Susanne Menge**, MdB, Mitglied des Verkehrsausschusses und Berichterstatterin der Fraktion Bündnis 90/Die Grünen für Luftverkehr	HAW		Online mit Zoom Biografie 0.7 MB
09.06.22	**Detection of Contrails** – Challenges and Future Perspectives DOI 10.5281/zenodo.6720795	Dr. **Tina Jurkat-Witschas** and Prof. Dr. **Christiane Voigt**, Institut of Atmospheric Physics, German Aerospace Center (DLR)	RAeS		Online with Zoom 6.2 MB
02.06.22	**Passenger Aircraft at End-of-Life** DOI 10.5281/zenodo.6648923	Prof. Dr.-Ing. **Dieter Scholz**, MSME, HAW Hamburg	HAW		Online with Zoom 10.1 MB Scholz: Verkehrsflugzeuge am Lebensende
28.04.22	**Fast Measures to Reduce the Climate Impact from Aviation** – Contrail Avoidance and New Fuels DOI 10.5281/zenodo.6554590	Prof. Dr. **Christiane Voigt**, Head of Department Cloud Physics, German Aerospace Center (DLR)	RAeS		Online with Zoom 5.7 MB
27.01.22	**Aviation and the Climate** – An Overview	Prof. Dr.-Ing. **Dieter Scholz**, MSME, HAW Hamburg	RAeS		Online with Zoom 8.2 MB
02.12.21	**Formation and Climate Impact from Contrails** DOI 10.5281/zenodo.5893117	Dr.rer.nat. **Ulrike Burkhardt**, Institute of Atmospheric Physics, German Aerospace Center (DLR)	RAeS		Online with Zoom 4.2 MB

Wissen

NANO vom 8. Mai 2024: Kondensstreifen sind Klimakiller

VERFÜGBAR
bis 08.05.2029

Die Luftfahrtindustrie wird die Klimaziele krachend verfehlen. Neben dem CO_2 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

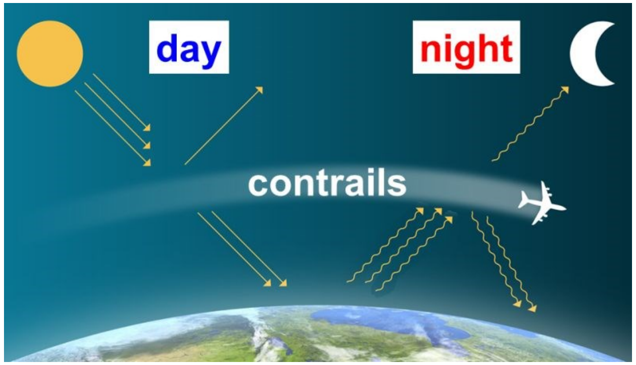
https://youtu.be/HYJawLmiLS8

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?



Contrails

HAW HAMBURG

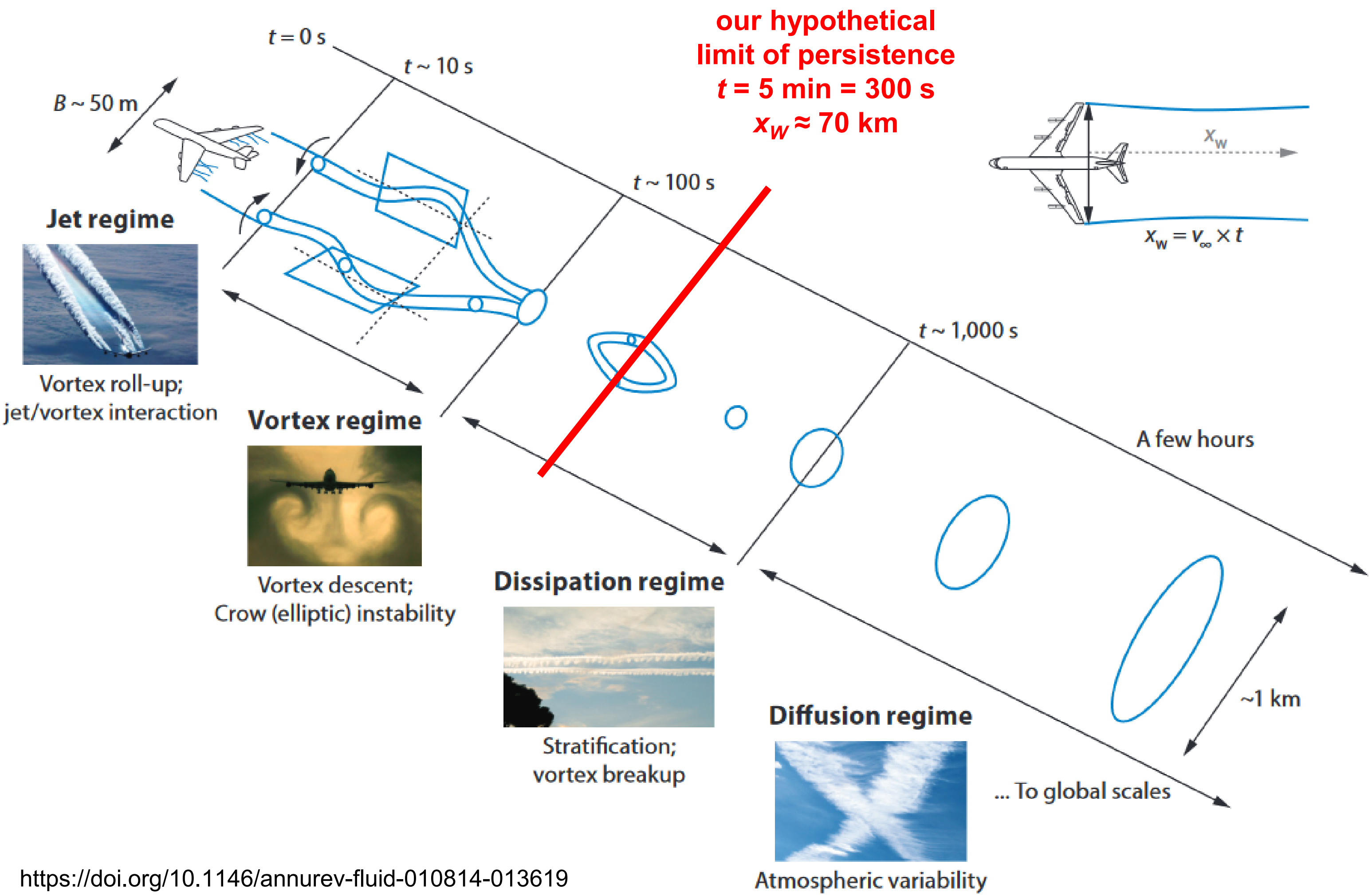
Contrail

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

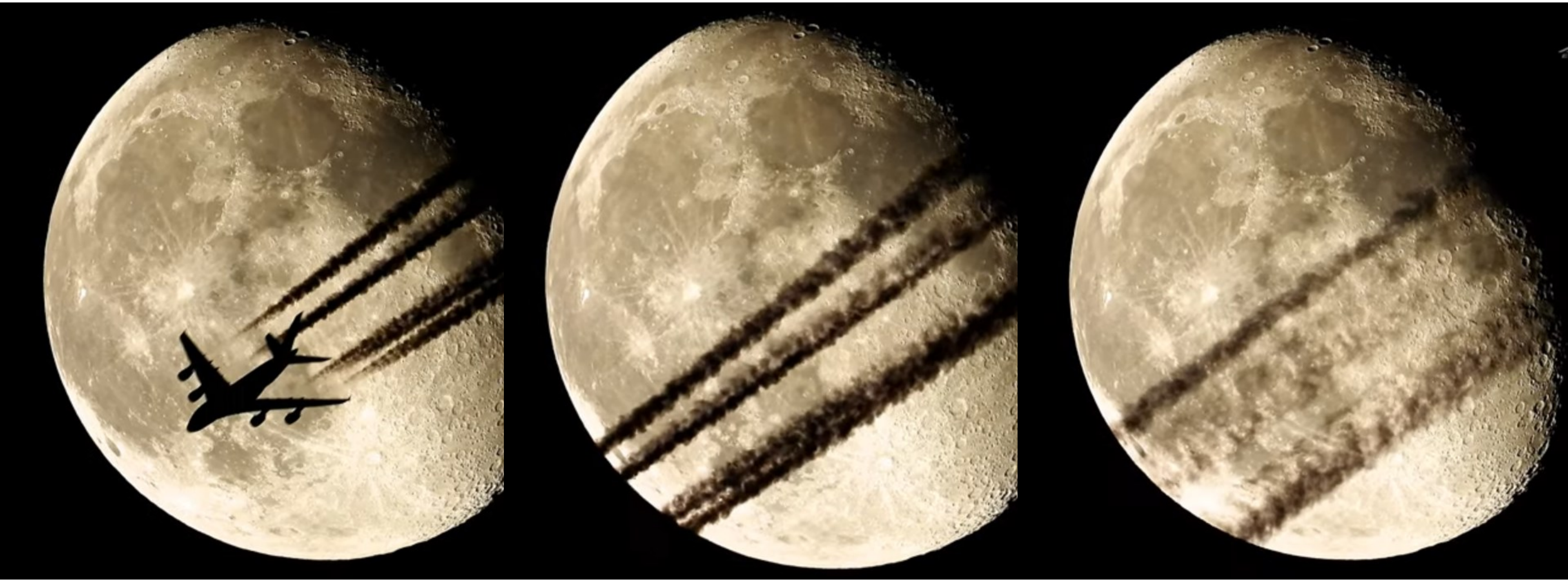


https://doi.org/10.1146/annurev-fluid-010814-013619

Cooling Persistent Contrails (Daytime)

Warming Persistent Contrails (Dawn and Dusk)

Warming Persistent Contrails (Night)

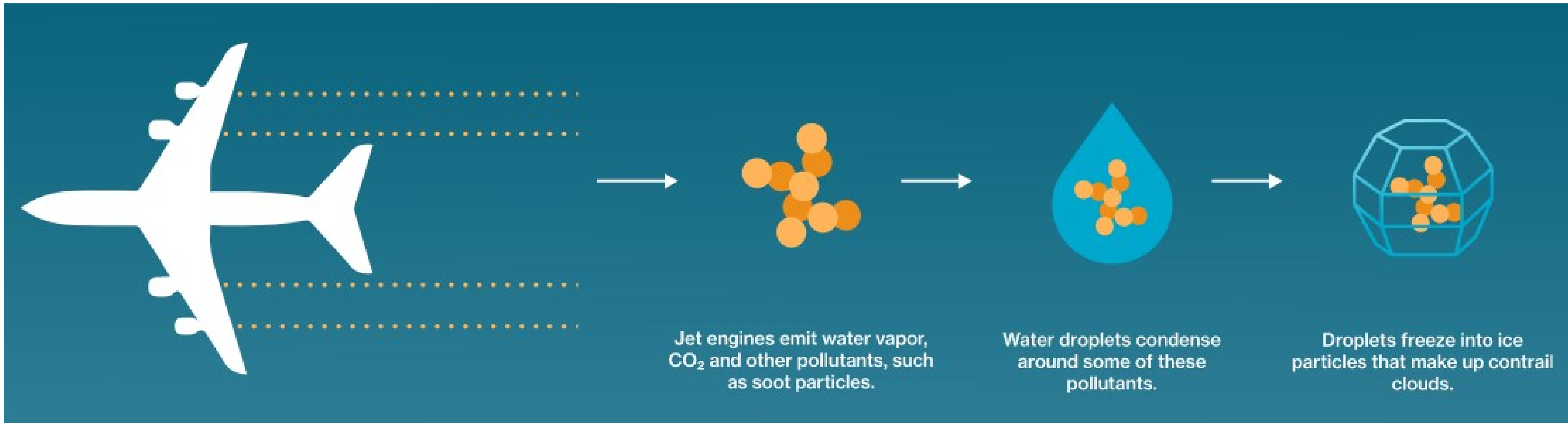


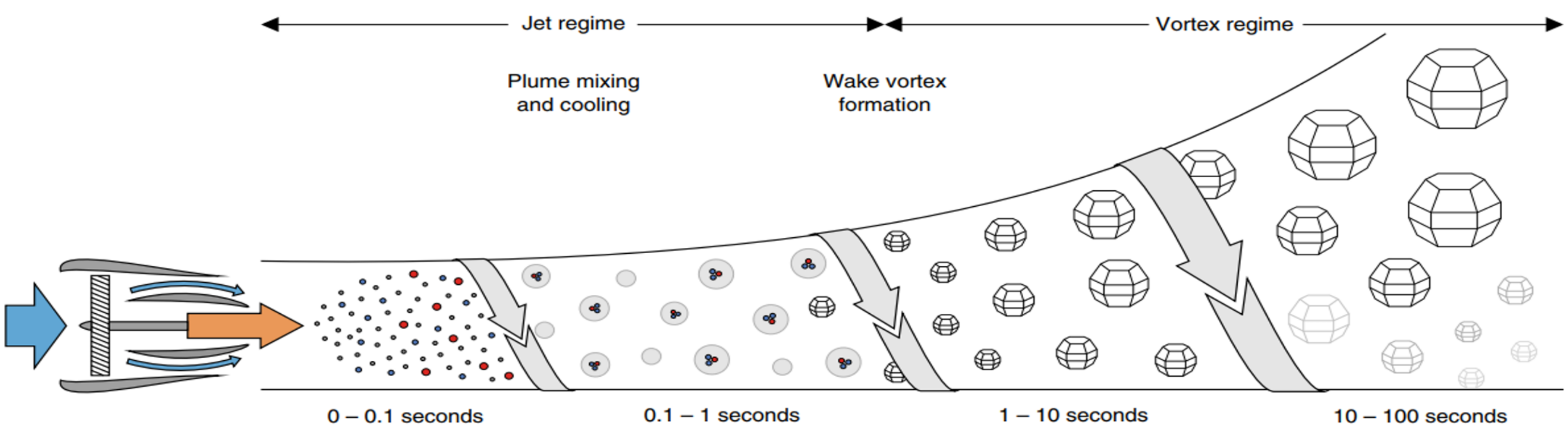
Emirates Airbus A380 registration A6-EKV operating flight EK-232 from Washington Dulles International Airport (IAD/KIAD) destination Dubai (DXB/OMDB) crossing the moon while flying at 39000 feet with ground speed of 497 knots, over Varna city at 01:55 local time on 13 March 2020.

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

Ice Crystal Growth in Contrails

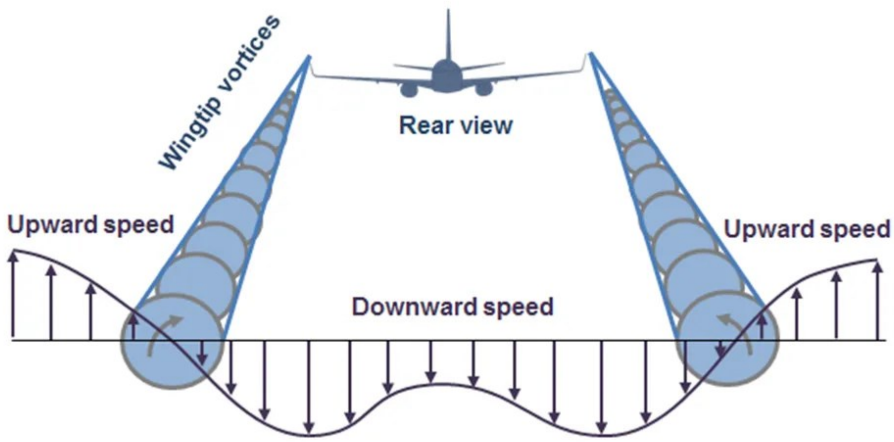
https://contrails.org/science





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

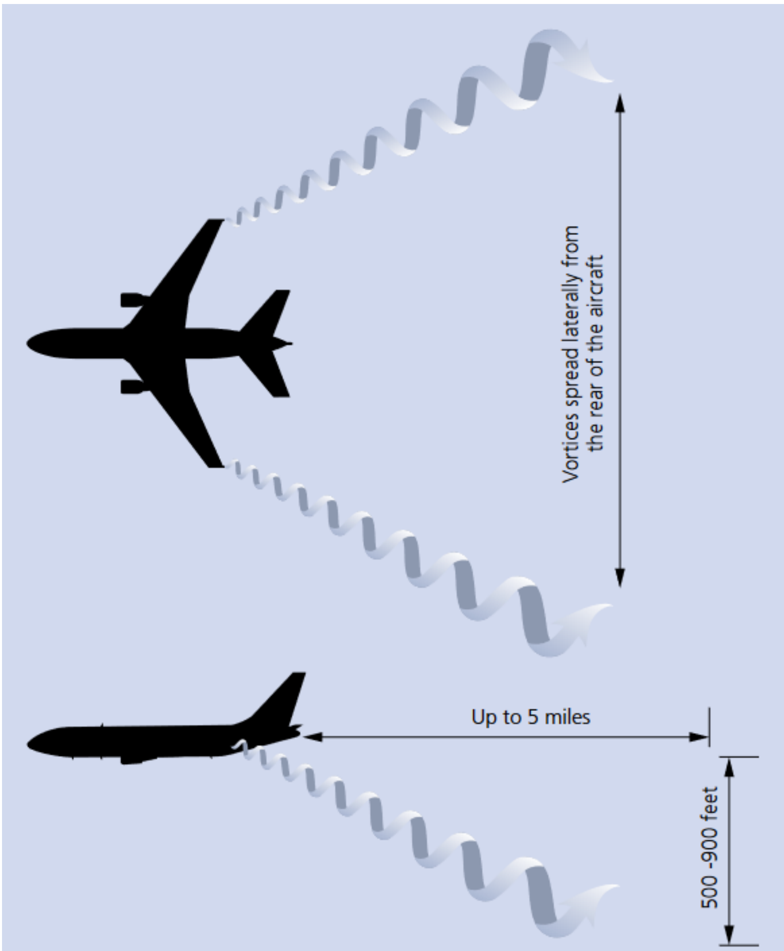


https://medium.com/@devavratatripathy/why-do-airplanes-have-winglets-db25ba41d833
https://www.reddit.com/r/pics/comments/pldog/photo_of_the_downwash_effect_from_a_passing_jet

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)

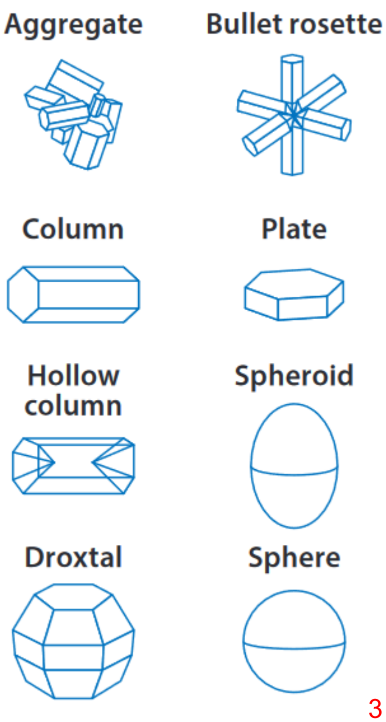
Aircraft	Max Gross Weight (w) lb	Span (b) ft	Airspeed (V) ft/sec	Vortex Spacing (b') ft	Vortex Sink Rate (w) ft/min	Vortex Radius (r) ft	Max Vertical Velocity (less w) (V_r) ft/min
Convair (C-131)	46,000	92	237	72	162	7	1800
Boeing 727	169,000	108	272	86	372	9	4100
Boeing 707	328,000	145	300	115	366	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

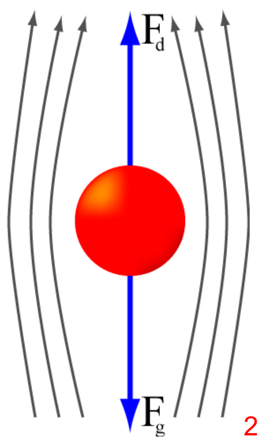
↑ ≈ **2 m/s**

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

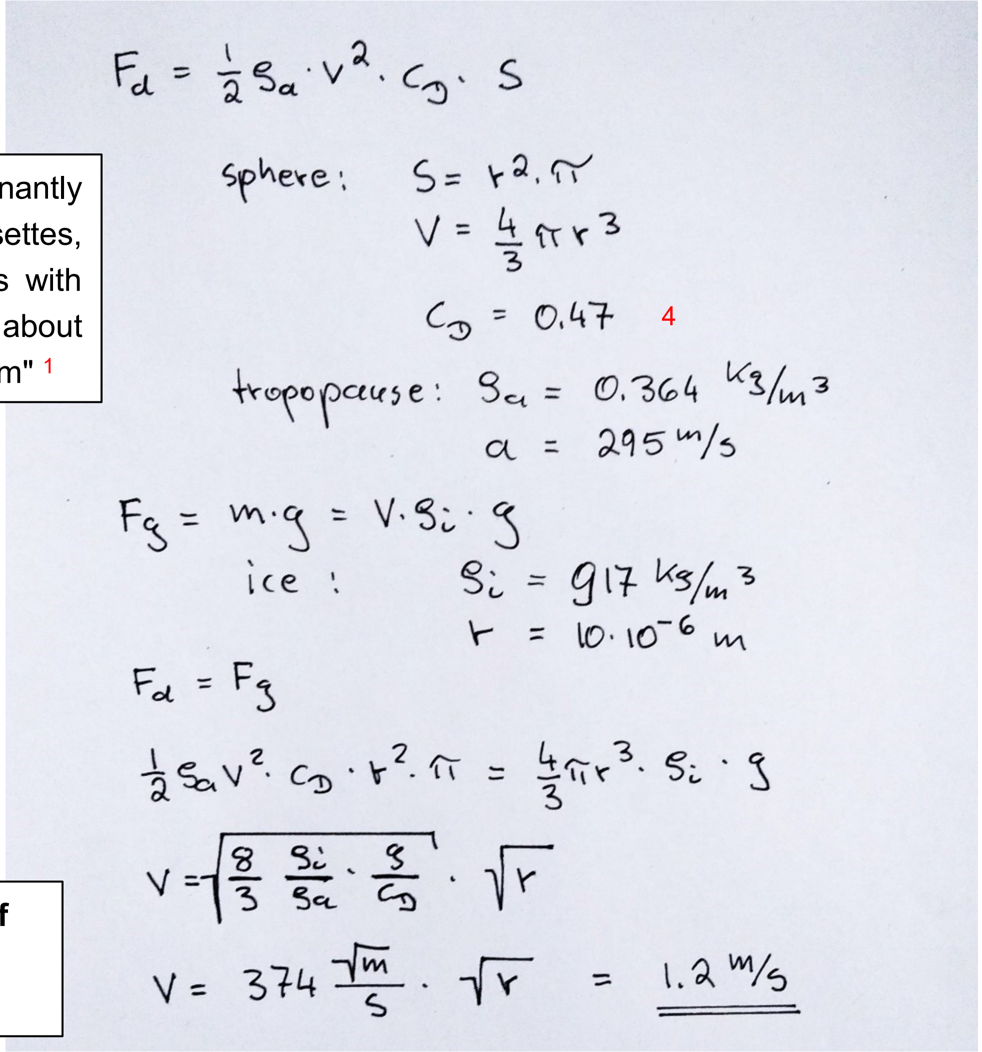
Sedimentation / Settling



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

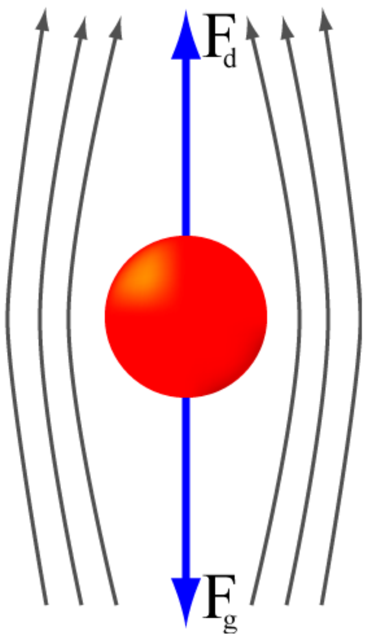


Terminal velocity of typical ice crystals in contrails:



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, $L = 0.0065\ K/m$

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

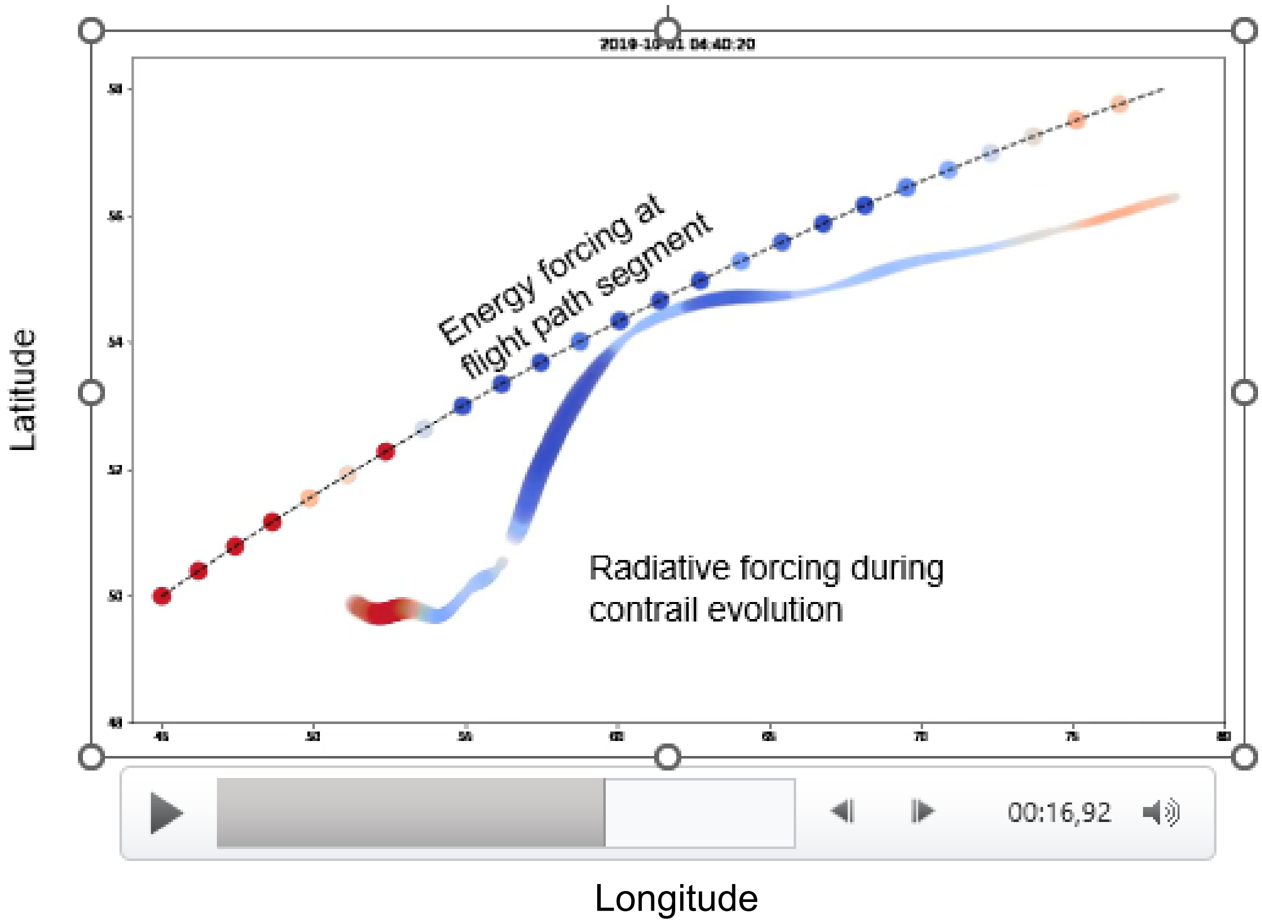
$$V = \frac{\Delta H}{\Delta t} \qquad \Delta t = \frac{\Delta H}{V} = \frac{\Delta T}{V \cdot L}$$

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

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.

JabberWok, CC BY-SA 3.0
https://commons.wikimedia.org/wiki/File:Terminal_Velocity.png

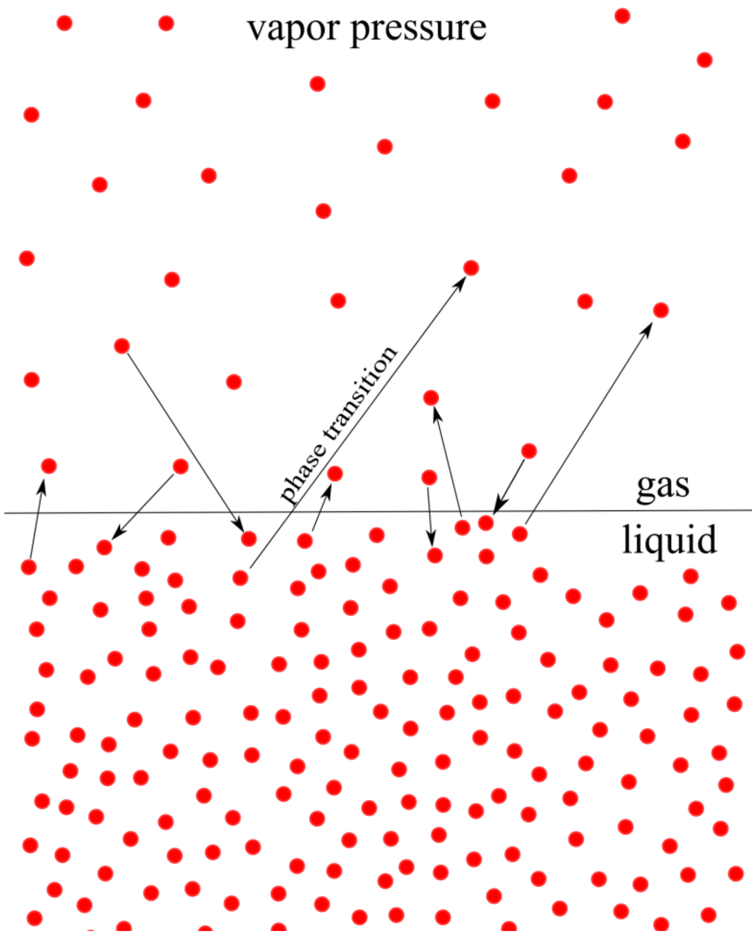
Contrail-Cirrus Prediction Tool (CoCiP)



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

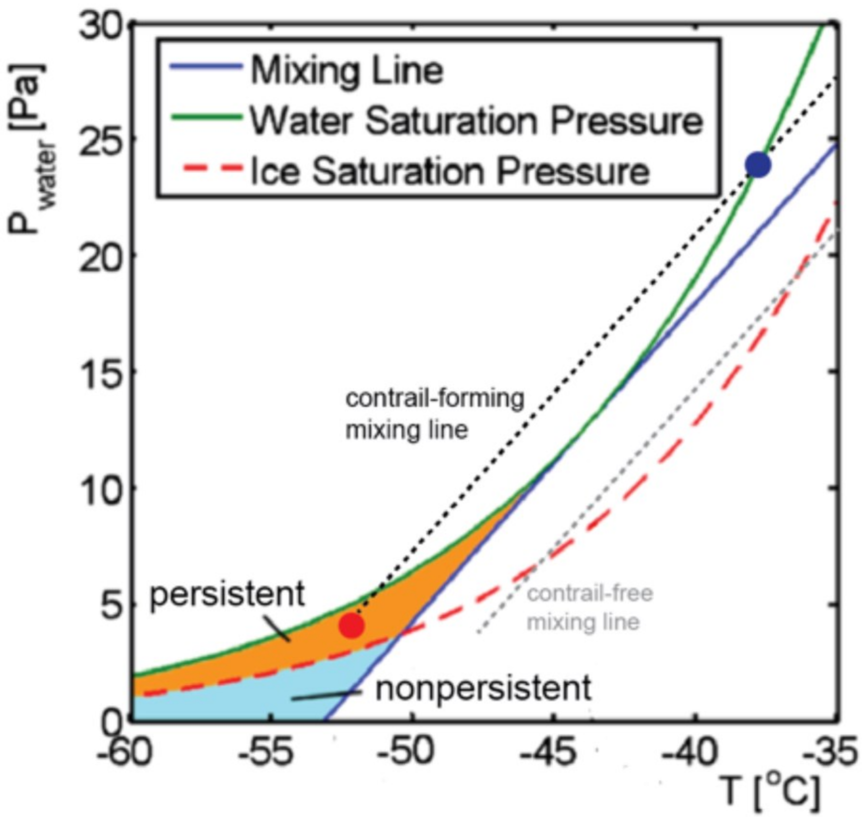
Flight on
10 Jan 2019, 0:00 to 6:00 h

Vapor Pressure



vapor pressure over water	over ice	
evaporation	sublimation	↑
air	air	
water	ice	
condensation	resublimation	↓

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

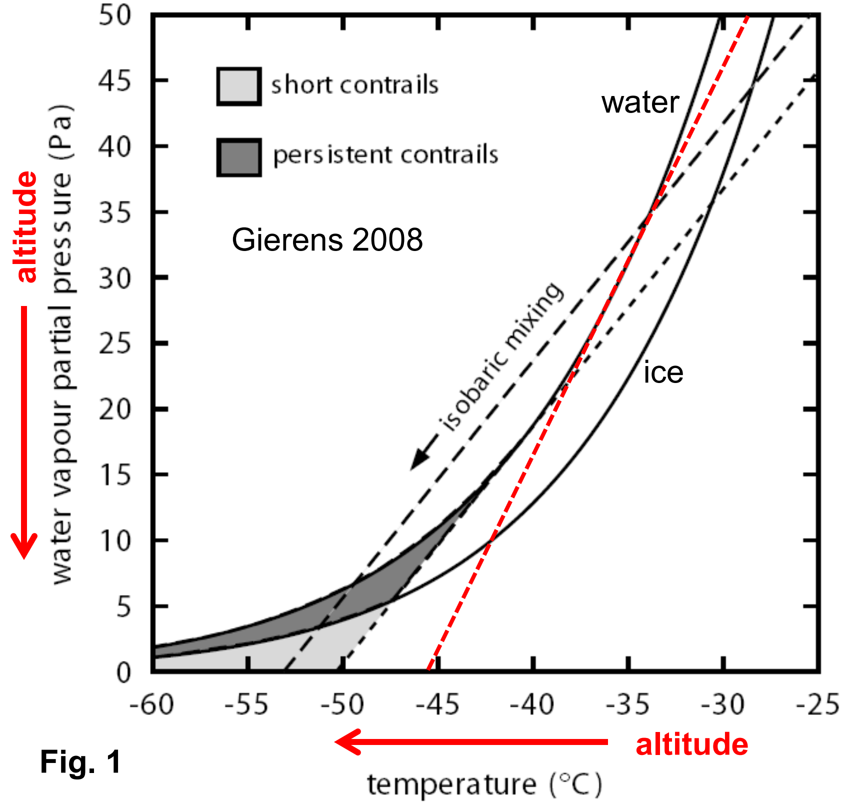


Fig. 1

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

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.

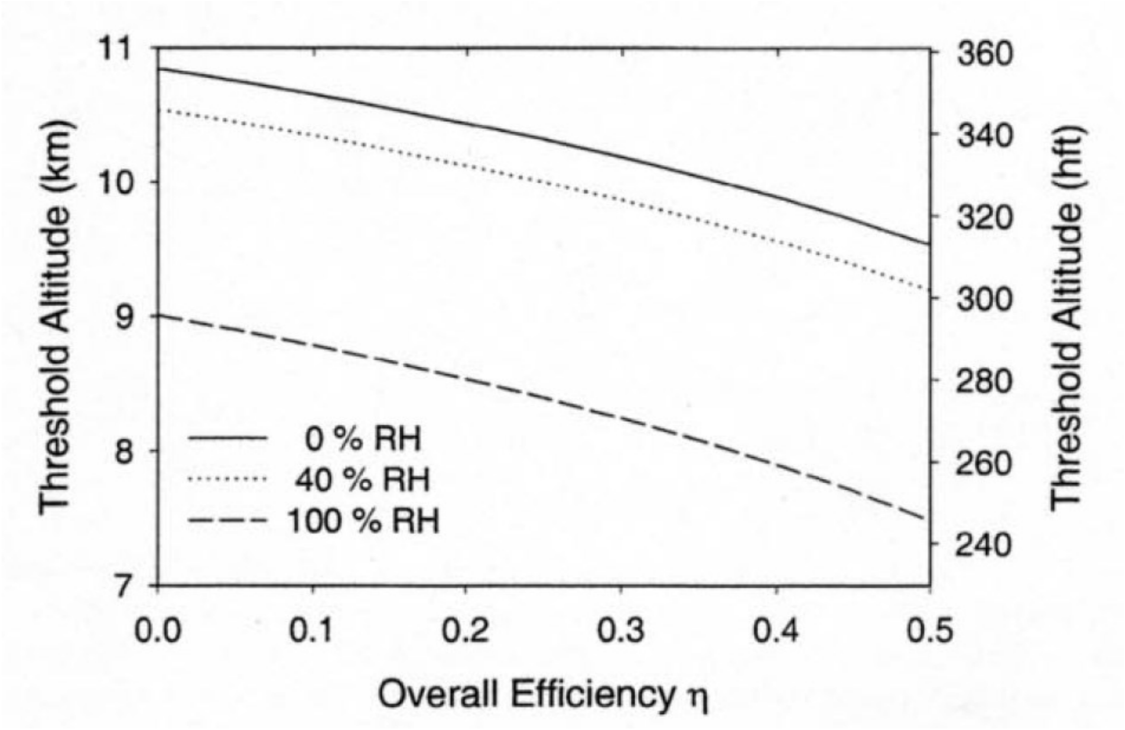
2,58 times more water vapor is produced with LH2 combustion compared to kerosene combustion (for the same energy used).

Effect of the Propulsion Efficiency

Propulsion efficiency

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

m_f: fuel flow
F: thrust or drag



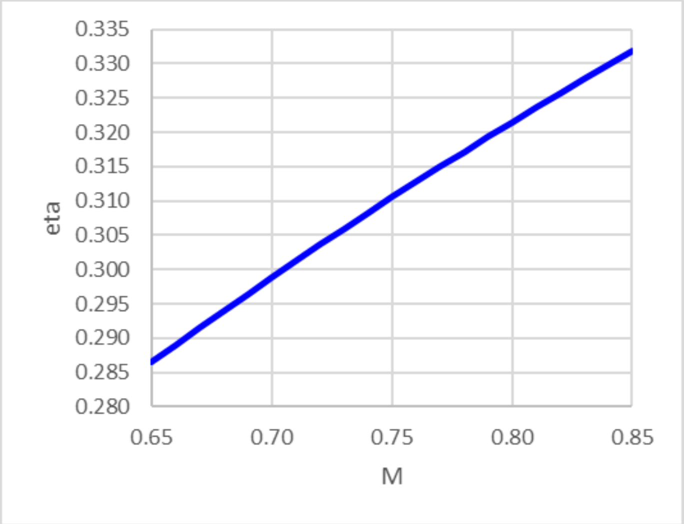
A lower efficiency, η means a smaller slope, *G* which is tangent to the water saturation line further left (at lower temperatures or increase altitude).

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

Efficiency η Does NOT Depend on Drag (only on SFC and Speed)

```
eta = F*V/(m_f*Q)        m_f mass flow rate of the fuel

m_f = c * F   with c Specific Fuel Consumption (SFC) in kg/(Ns)

F cancels out

eta = V/(c*Q)

c = c_a*V + c_b

See: Poster from DLRK 2024 for details.

eta = V/(Q*(c_a*V + c_b))

eta = 1/(Q*(c_a + c_b/V))

eta is function of V (a little depending on thrust, T)
and clearly of BPR and altitude, h.
```



Example calculation: FL 360
c_a = 3.38E-08 kg/(Ns)/(m/s)
c_b = 1.04E-05 kg/(Ns)
c = 16 mg/(Ns) at M = 0.7

https://purl.org/aero/M2017-07-15 (Memo)
https://www.fzt.haw-hamburg.de/pers/Scholz/Aero/AERO_POS_DLRK2024_SFC_2024-09-30.pdf (Poster, => Database)
https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2021-09-15.018 (Master Thesis)

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

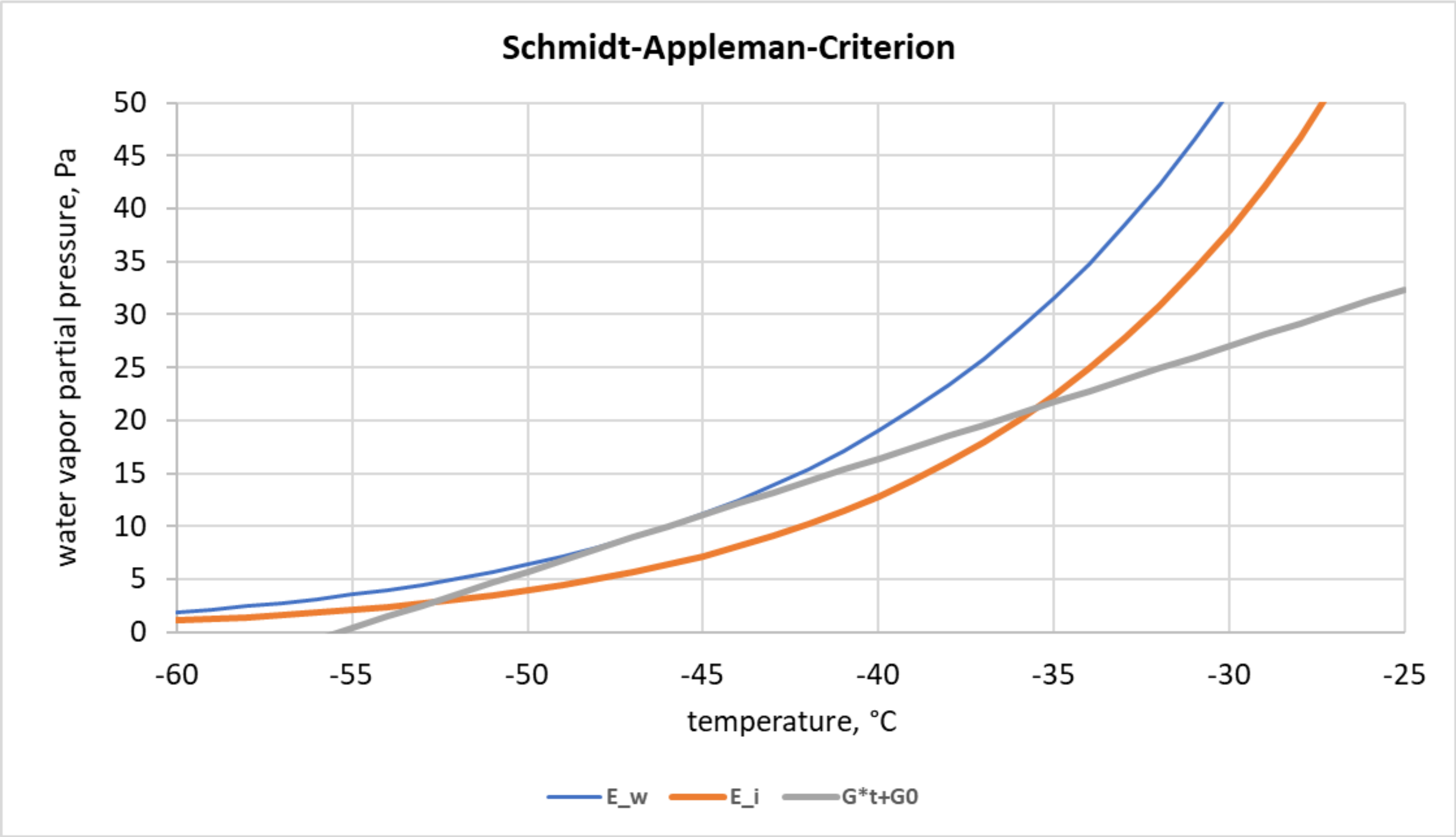
This equation can be solved for *t* with the *Solver* in Excel

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

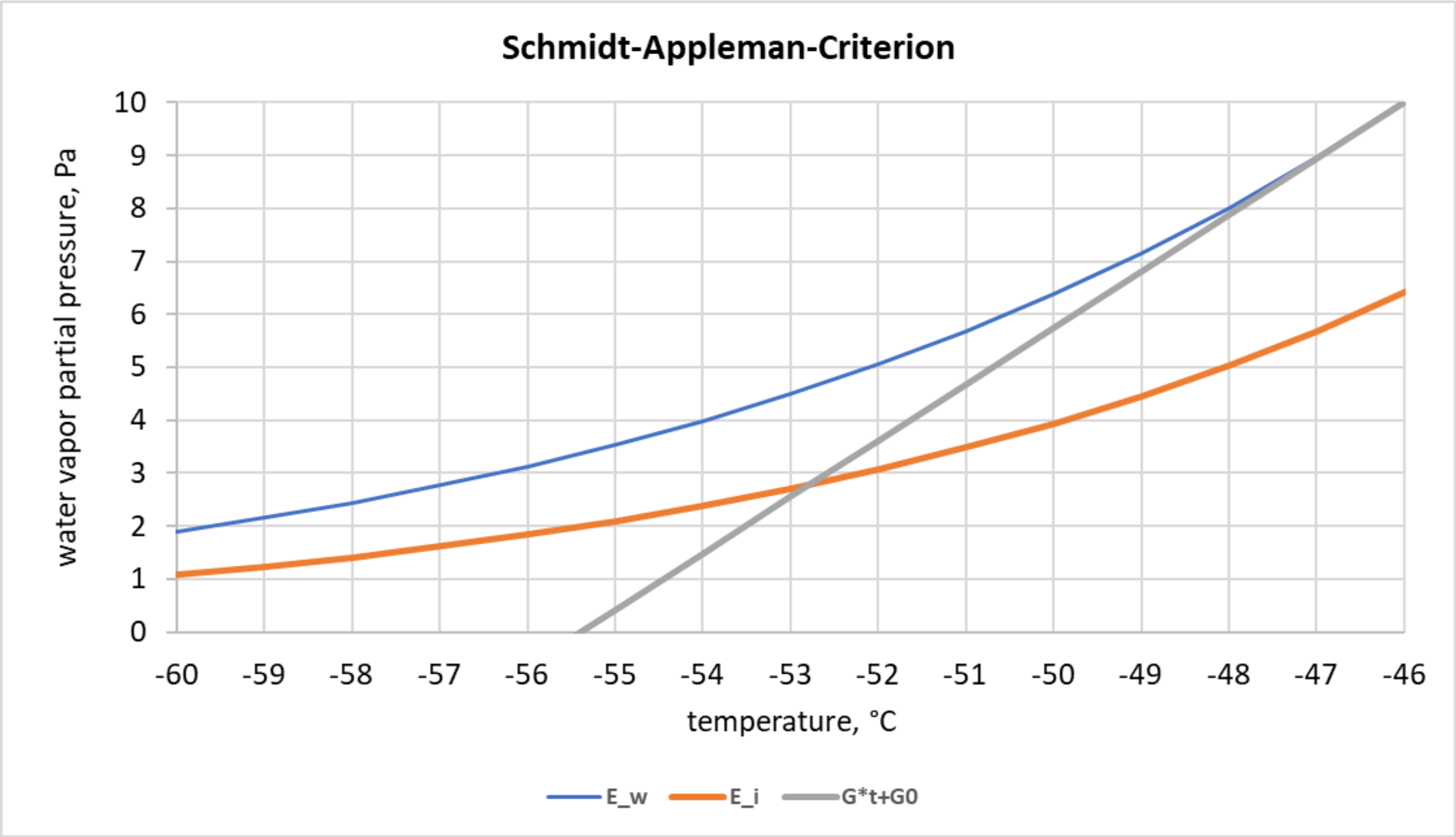
The temperature, *t* is where $E_w(t)$ and f(t) touch. This temperature is called t_{SAC}.
It is the highest temperature for contrails to form.

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?

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

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

Results need to be limited, if:

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

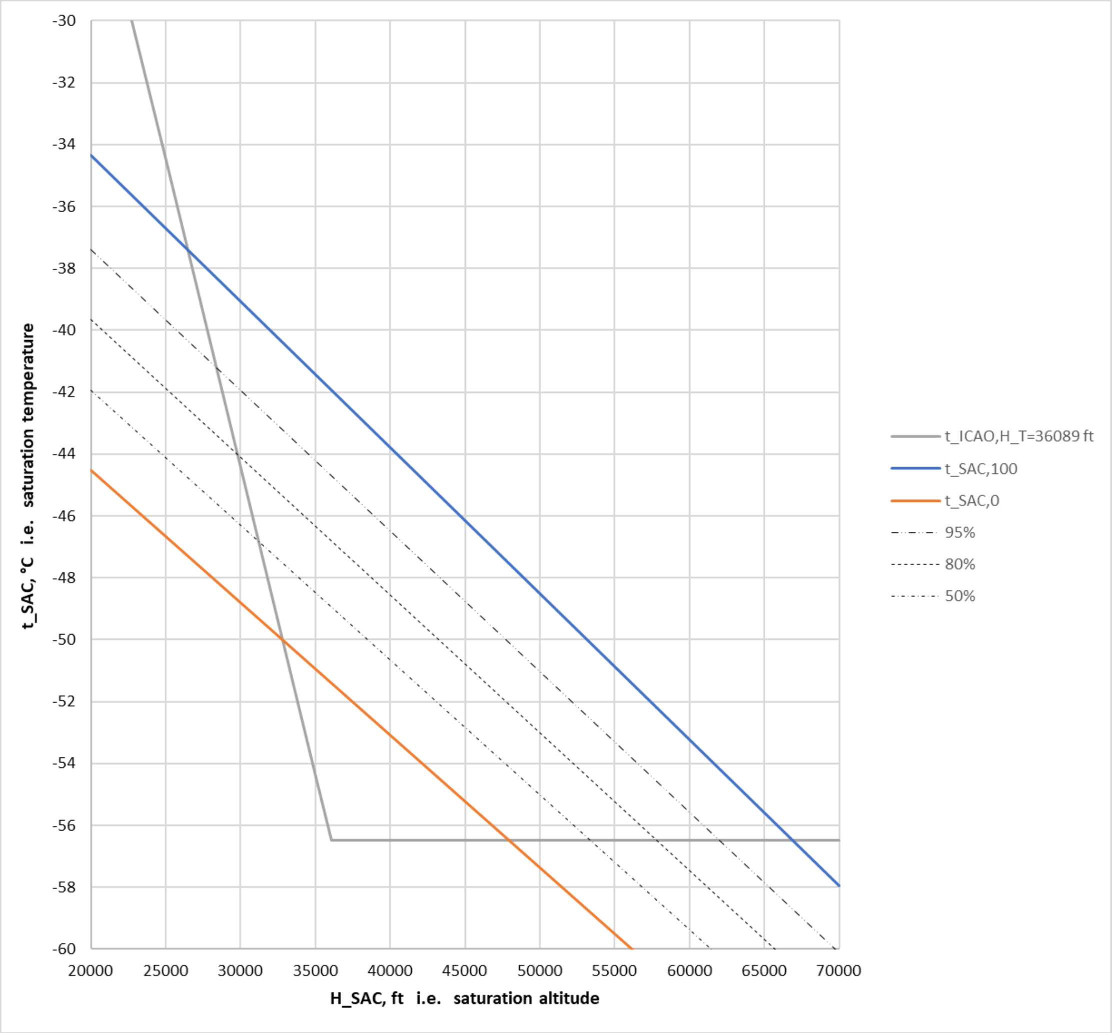
$t > t_{SAC} \Rightarrow \varphi > 100\%$ (not defined)

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)

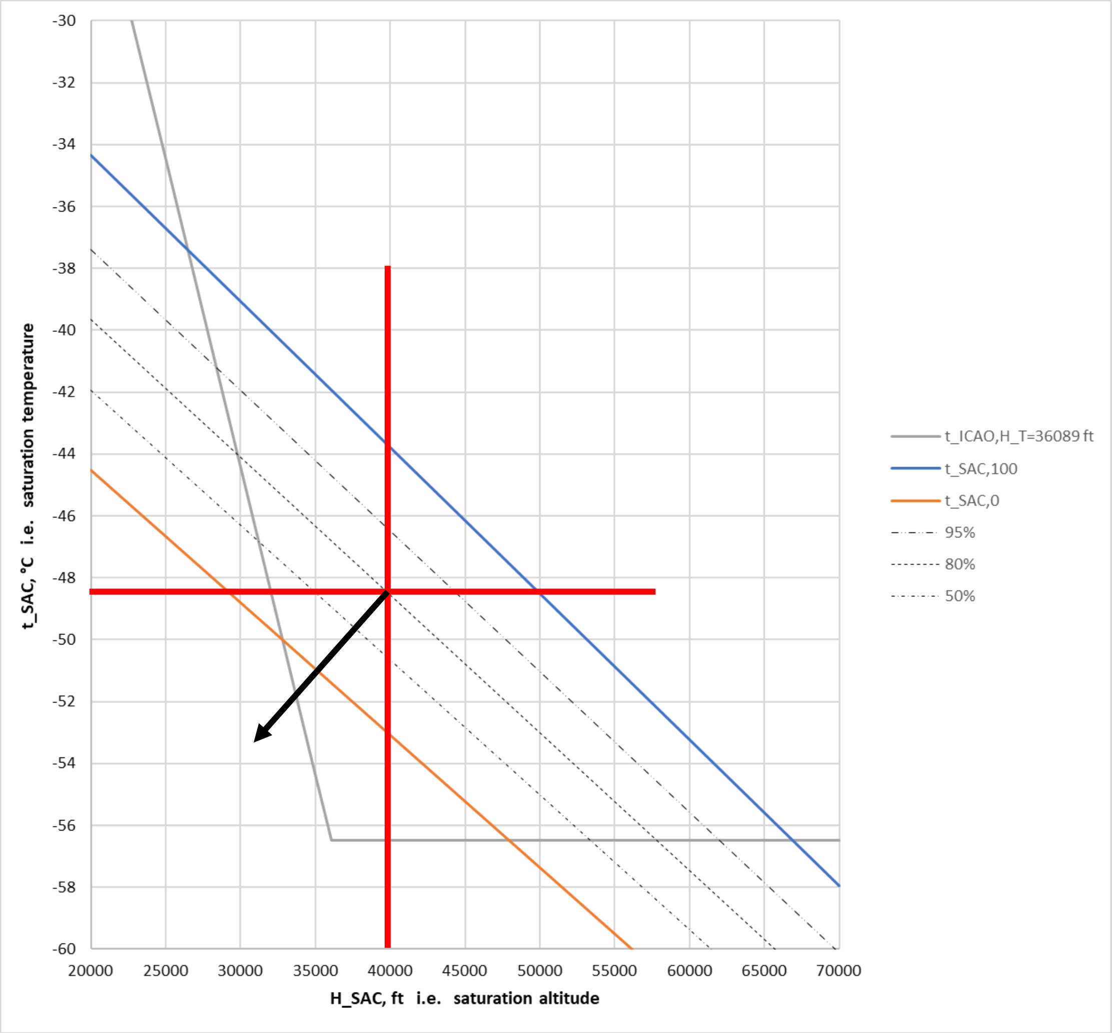


Contrails form down or left of the respective humidity lines.

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)



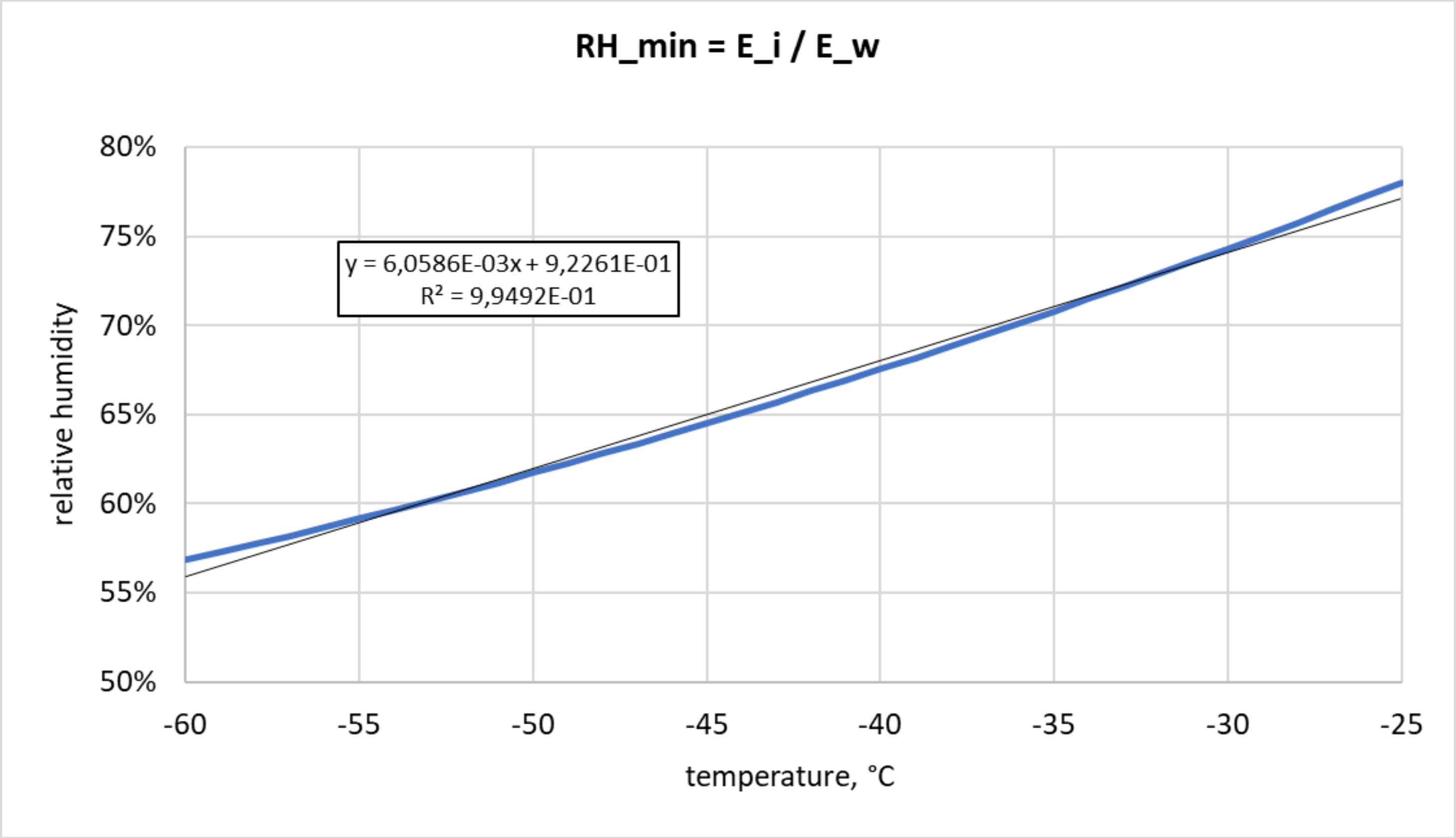
An aircraft flies at altitude, *H* and air temperature, *t*.

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.

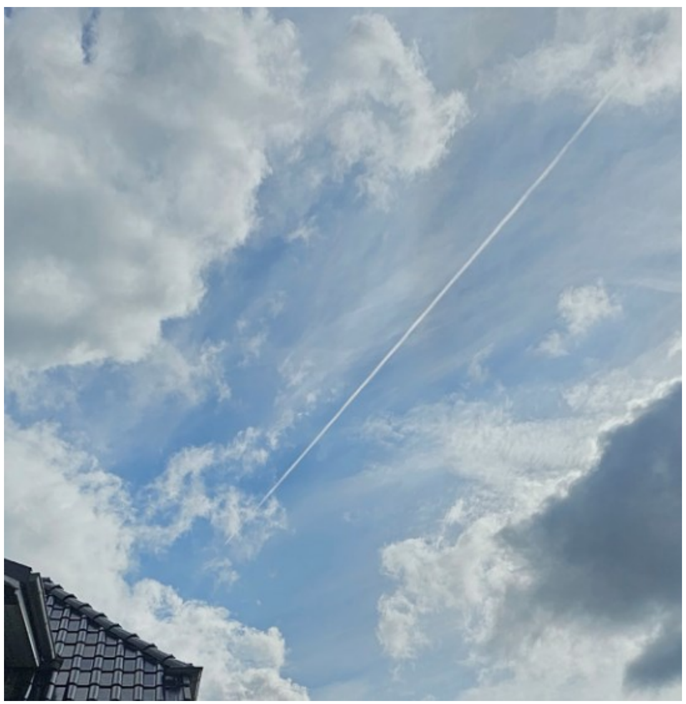
Contrail

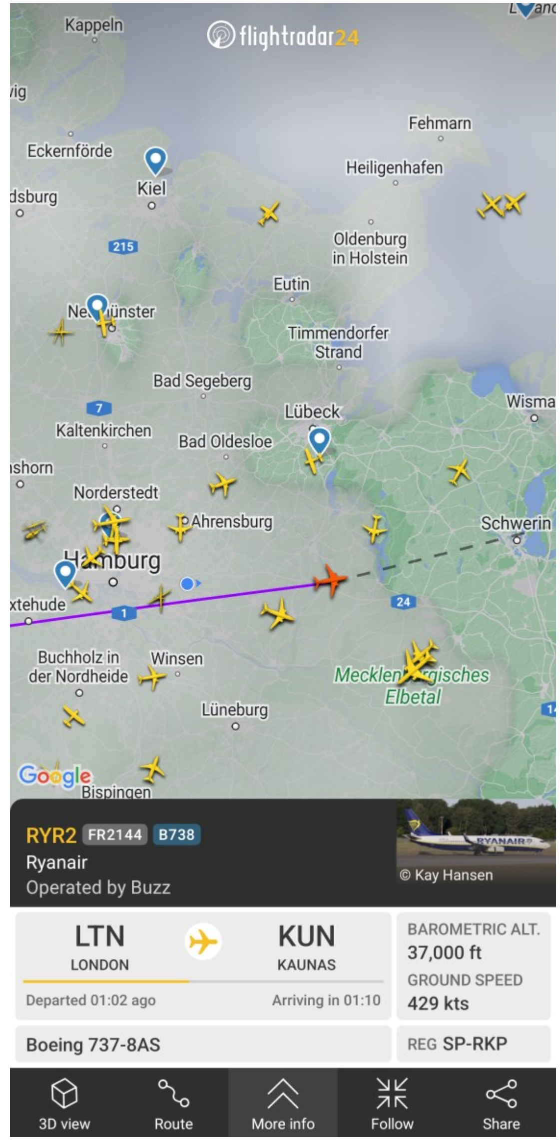
Prediction & Observation

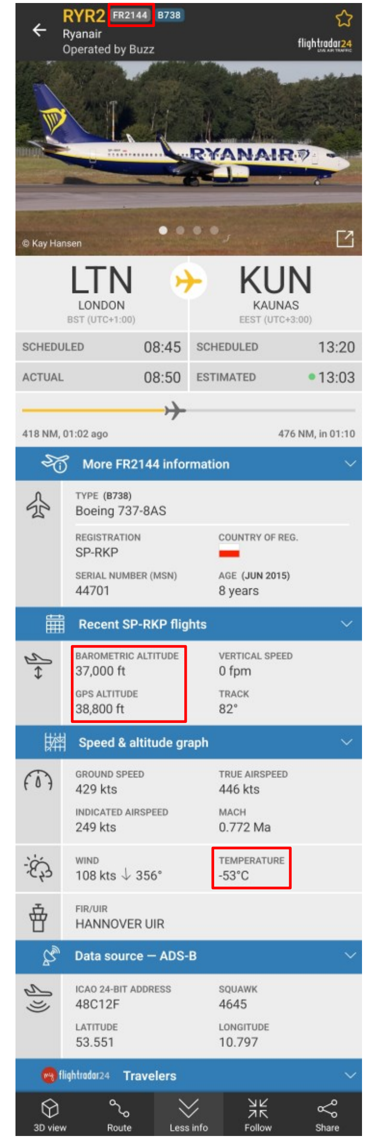
BRIEGERT, Finn, 2024. *Aircraft Contrails – Observation and Prediction*. Project. Hamburg University of Applied Sciences, Aircraft Design and Systems Group (AERO). Available from: https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2024-03-14.019

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.

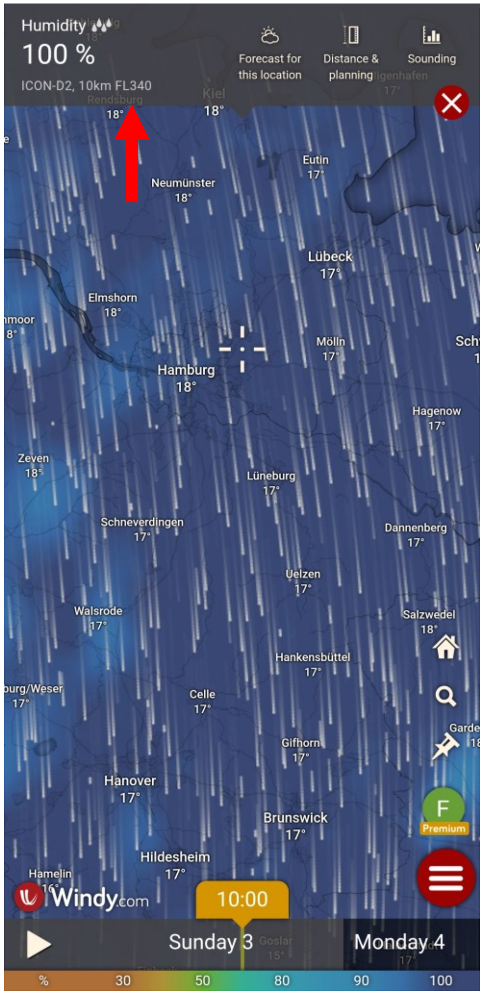


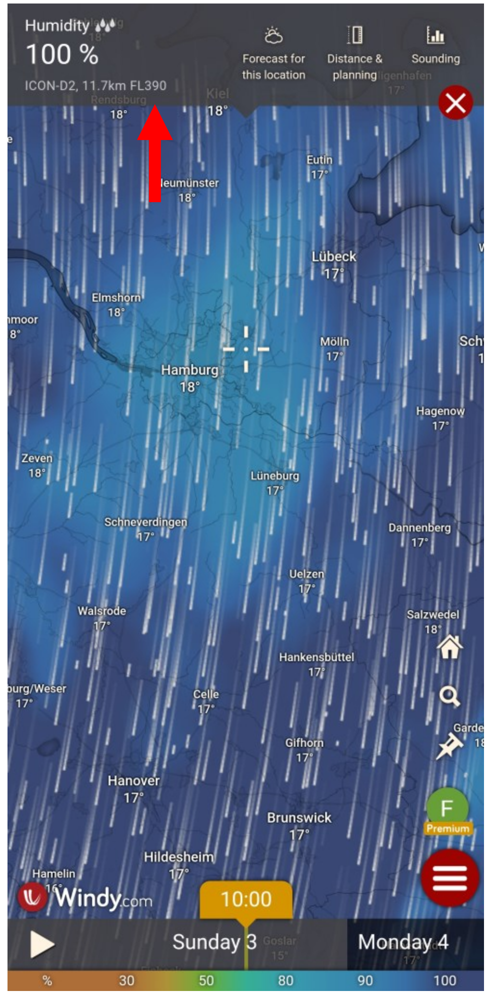




EGGW - EYKA

Relative Humidity





Relative humidity at FL340: 100%

Relative humidity at FL390: 100%

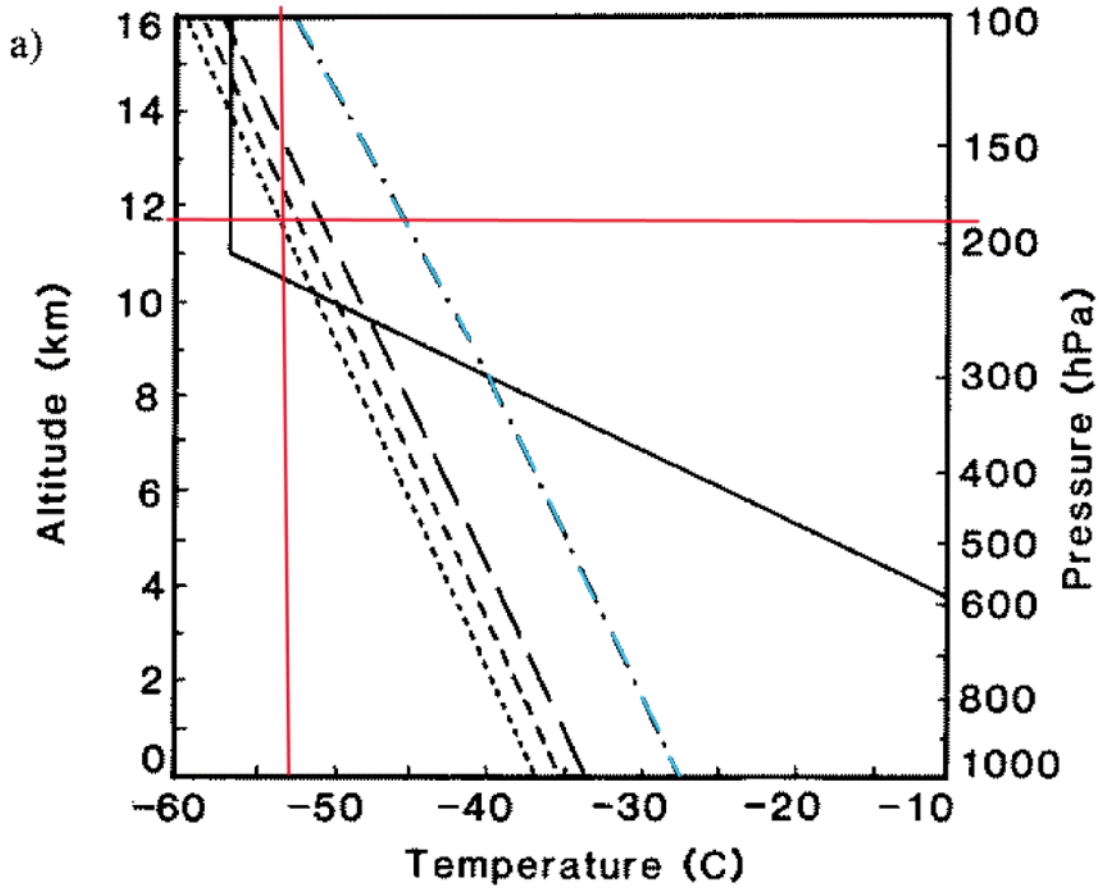
Interpolated relative humidity at FL370: 100% (trivial here).

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**.

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

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.

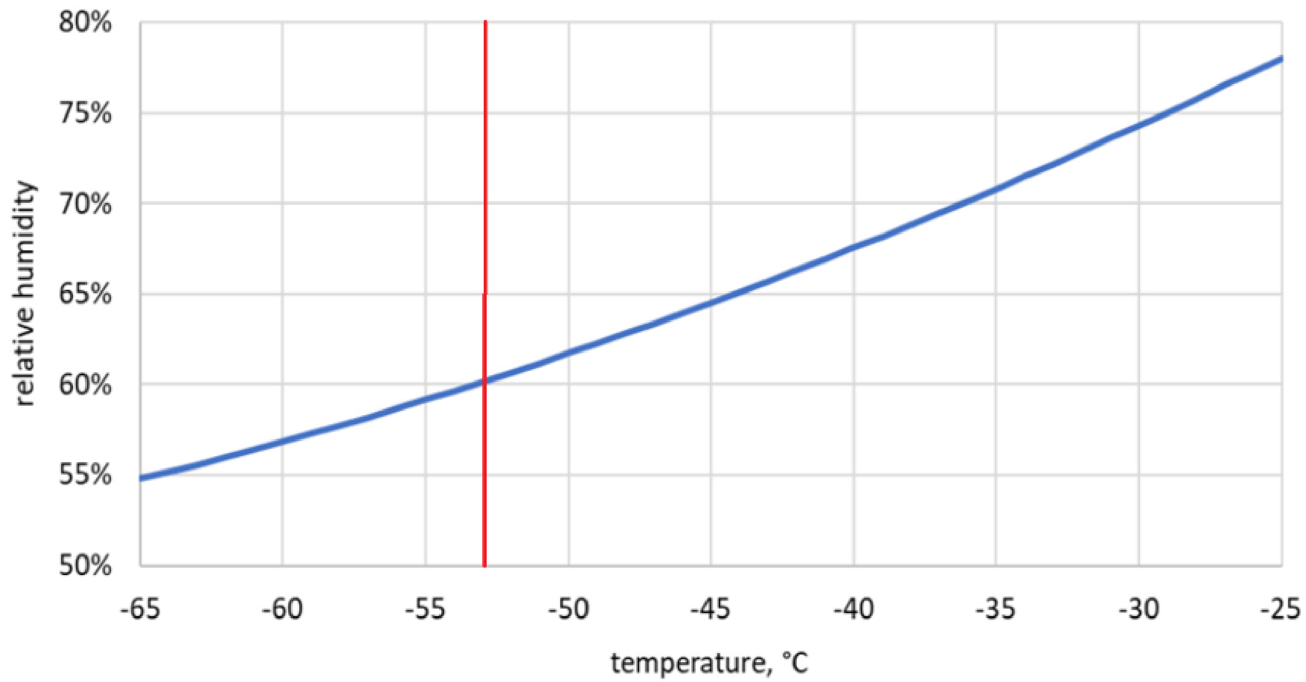
This project starts with this hypothesis:

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

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.)

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.

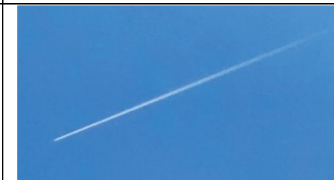
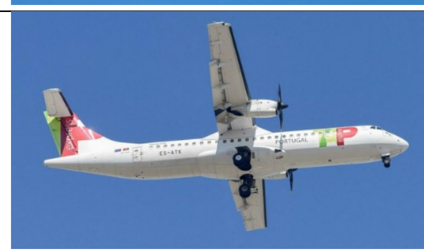
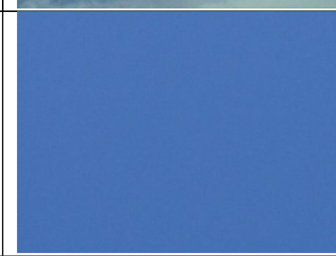
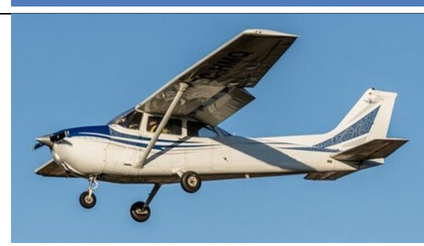
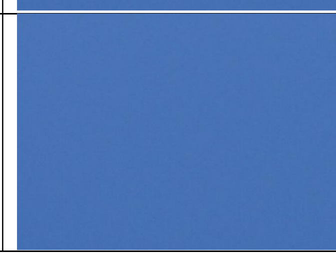
Definition

	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.*

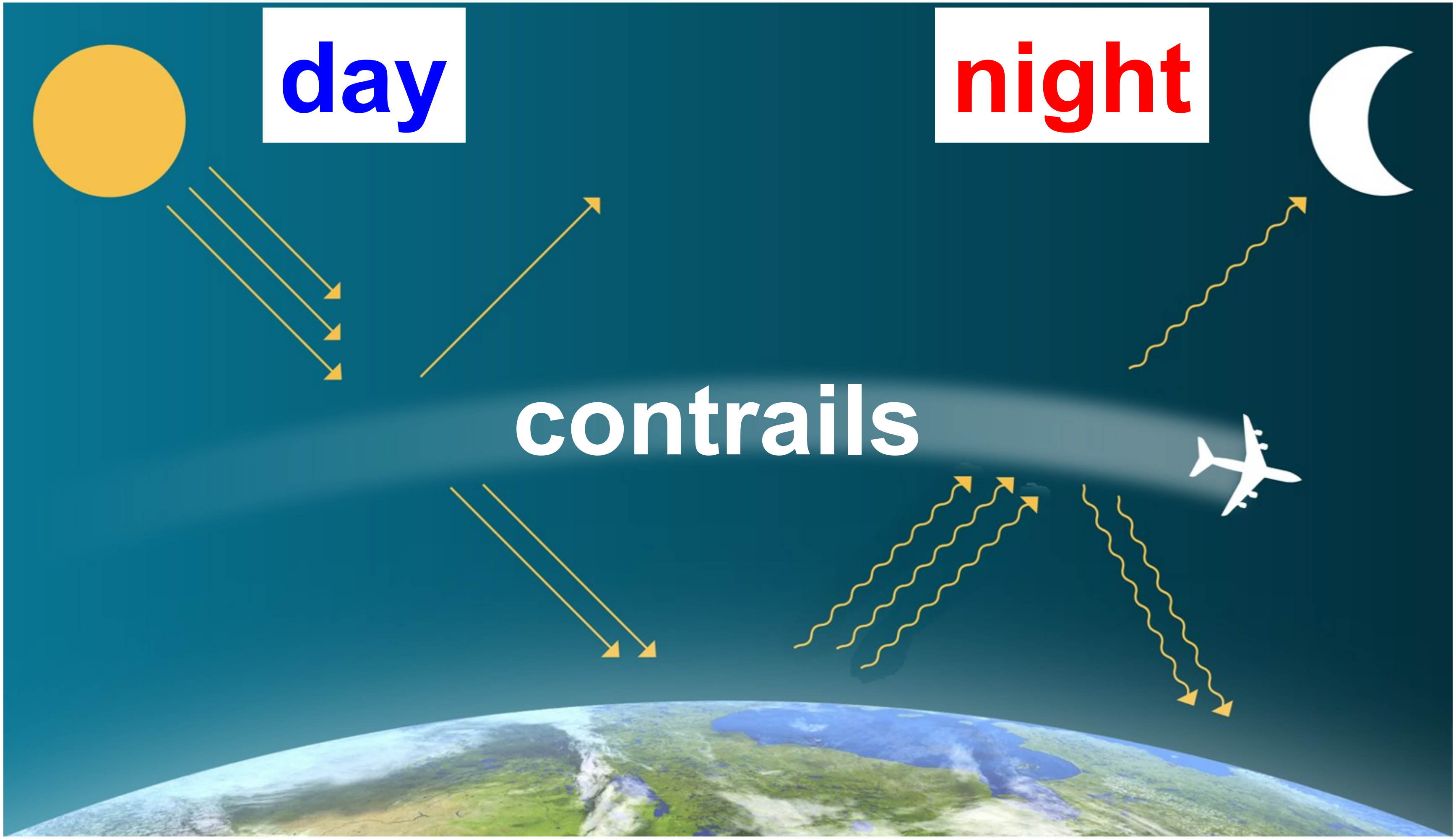
More flights in a database, but not yet fully evaluated.

Which Aircraft Types Potentially Produce Contrails?

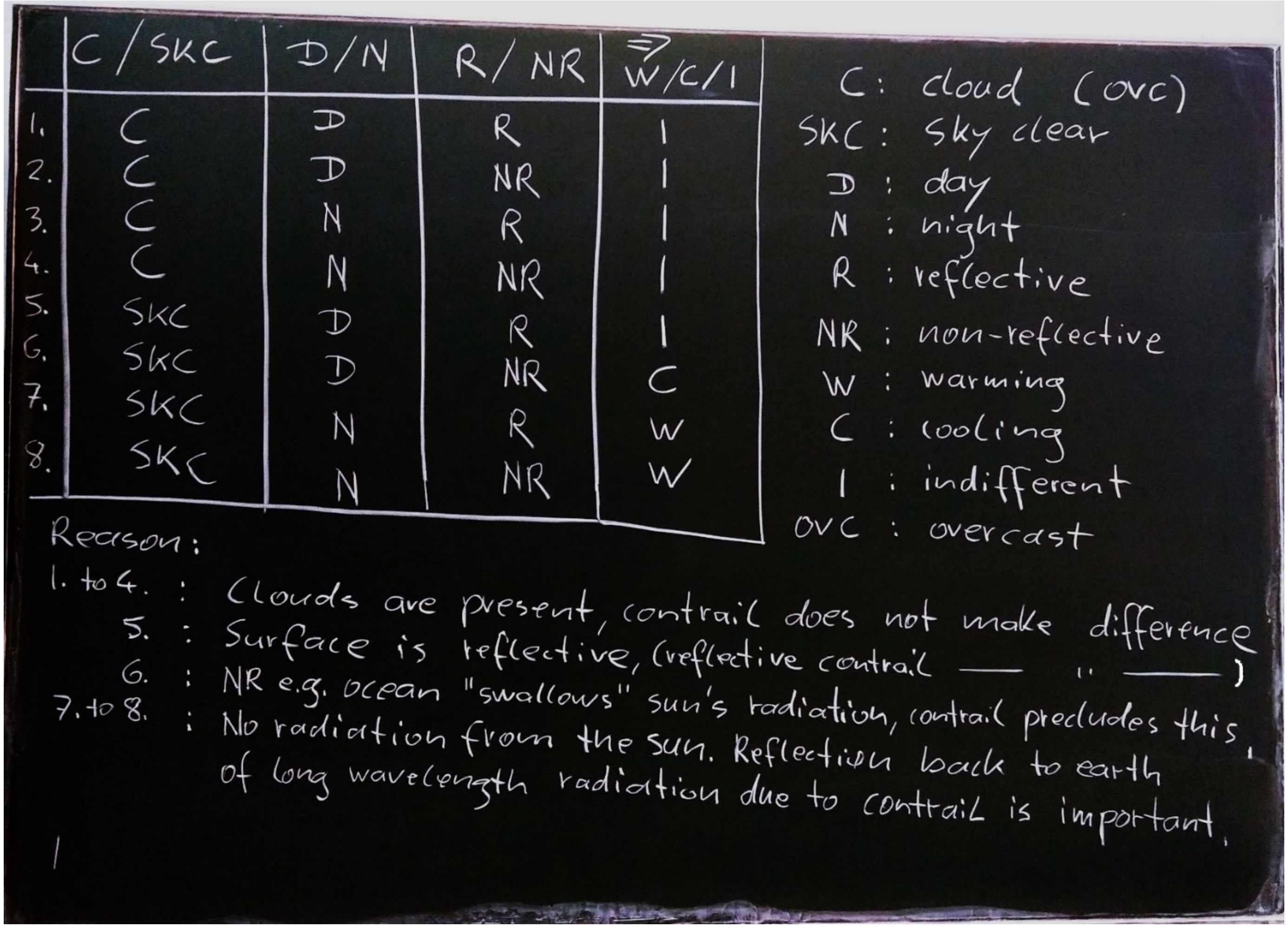
aircraft typ	example	altitude	contrail ?
business jet		very high	
passenger jet		high	
propeller aircraft		low	
single engine piston aircraft		very low	

Contrail
Avoidance

Cooling (Day) versus Warming (Night) Contrails



Systematic of Cooling and Warming Contrails

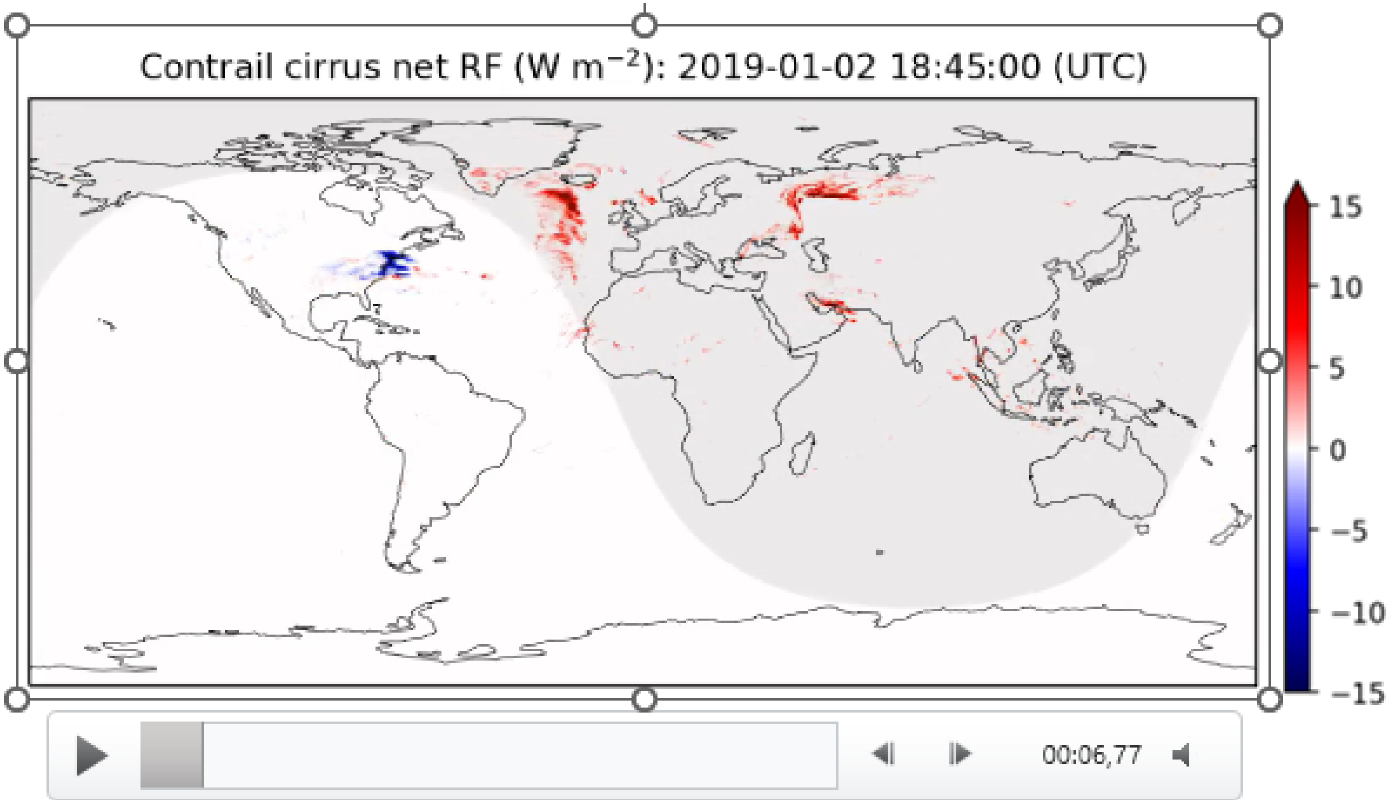


	C / SKC	D / N	R / NR	⇒ W / C / I
1.	C	D	R	I
2.	C	D	NR	I
3.	C	N	R	I
4.	C	N	NR	I
5.	SKC	D	R	I
6.	SKC	D	NR	C
7.	SKC	N	R	W
8.	SKC	N	NR	W

C : cloud (ovc)
SKC : sky clear
D : day
N : night
R : reflective
NR : non-reflective
W : warming
C : cooling
I : indifferent
OVC : overcast

Reason:
1. to 4. : Clouds are present, contrail does not make difference
5. : Surface is reflective, (reflective contrail —— " ——)
6. : NR e.g. ocean "swallows" sun's radiation, contrail precludes this.
7. to 8. : No radiation from the sun. Reflection back to earth of long wavelength radiation due to contrail is important.

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.

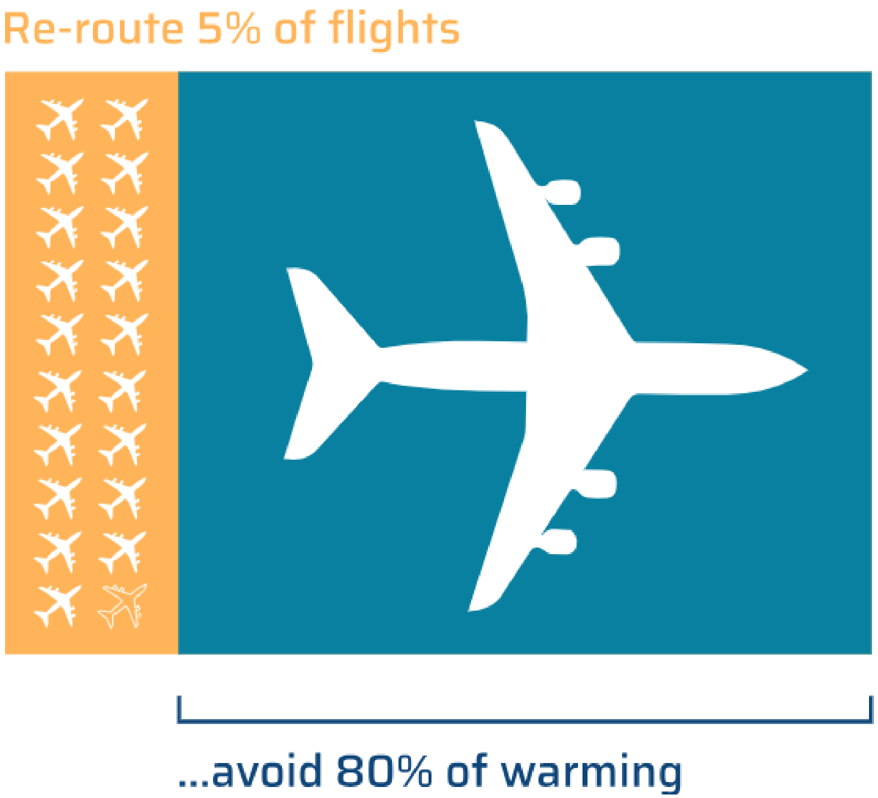
Teoh, Stettler, Imperial College; Shapiro, Breakthrough Energies; Schumann, Voigt, DLR

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

Contrail

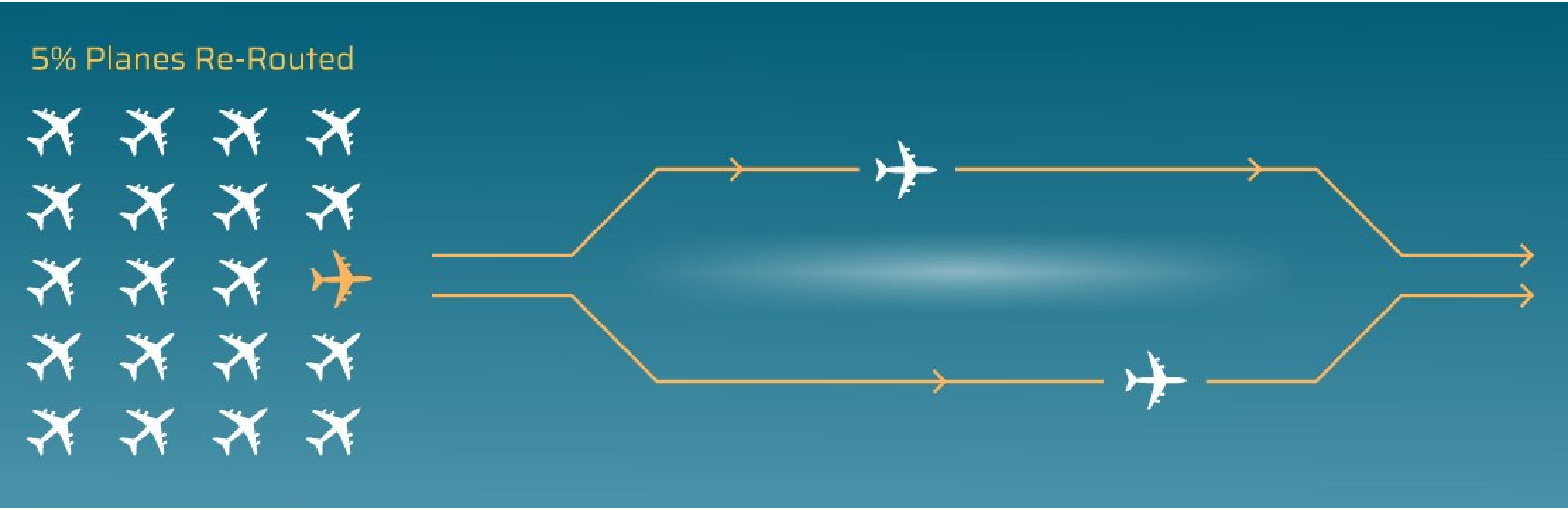
Management

https://contrails.org



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 ton of CO_2 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

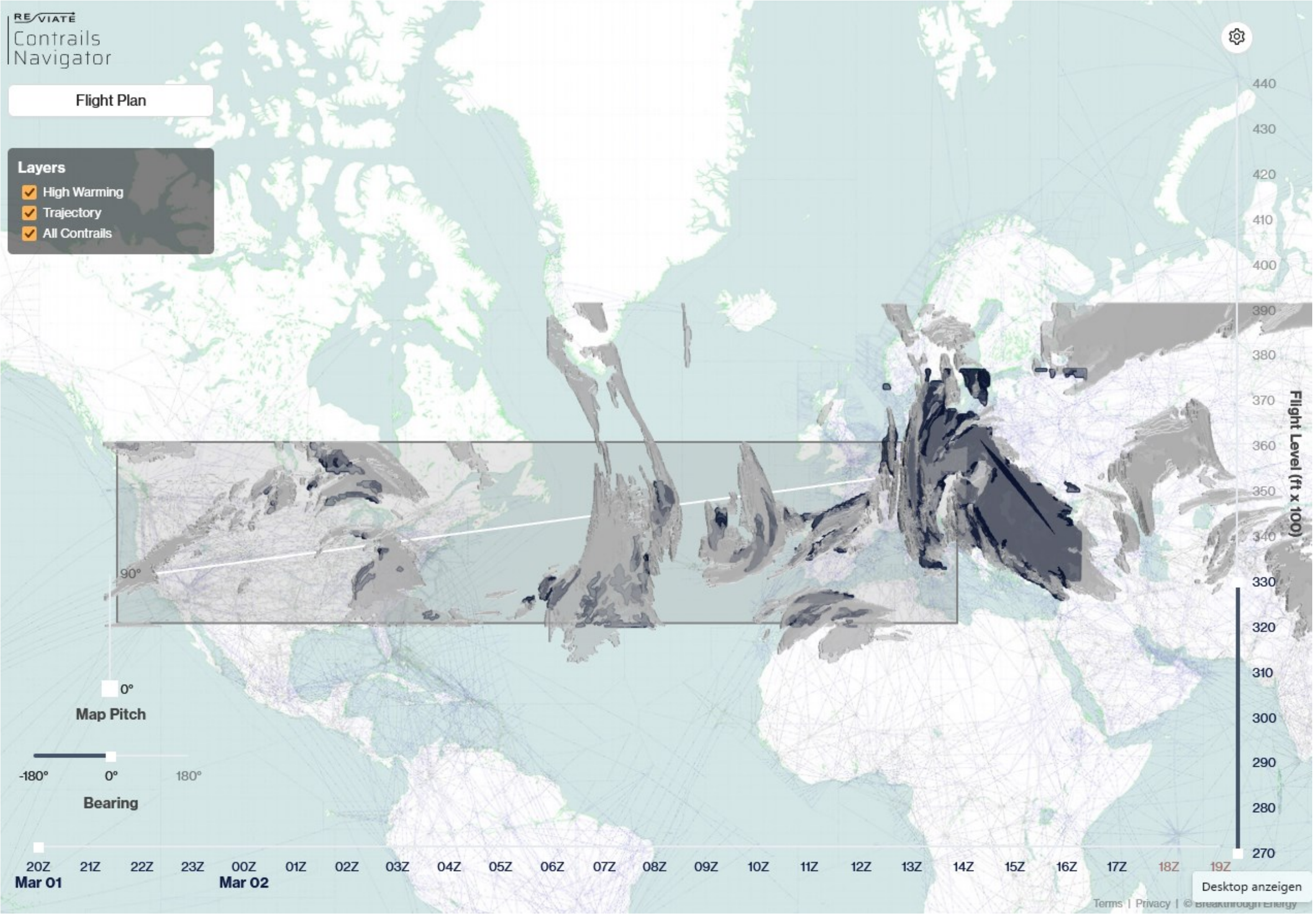
REVIATE
BY BREAKTHROUGH ENERGY

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:

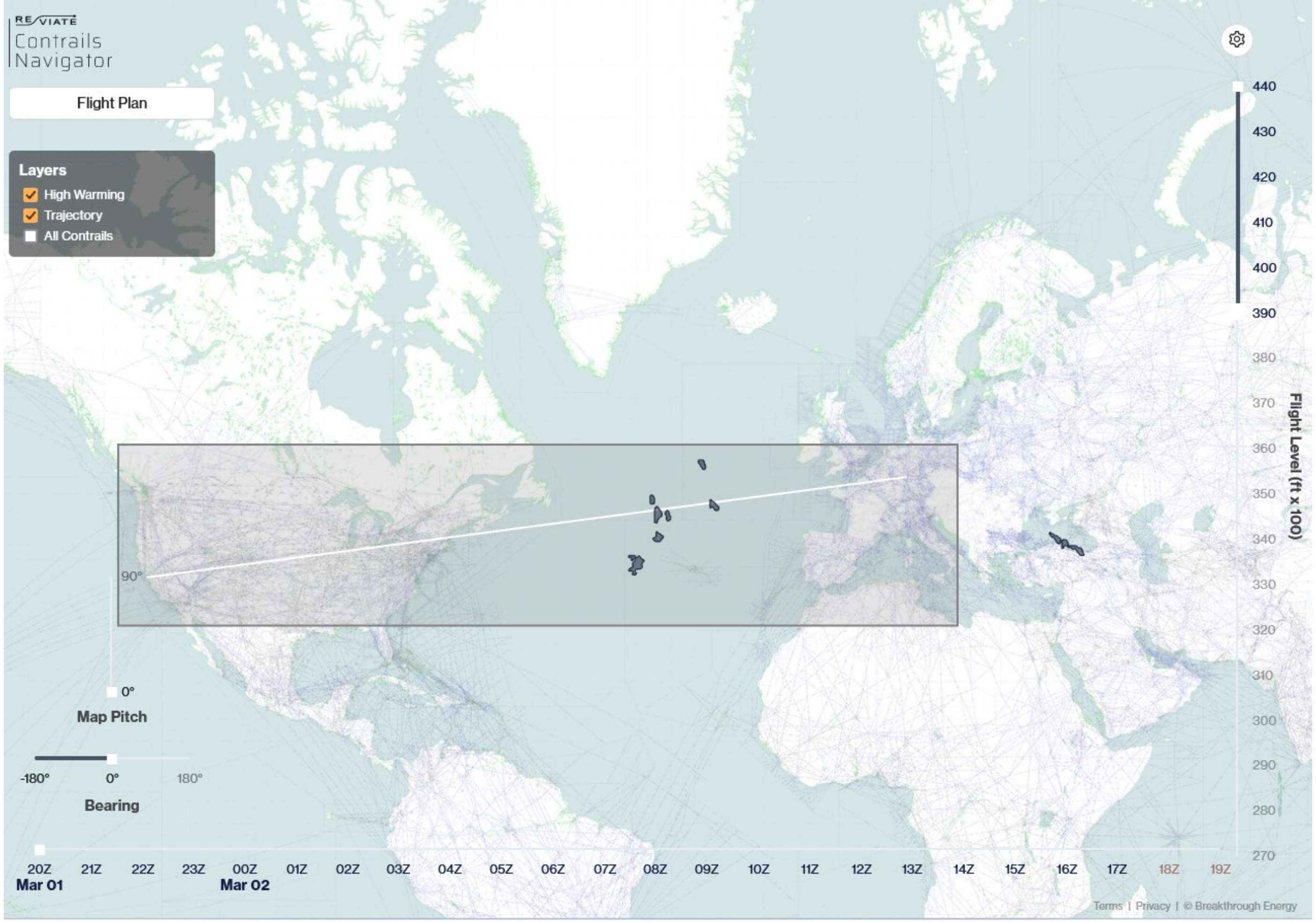
Only highly warming contrails are shown in FL270 to FL440.

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

Here:

Only highly warming contrails are shown in FL330 to FL440.

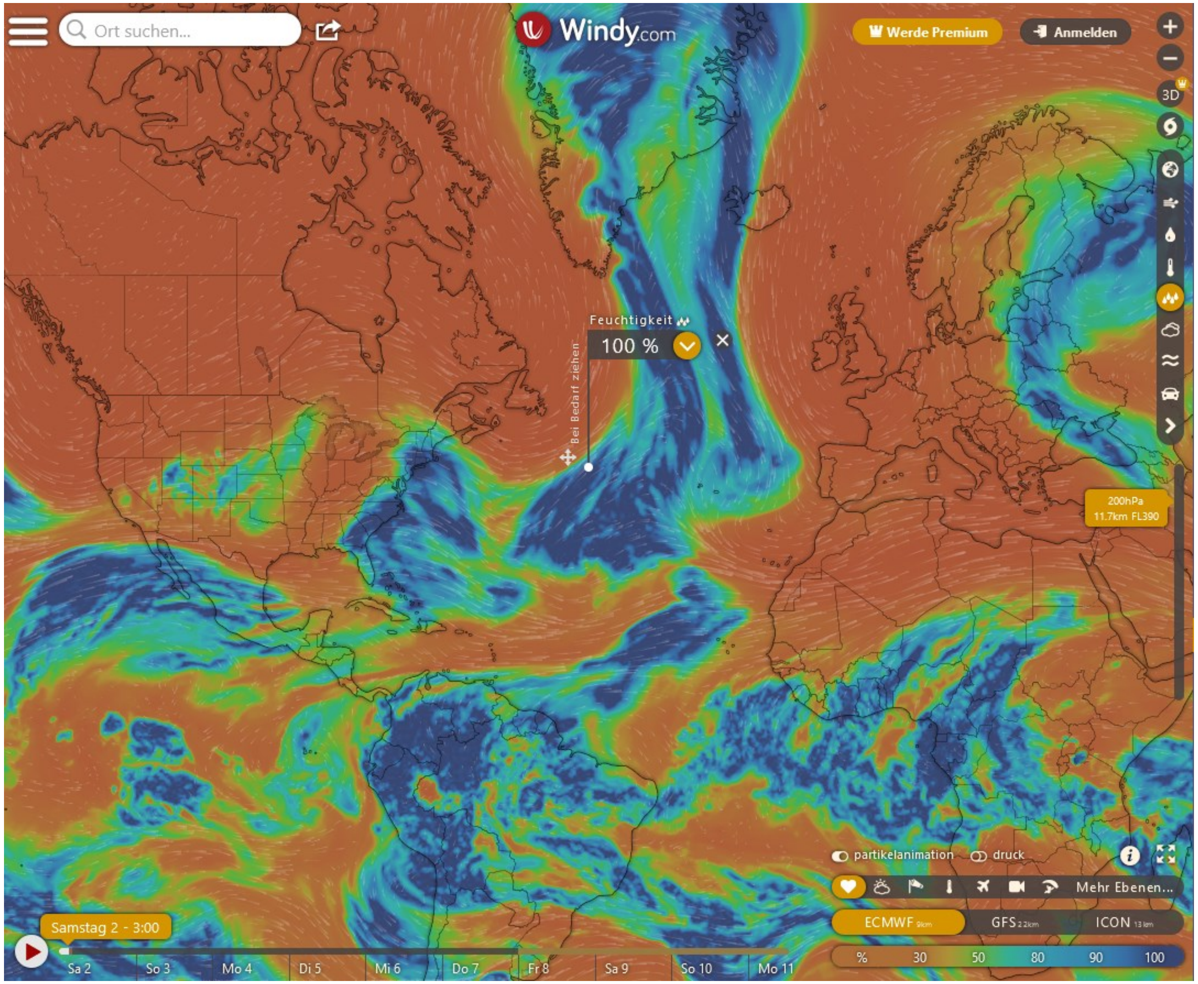
Flight Planning with https://forecast.contrails.org



Here:
Only highly warming contrails are shown in FL390 to FL440.

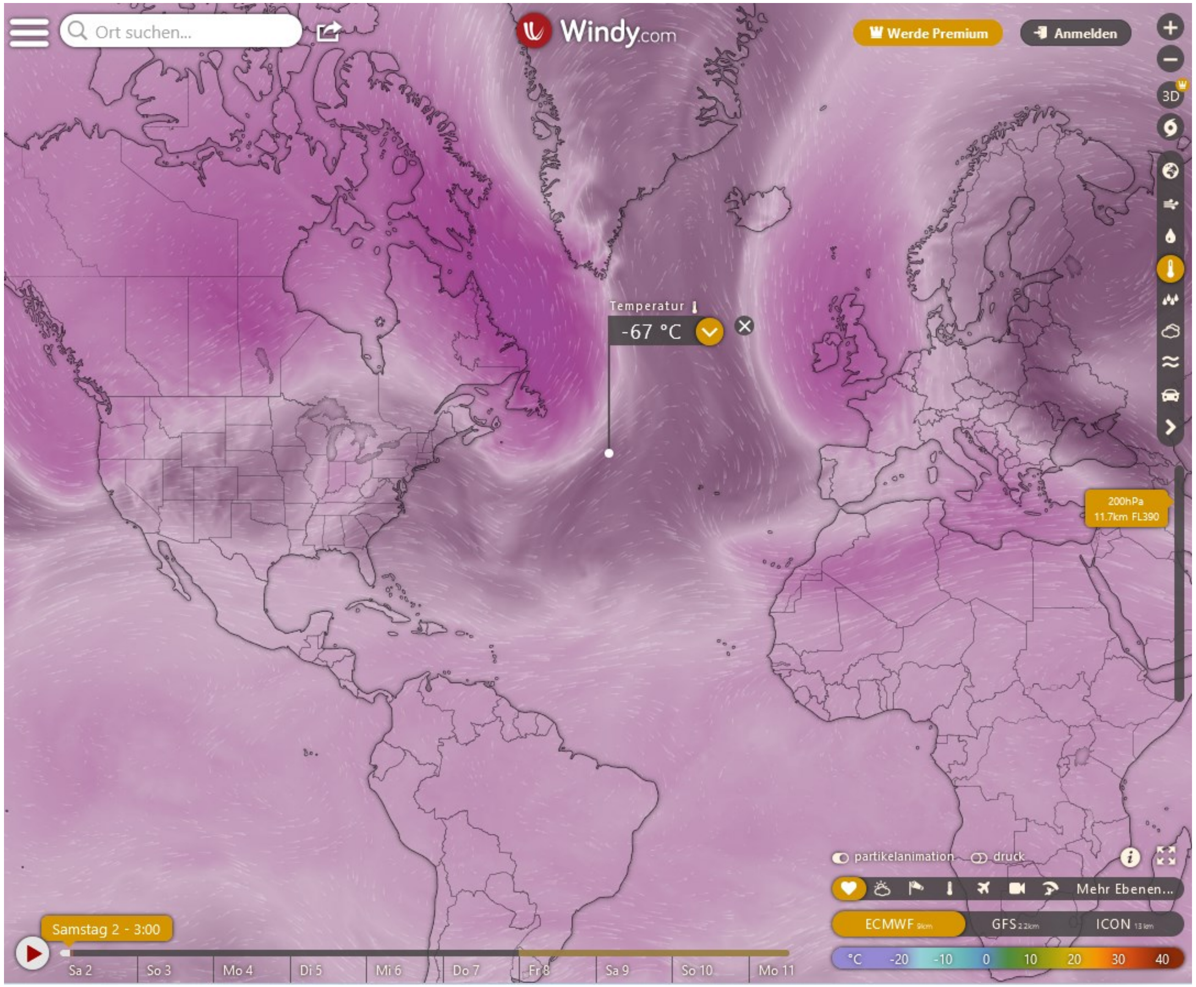
A business jet using these high flight levels would not need to be rerouted for contrail avoidance.

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



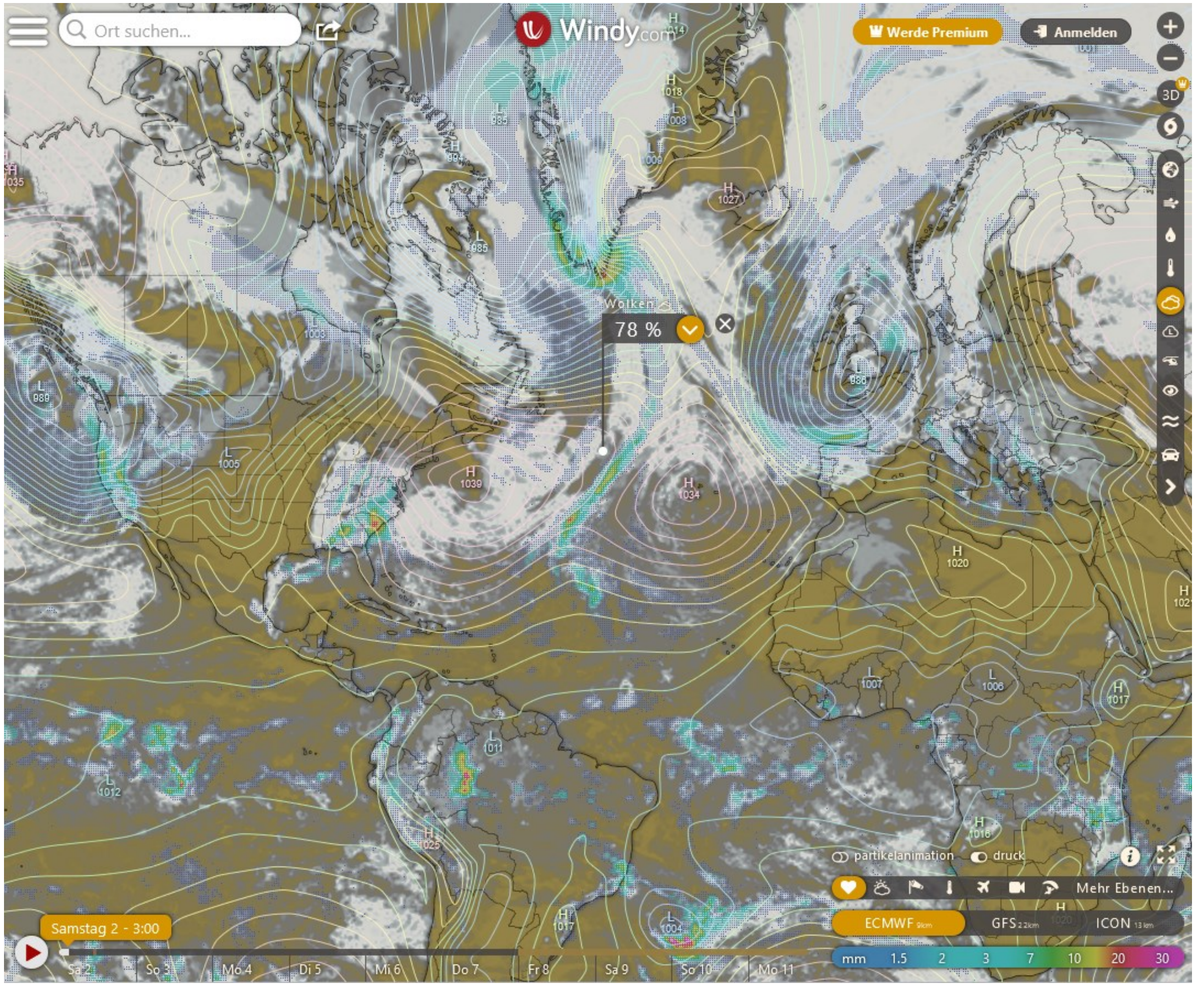
Relative humidity. Data from ECMWF and 7 other weather models. Forecast 5 days ahead. Vertical resolution is rather course: FL 100, 140, 180, 240, 300, 340, 390, and 450.

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



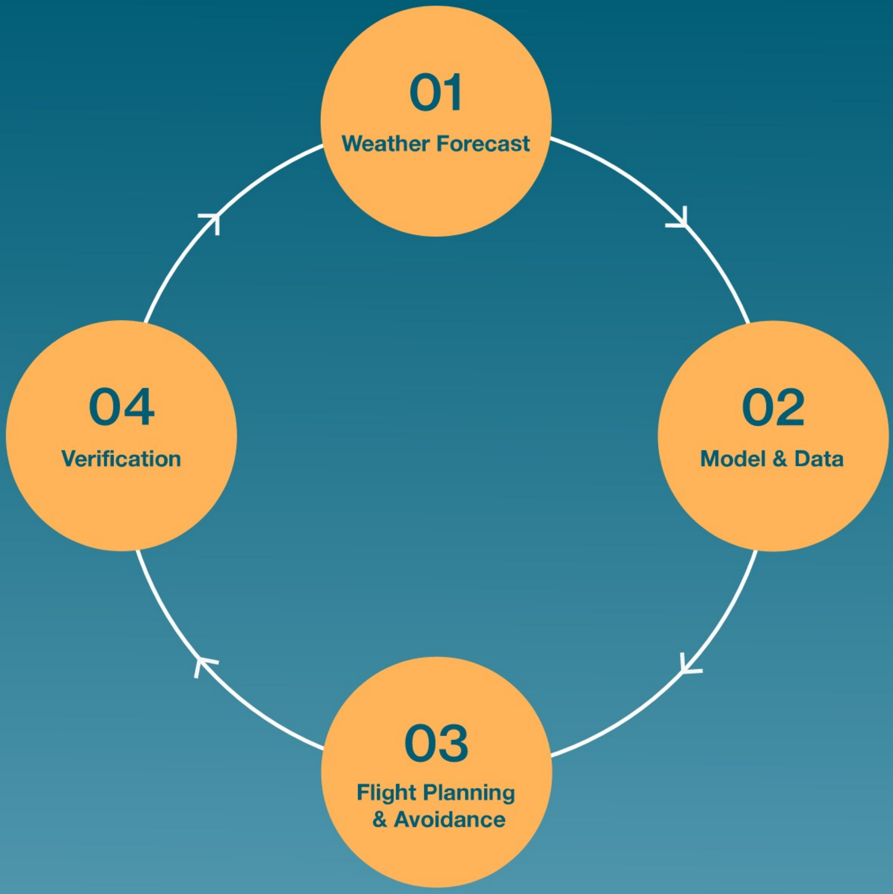
Temperature. Data from ECMWF and 5 other weather models. Forecast 5 days ahead. Vertical resolution is rather course: FL 100, 140, 180, 240, 300, 340, 390, and 450.

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.

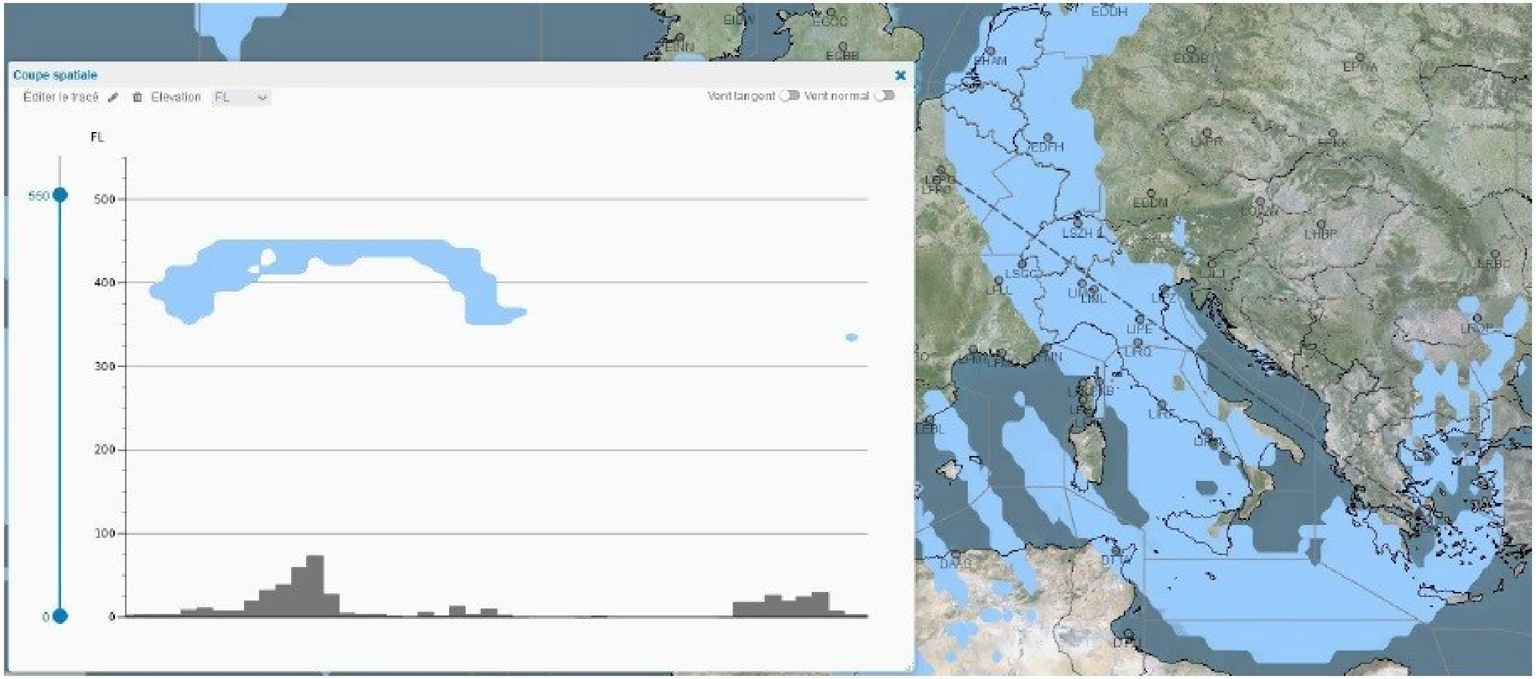
https://contrails.org



- **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

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

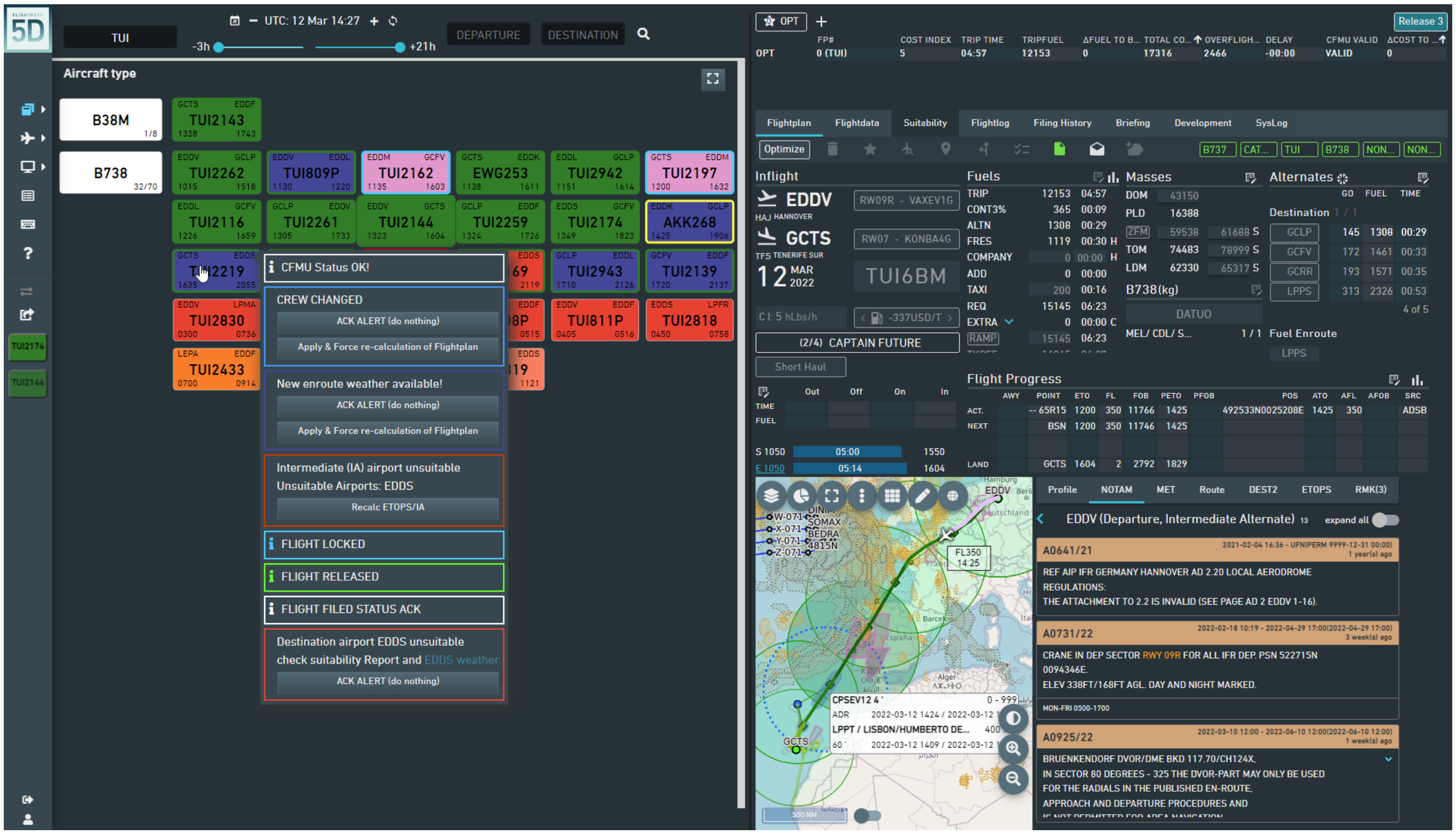
METEO FRANCE

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

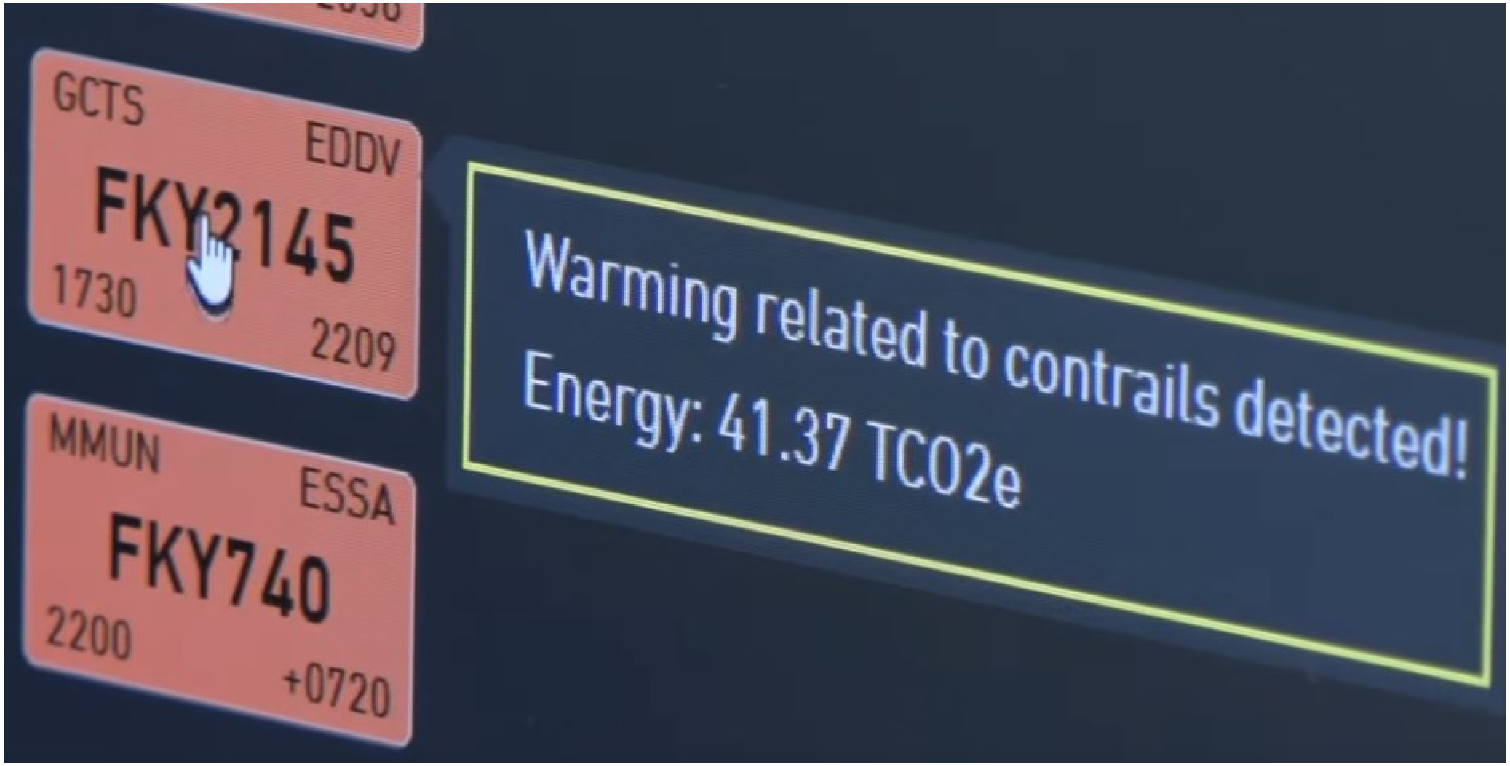
FlightKeys

https://www.flightkeys.com



FlightKeys flight planning system "5D".

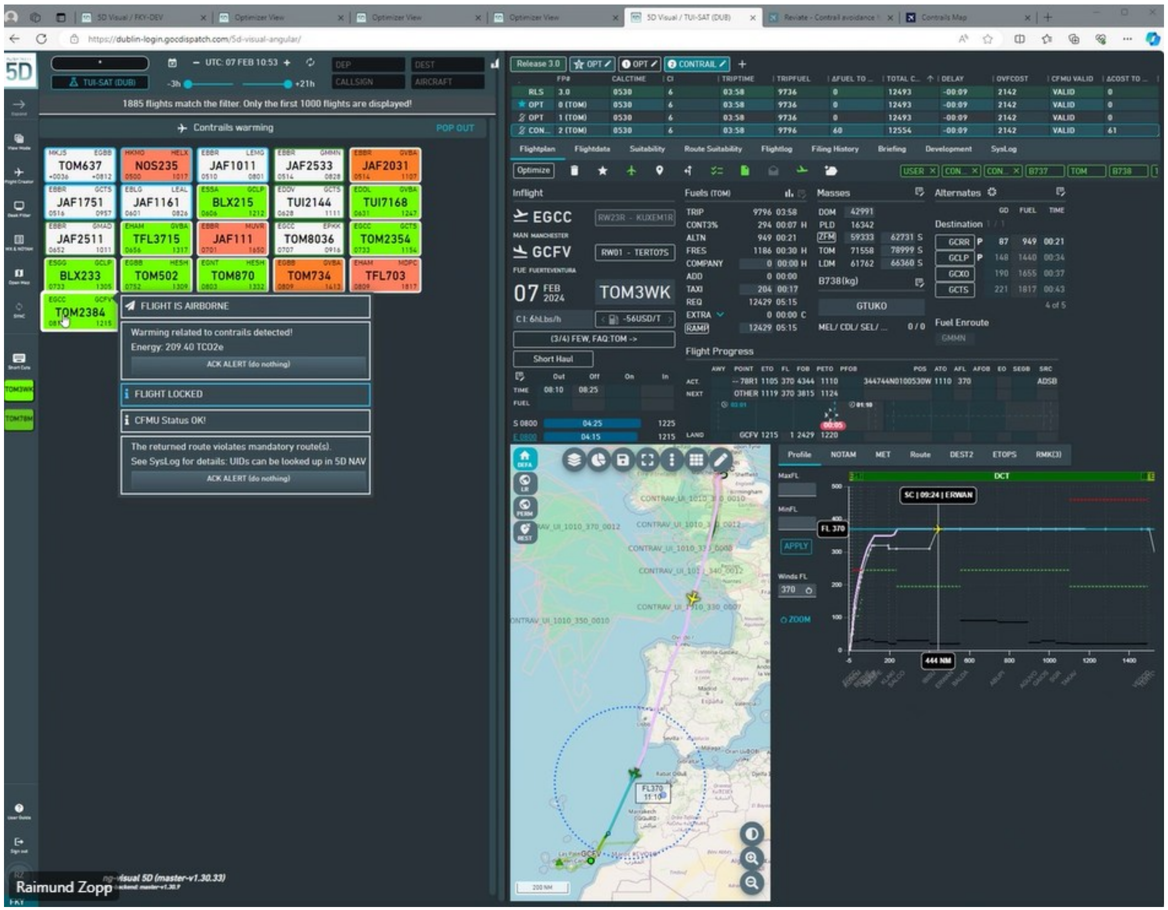
FlightKeys



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

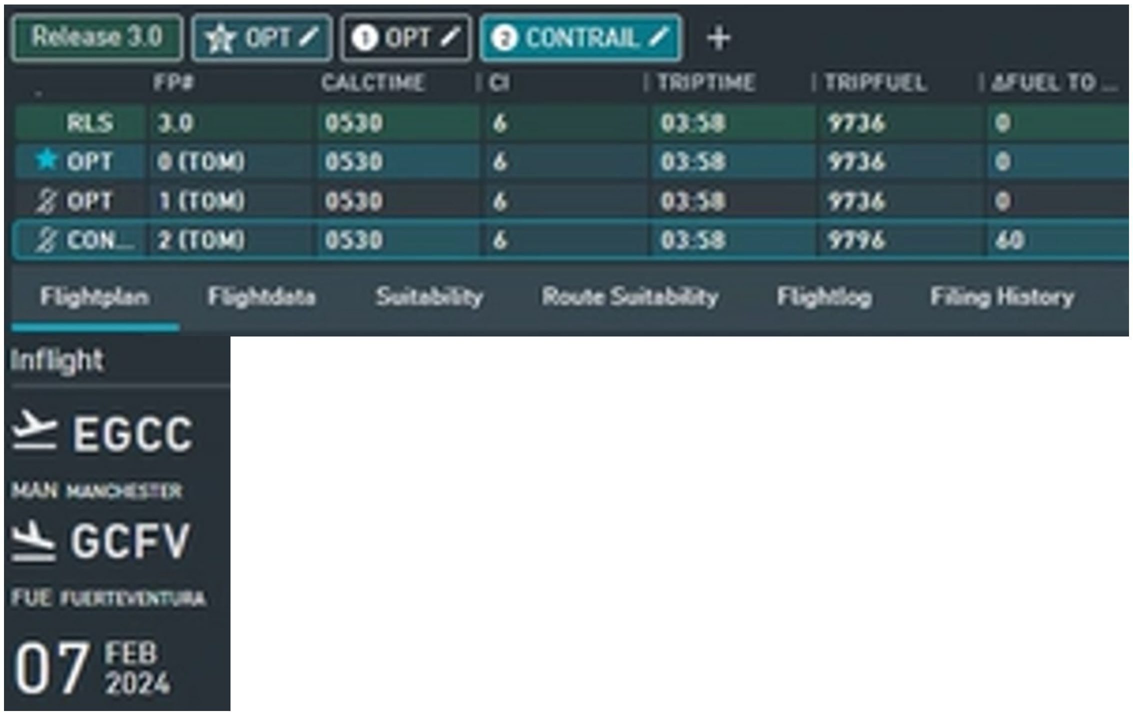
https://youtu.be/HYJawLmiLS8

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

https://youtu.be/HYJawLmiLS8

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

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

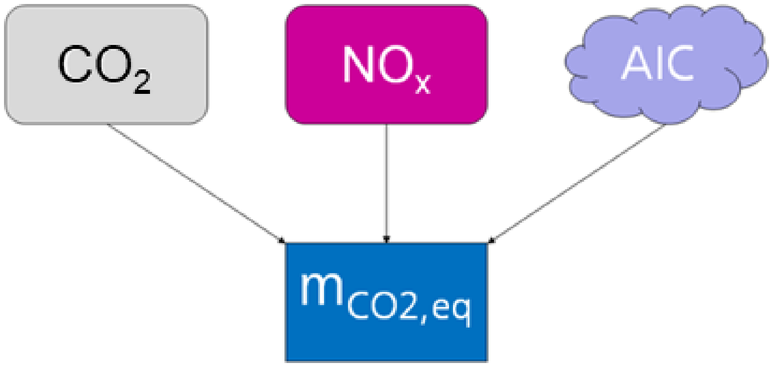
FlightKeys

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.

Equivalent CO2 Mass: The Equation for Aircraft Design & Ecolabel for Aircraft with Improved AIC Calculation



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):

$$CF_{midpoint,CO_2} = 1$$

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

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

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)

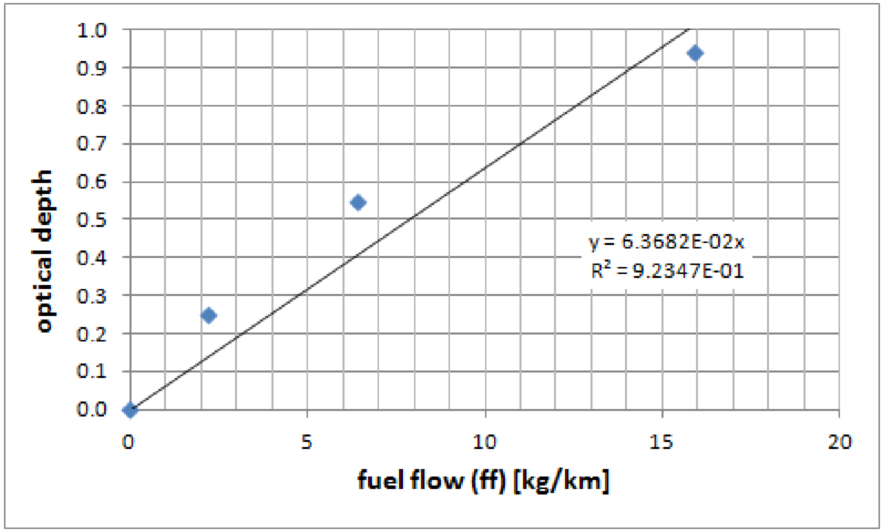
Aircraft	A319-111	A340-311	A380-841
Encounter time	09:14–09:27	08:45–08:48	12:14–12:29
Contrail altitude (km)	10.5–10.7	10.5–10.7	10.3–10.7
Latitude	52.91° N	53.35° N	52.37° N
Longitude	8.06° E	8.94° E	9.66° E
Pressure p (hPa)	241	242	241
Temperature T (K)	217	217	218
T_C (K)	223.5	223.6	223.6
Brunt–Väisälä 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

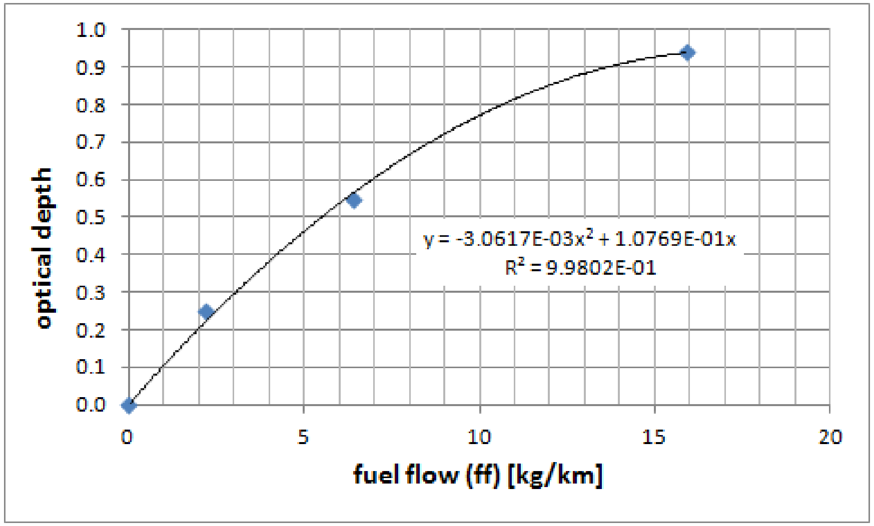
τ		ff		τ / ff [km/kg]	aircraft
0.25	/	2.2	=	0.114	A319
0.55	/	6.4	=	0.0859	A340
0.94	/	15.9	=	0.059	A380

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(±0.14)×10^3	4.1(±1.0)	2.1(±0.3)	120	0.25
A340	164±0.11	5.8(±1.7)	1.12(±0.17)×10^3	4.0(±1.0)	2.5(±0.4)	220	0.55
A380	235±10	5.9(±1.7)	1.45(±0.22)×10^3	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

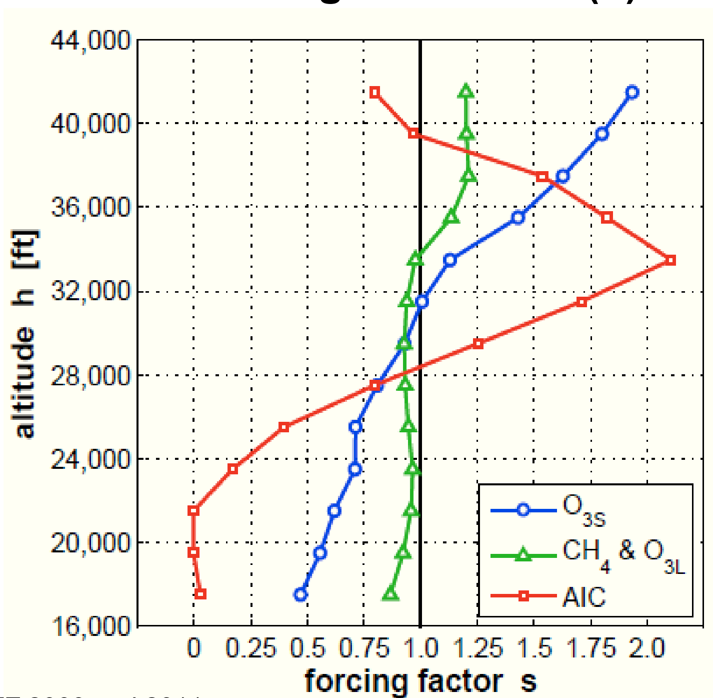
Calculating Altitude-Dependent Equivalent CO2 Mass

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*)



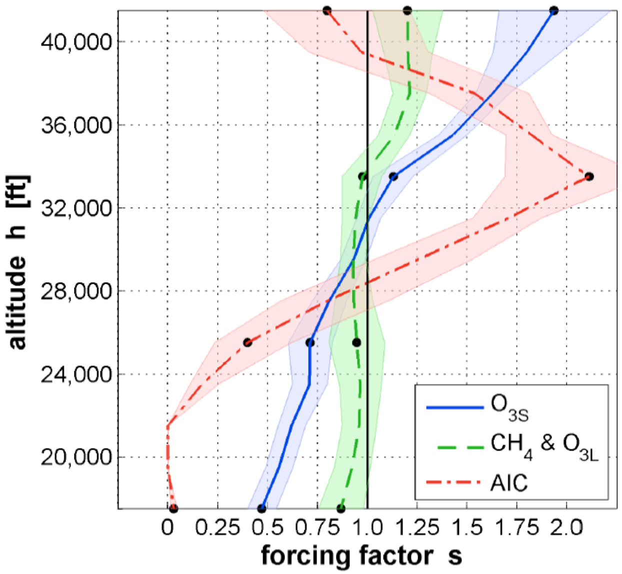
SCHWARTZ 2009 and 2011

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



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

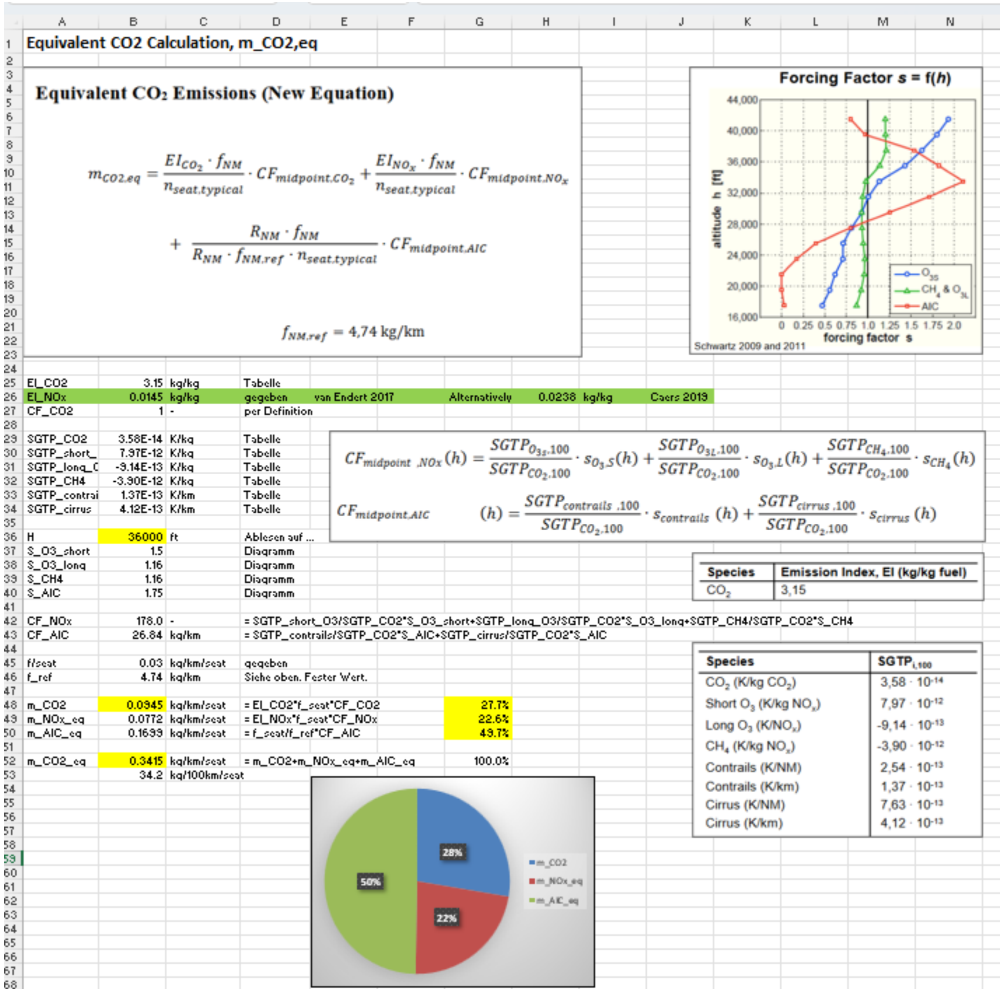
Based on KÖHLER 2008 and RÄDEL 2008.

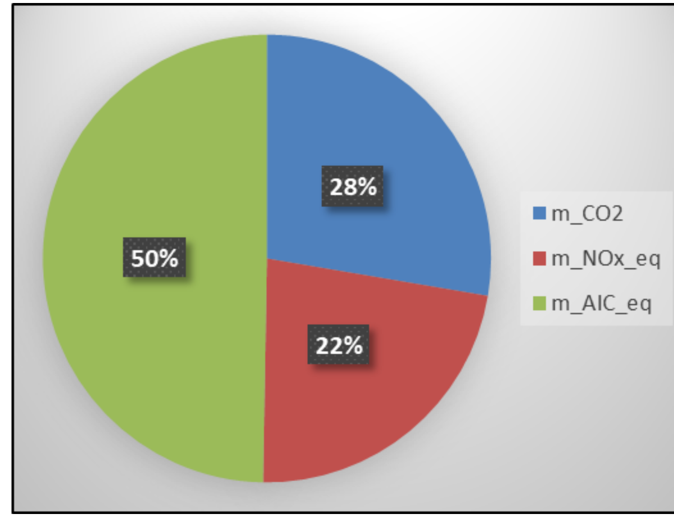
SCHWARTZ DALLARA, Emily, 2011. *Aircraft Design for Reduced Climate Impact*. Dissertation. Stanford University. Available from: http://purl.stanford.edu/yf499mg3300

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





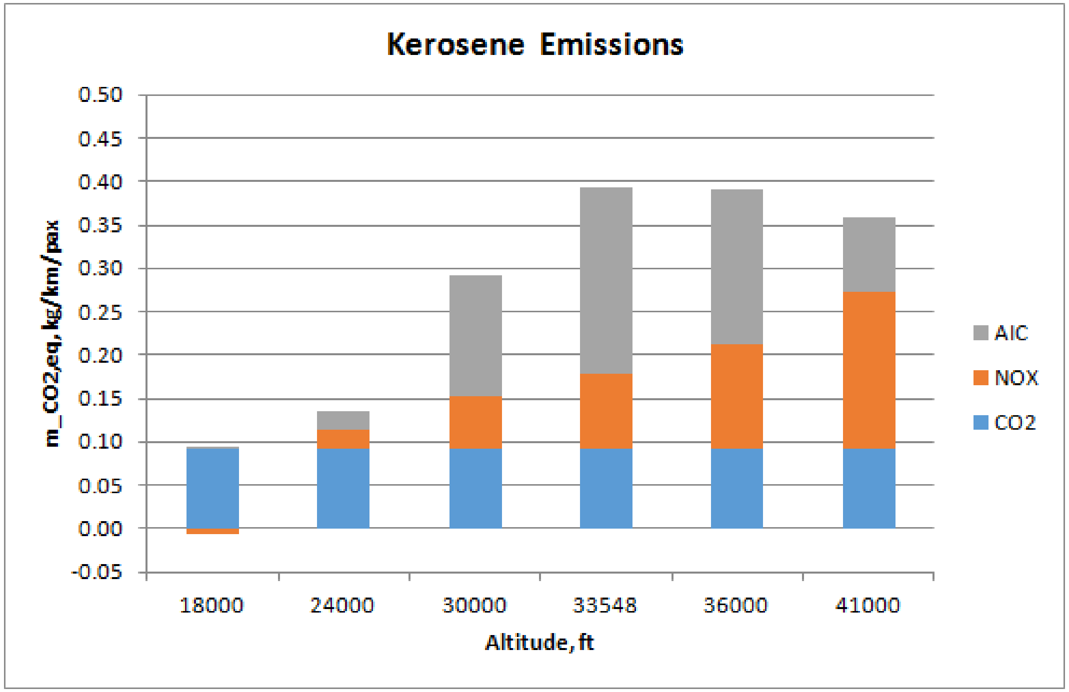
EI_NOx = 0.0145 kg/kg

h = 36000 ft

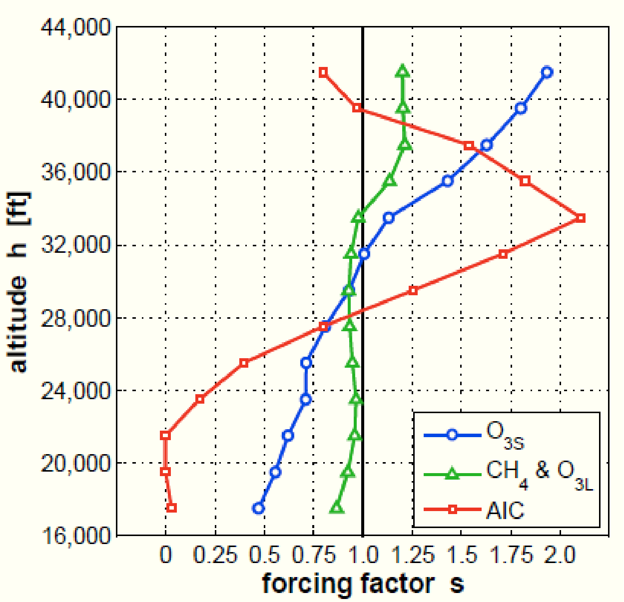
Standard split of CO2,eq:

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

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**.

Summary

Contrail Formation is Physics

Contrail Management – Now !

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Available from: https://doi.org/10.48441/4427.2104.