CLIMATE IMPACT OF AVIATION

Scientific knowledge, developments and measures

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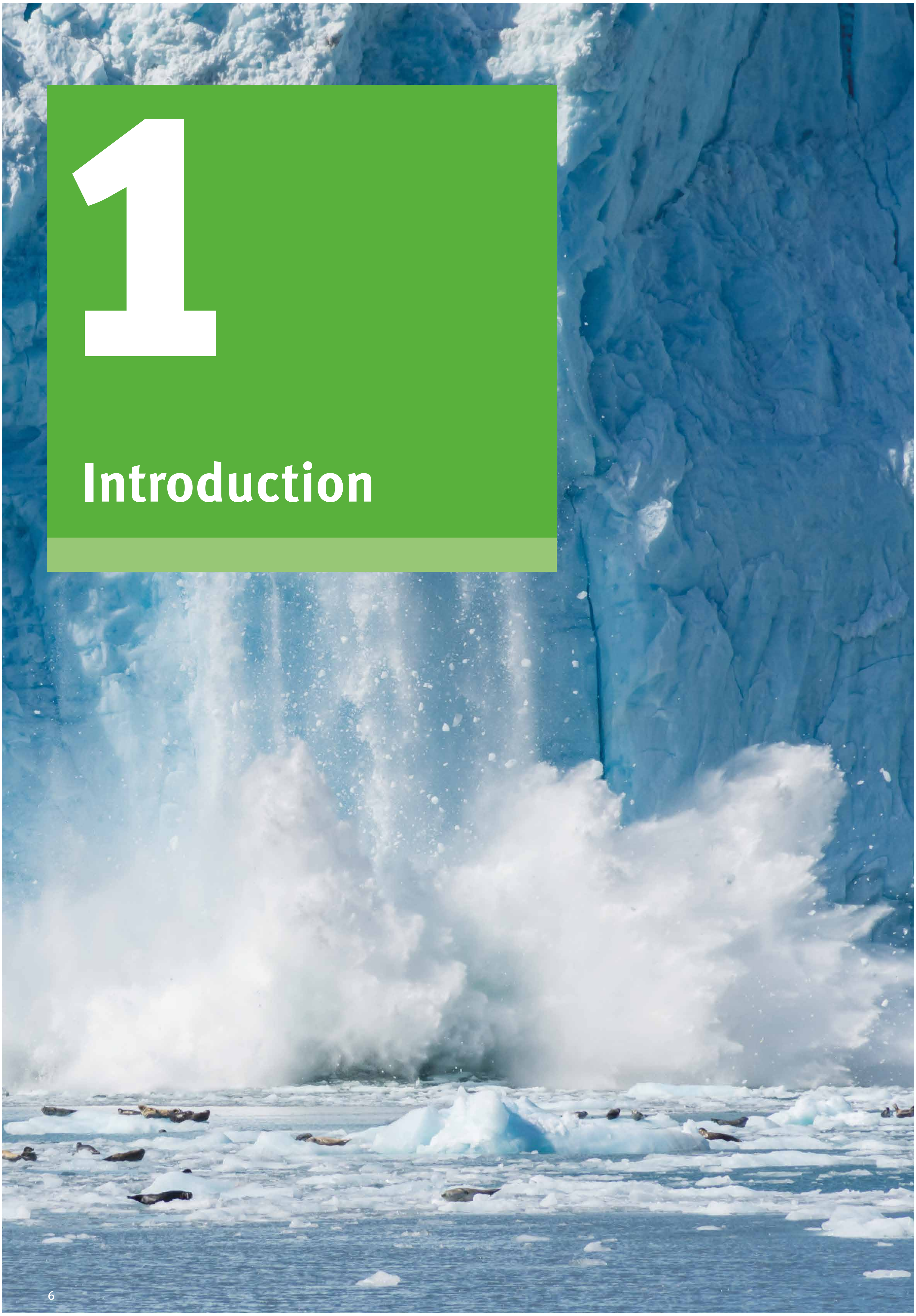


1. Introduction

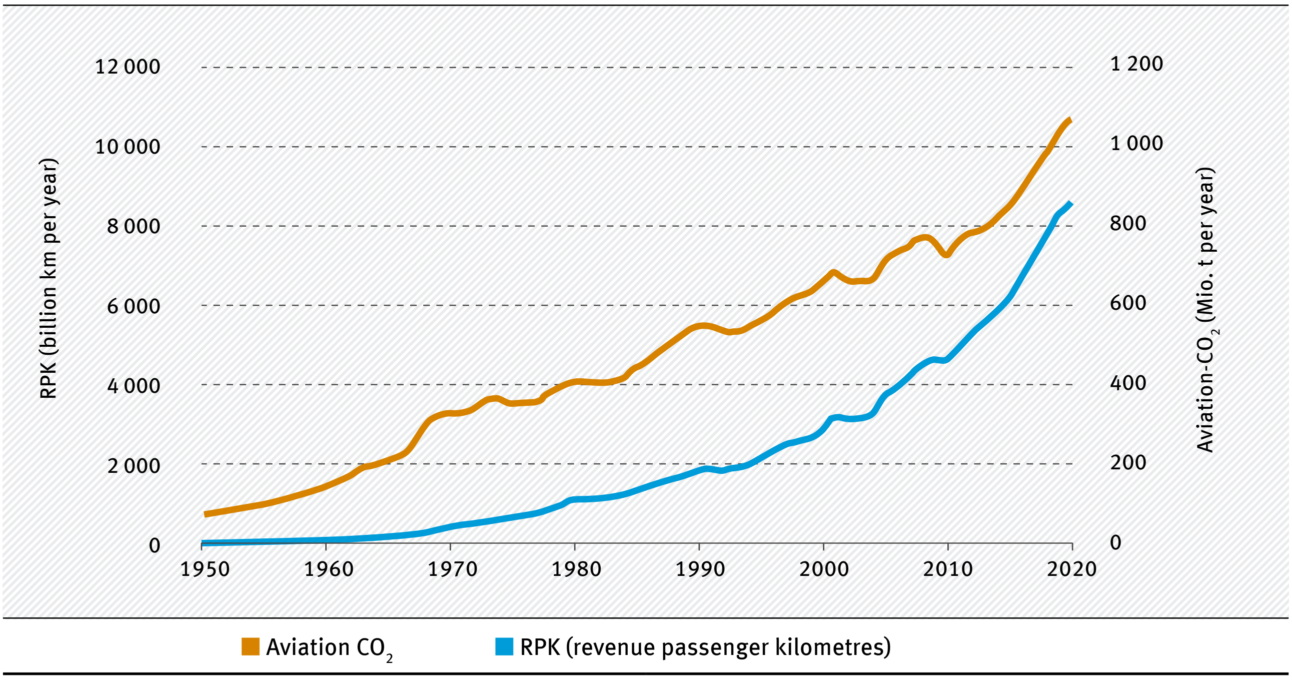
In recent years, man-made climate change has increasingly attracted public attention. In order to limit global warming to below 1.5 °C in accordance with the Paris Climate Agreement, global emissions must be drastically reduced[1].

In 2018, aviation's contribution to man-made carbon dioxide emissions (CO_2) worldwide was approximately 2.5 %. Global air transport has been a rapidly growing industry over the past few decades and is expected to continue to grow in the future. For example, since 1980, global passenger kilometres have doubled every 15 years (growing at about 5 %/year, figure 1, revenue passenger kilometres (RPK)).

As a result of the strong growth in air traffic, CO_2 emissions from air traffic also increased continuously, albeit at a significantly slower rate than RPK (figure 1). Reasons for the lower growth in CO_2 emissions are improvements due to use of new aircraft, more efficient flight operations as well as higher utilisation of existing seats and tighter aircraft seating. However, these measures were not sufficient to compensate for the growth in emissions due to increased demand. Despite these improvements, CO_2 emissions increased by an average of 3.7 % per year.

Figure 1

Development of CO_2 emissions and passenger kilometres over time



Source: own representation, DLR, based on data from Lee et al., 2021

1 To maintain the goal of no more than 1.5° global warming in the longer term, greenhouse gas emissions must fall by 45 % by 2030 and approach minus 60 % by 2035 (IPCC, 2023).

In addition to CO_2 emissions, non-CO_2 climate effects also play a special role in aviation. One of the most obvious effects is the formation of contrails visible in the sky. Atmospheric conditions present at conventional flight altitudes favour processes (cloud formation) and chemical reactions (including ozone production). Considering the cumulative effect of all previous aviation emissions on the current radiation balance of the atmosphere, close to two-thirds are caused by non-CO effects[2].

Particularly relevant in this context are ozone production due to nitrogen oxide emissions (NO_x) from aircraft and the formation of long-lived contrails, so-called contrail cirrus, which are not directly related to fuel consumption and account for the largest share of non-CO_2 effects. The effect of the individual climate species[3] depends not only on emission strength but also on other factors such as local and meteorological conditions (e.g. temperature, humidity, background concentration of various trace substances in the atmosphere and position of the sun). Therefore, the magnitude of non-CO_2effects can vary widely by aircraft type, flight region, altitude, and current weather.

2 This is true for the effective radiative forcing (ERF) of all historical aviation emissions through 2018. However, the share of non-CO_2 effects in the total climate impact is highly dependent on which metric is used. This is explained in more detail in chapter 3.
3 Climate species refers to the different components of climate impact, e.g., carbon dioxide, ozone, methane, contrails, and water vapour.

One way of further reducing CO_2 emissions beyond the measures mentioned above is the use of synthetic fuels produced from biomass or with the help of electricity from renewable energy sources. However, CO_2 emissions from these fuels can only be considered CO_2-neutral if solely those quantities of CO_2 that were previously removed from the atmosphere through plant growth or technical processes are emitted, and if no climate-damaging emissions are caused by further processing the fuels. Another advantage of synthetic fuels is that fewer soot and sulphate particles are emitted during combustion compared with conventional fuels. This further reduces radiative forcing (inbalance of radiative budget (see next section)) of contrails, and thus of non-CO_2 effects. However, use of synthetic fuels is currently severely limited by the still rather low production capacities.

Effective mitigation of all climate effects of aviation requires more than a mere reduction in fuel consumption or emission levels of CO_2, nitrogen oxides and water vapour. For example, recent studies show that non-CO_2 effects can be effectively reduced particularly through optimising individual flight routes and altitudes. In some regions, aircraft emissions have a greater impact on the climate (e.g., at high altitudes) than in others. If such areas are circumflown, the formation of long-lived contrail cirrus can be avoided. Although avoidance increases CO_2 emissions, the resulting climate impact can still be significantly reduced in many cases.

Currently, airlines are optimising their route planning from a cost perspective. Minimising CO_2 emissions is beneficial for the airline as it goes hand in hand with a reduction in fuel consumption, and associated costs. As there is currently no established procedure for reducing and measuring non-CO_2 effects, these are not yet taken into account in route planning. Procurement of new aircraft is based on economic considerations. Continuous improvements in aircraft and fuel consumption lead to a continuous reduction in emissions per flight. Targeted funding of technologies and available options for action could accelerate the development of marketable, and at the same time more climate-friendly, aircraft. A feasible additional incentive would be to address the climate impact of aviation in regulatory terms on the basis of scientifically sound findings. This is done, for example, in the EU emissions trading system, although so far only CO_2 emissions have been taken into account.

In addition, travellers' choices can lead airlines to fly in a more climate-friendly manner by specifically paying attention to their climate compatibility when choosing airlines and opting for providers that limit their climate impact more than others, through technical and operational measures.

Climate impact of aviation

2

Emissions

Atmospheric changes

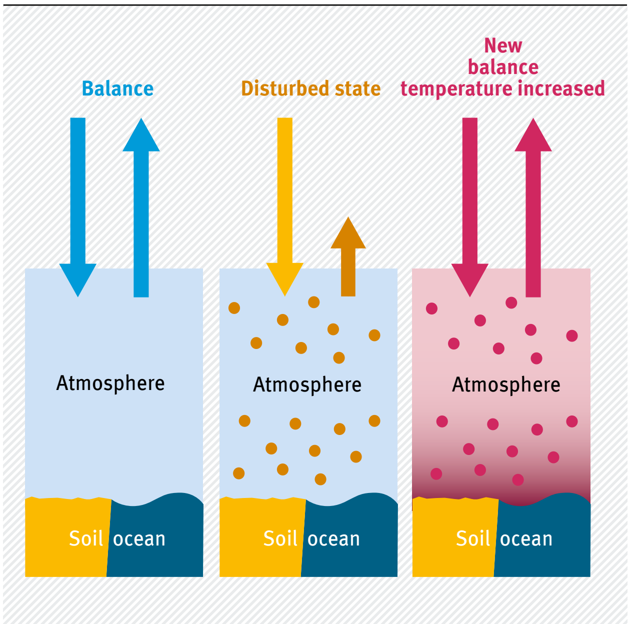
Resulting climate impact

Climate impact of aviation

Without human-induced emissions, the earth is in radiative equilibrium: the atmosphere loses just as much energy through the emissions of longwave radiation into space as it receives from the irradiation of sunlight (figure 2). This equilibrium is destabilised by man-made emissions. By increasing the concentration of greenhouse gases, for example, some of the longwave radiation is trapped in the atmosphere. As a result, less radiation can leave the atmosphere and the radiation balance is disturbed. This change in the radiation balance is called radiative forcing. The resulting imbalance is offset by an increase in the near-surface temperature. If the near-surface temperature increases, emissions of longwave radiation increases and the atmosphere enters a new equilibrium, but at a higher near-surface temperature. This change in temperature can affect precipitation, sea level, or even ocean circulation, which in turn can increase the frequency of droughts and floods or cause storms to intensify, causing damage.

Figure 2

Radiation balance of the atmosphere



Source: own representation, DLR

Emissions from air transport also change the composition of the atmosphere, causing a disturbance in its radiation balance. In figure 3 this effect is shown schematically. Aviation emissions can affect the climate in several ways. There are direct greenhouse gas emissions, such as CO_2 and water vapour, but also indirect greenhouse gas emissions, such as nitrogen oxides, which do not act as greenhouse gases themselves but change the concentration of greenhouse gases (ozone, methane, and stratospheric water vapour). Furthermore, the emission of particles affects the radiation balance directly – through enhanced reflection or absorption of radiation – but also indirectly as particles can affect the formation and properties of contrails and natural clouds. While CO_2, contrail cirrus, ozone, and water vapour cause atmospheric warming, a reduction in methane concentration and the indirect aerosol effect cause atmospheric cooling. Contrails can both warm and cool but, averaged globally, cause warming. Overall, aviation emissions lead to a warming of the near-surface temperature and thus contribute to climate change.

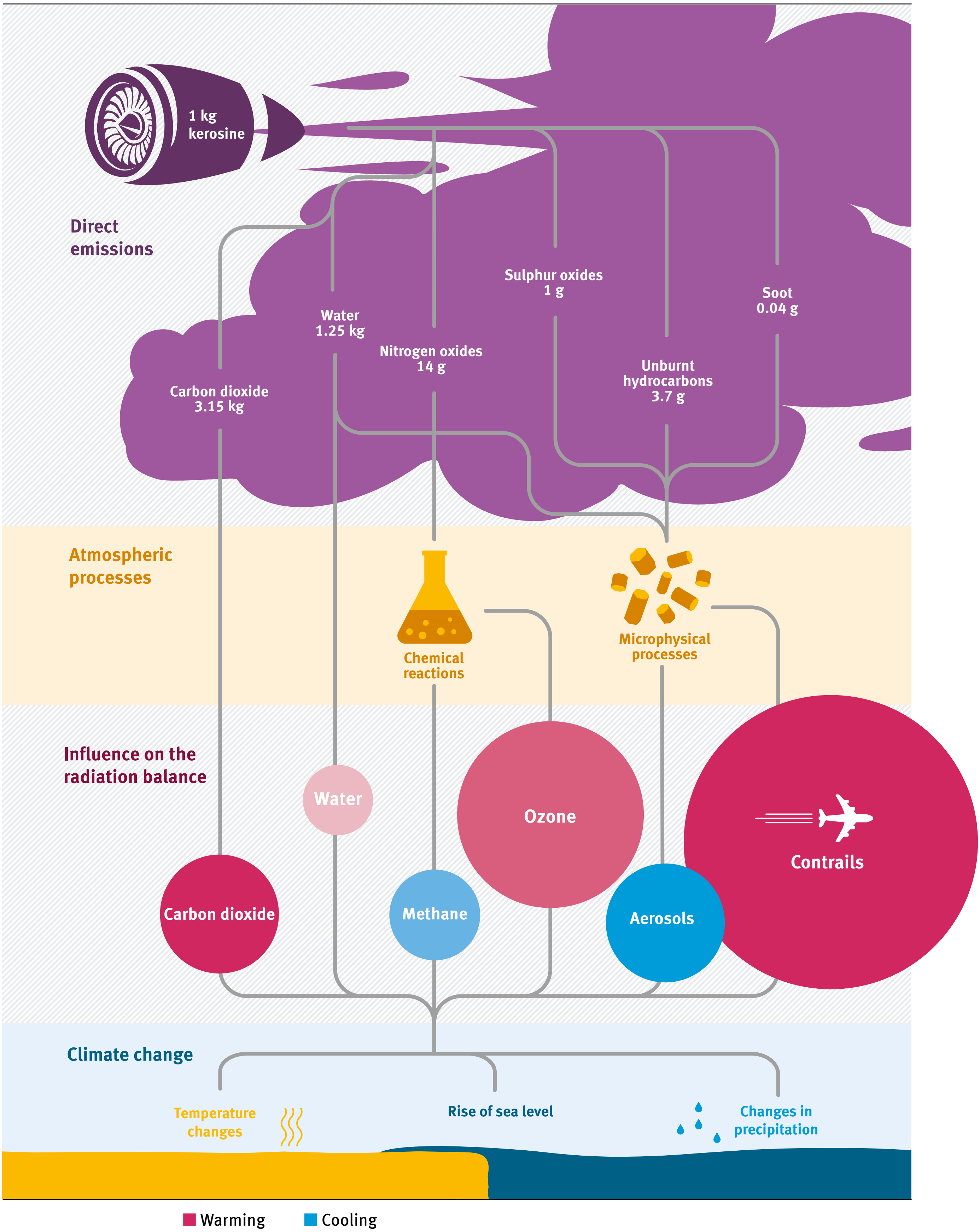
2.1 Emissions

In aircraft engines, hydrocarbons contained in kerosene are combusted using atmospheric oxygen to form CO_2 and H_2O. Thus, combustion of one kilogramme of kerosene produces about 3.15 kilogrammes of CO_2 and 1.26 kilogrammes of water vapour[4]. As a result of incomplete combustion, small amounts of hydrocarbons (HC) and carbon monoxide (CO) are also present. As aircraft engines achieve a burnout rate of more than 99.9 %, these substances are only detectable in trace amounts in the exhaust gas during cruising flight.
A significant climate effect is not known for HC and CO. However, this is different for two byproducts of hydrocarbon combustion: nitrogen oxides (NO_x): sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) and non-volatile particulate matter (nvPM). These lesser-known emissions are explained in more detail below.

4 Since the components of kerosene react with the oxygen in the air, the amount of emissions per kilogramme of fuel is greater than 1 kilogramme.

Figure 3

Impact of aviation emissions on the climate



Source: own representation, DLR

Nitrogen oxides (NO_x)

Under the conditions that occur in an engine combustion chamber (high pressure and temperature), some of the nitrogen contained in the air is oxidised to nitrogen oxides (NO_x). Since this reaction requires a lot of energy, a long residence time of the combustion air in the combustion chamber favours NO_x formation. At the same time, however, high pressure and temperature also improve the efficiency of the engine process and thus reduce the aircraft's fuel consumption and CO_2 emissions.

Due to the dependence of nitrogen oxide production on combustion chamber pressure and temperature, more nitrogen oxides are produced when the thrust setting increases. This increase in NO_x emissions is disproportionate to fuel consumption and therefore rises sharply toward maximum thrust. However, this maximum thrust is only required for takeoff of the aircraft. In cruise flight, the engine is operated at lower thrust, and lower air pressure at high altitude also causes a reduction in NO_x production.

Soot particles (nvPM)

Finally, very small, non-volatile particles are also contained in the exhaust gas, consisting mainly of carbon (soot). Many chemical and physical processes are involved in the formation of soot, which are currently still the subject of research. According to the current state of knowledge, hydrocarbons with carbon rings (so-called aromatic hydrocarbons or aromatics for short) contained in the fuel play an important role.

A large proportion of the particles formed at the beginning of combustion is immediately oxidised again in the further course of the process; the amount of soot remaining at the outlet of the combustion chamber is therefore several orders of magnitude smaller than that originally formed. As a result, different engine types sometimes exhibit very different emission characteristics of the particles with increasing engine thrust. Furthermore, a dependence of the nvPM emissions on the combustor pressure and the fuel/air ratio was identified. During cruising operation, in addition to reduced combustor pressure, there is also an increase in the fuel/air ratio due to lower air density at higher altitude. These mechanisms have opposing effects, but in total lead to fewer nvPM emissions.

To what extent do engines combusting synthetic kerosene produce more or less water vapour than engines combusting conventional kerosene?

The amount of water vapour produced depends on the amount and hydrogen content of the fuel used. Kerosene from fossil sources contains compounds with carbon rings, which have a higher carbon content. Synthetic kerosene does usually not contain carbon rings, so its hydrogen content is higher. The combustion of synthetic kerosene therefore generally produces more water vapour but less carbon dioxide.

Furthermore, synthetic kerosene may have a higher energy content (indicated by the heating value of the mixture), in which case less fuel would be needed for the same flight and therefore less water vapour would be produced (with the same hydrogen content).

However, the contribution of water vapour to the effective radiative forcing (see section 2.3) of all historical aviation emissions is only about 2 % of the total aviation impact.

Since it is not yet fully understood how particles form, it has not as of now been possible to develop concepts specifically for reducing particulate emissions. However, measurements have shown that modern combustion chamber concepts for NO_x reduction also reduce particulate emissions. In particular, combustion concepts with excess air enable almost particle-free combustion.

Furthermore, soot formation is greatly reduced when fuels with a low aromatic hydrocarbon content are used, regardless of the combustion concept. Synthetically produced climate-compatible fuels (see section 4.2) usually do not contain aromatics and could therefore make an important contribution to reducing not only CO_2 emissions but particulate emissions from aviation as well. In contrast, no significant influence on NO_x emissions could be determined regarding the use of synthetic fuels.

Distribution of emissions

The geographical distribution of CO_2 emissions from today's air traffic is shown in figure 4. It can be seen that most air traffic takes place in the northern hemisphere. A particularly large amount of air traffic takes place between Europe and the USA. The altitude profile in figure 4 shows that emissions occur primarily at cruising altitudes of about 10 to 12 kilometres. This roughly corresponds to flight levels FL330-FL390. Flight levels are an important unit of measurement for flight altitude and represent flight altitudes at the same air pressure. Therefore, aircraft can be safely separated vertically even at great altitudes.

2.2 Atmospheric changes

Carbon dioxide

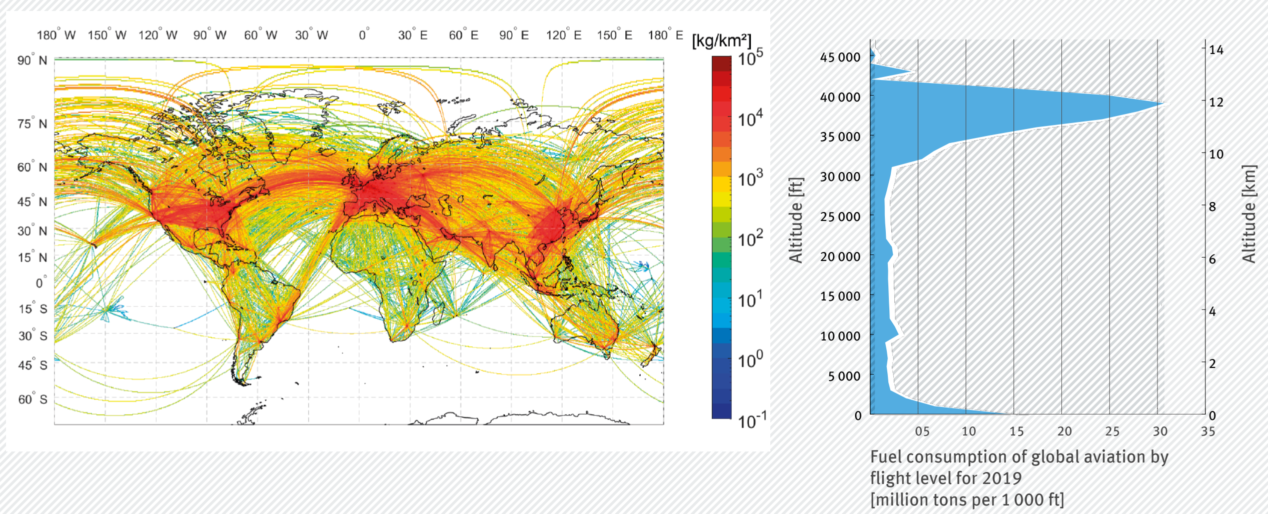
Carbon dioxide is the best-known and most important greenhouse gas caused by humans. It mainly absorbs radiation emitted from the earth's surface, while it hardly affects radiation coming from the sun. As a result, it leads to a warming of the atmosphere.

An essential factor for the effect of CO_2 emissions on the climate is the long residence time for a large portion of the gas in the atmosphere. No uniform residence time can be given for CO_2. A part of the CO_2 is rapidly taken up by plants. The oceans also absorb large amounts of CO_2, removing it from the atmosphere. After about 80 years, roughly half of the carbon dioxide emission is removed. However, about 20 % of the emissions are still in the atmosphere after 1 000 years. Because of the long residence time, CO_2 is evenly distributed in the atmosphere.

Because of high background concentration, the relative contribution of the annual emission from aviation is numerically small, but CO_2 emissions accumulate due to the long residence time in the atmosphere, intensifying their effect. Figure 5 shows that, based on 2018 numbers, CO_2 accounts for about one third of the total effective radiative forcing from past air transport.

Figure 4

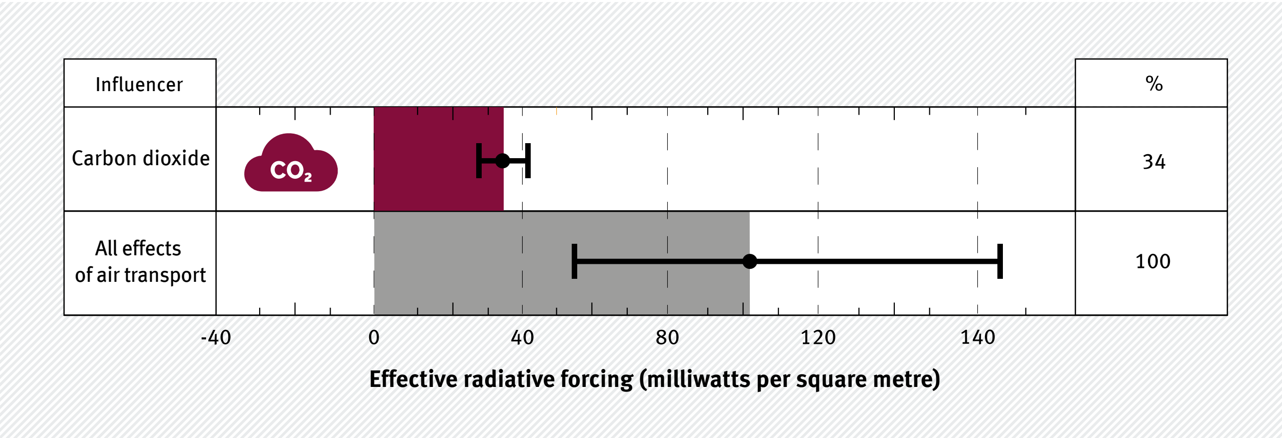
Global distribution of aviation emissions 2019



Source: own figure, DLR

Figure 5

CO_2 share of the total effective radiative forcing in 2018 from past air traffic



95 % confidence interval

Source: own figure, DLR, based on data from Lee et al., 2021

Contrails

A clearly visible effect of air traffic are contrails (see figure 6). Hot water vapour emitted by aircraft is mixed in the wake of the aircraft with ambient air. In the process, the exhaust gases cool down. This process continues until the temperature and humidity of the ambient air are reached. In the course of this mixing process, air humidity may temporarily exceed the saturation limit. Then, water droplets form spontaneously (similar to breathing in cold and humid autumn air). If it is cold enough, the droplets freeze in the course of further cooling and form a contrail. Whether the contrail disappears immediately or persists for a longer period of time depends on the atmospheric conditions (see infobox).

If these linear clouds persist over a longer period of time, they are moved onward by the wind, and fanned out. In the process, they can grow into so-called contrail cirrus which can hardly be distinguished from natural ice clouds (cirrus clouds) due to the deformation caused by wind.

Contrails can have warming or cooling effects, depending on radiation conditions[5], because they both backscatter solar radiation into space, thus cooling, and keep radiation emitted from the earth's surface in the atmosphere, thus warming.

Does CO_2 emitted at high altitudes have a higher climate impact than at ground level?

In principle, increasing a concentration of greenhouse gases has a greater effect at higher altitudes because the temperature difference between the emission layer and the ground becomes greater. However, CO_2 has an effect over a very long period of time, during which it is distributed uniformly in the atmosphere regardless of where it is emitted. Thus, the long-term effect of a CO_2 emission at higher altitudes is the same as that of an emission at ground level.

5 Position of the sun, brightness of the background, other clouds.

Contrails

The colder the air, the less water it can hold in form of vapour. Once this quantity is reached, the air is saturated. If the amount of water vapour exceeds this saturation value (solid curve or point 1 on dashed curve), the excess water vapour condenses into liquid water (clouds or fog formation) or solidifies into small ice crystals, which form natural cirrus clouds or artificial contrails (point 2). If the ice supersaturation is only temporarily exceeded during the cooling process of the hot exhaust gas (point 0) with the cold ambient air (along the red straight line), contrails will dissipate after a short time (point 4). However, if the humidity of the ambient air is above ice saturation (point 3), the ice crystals of the contrail can continue to grow and consist for several hours. Humidities above water saturation do naturally not occur in the upper troposphere.

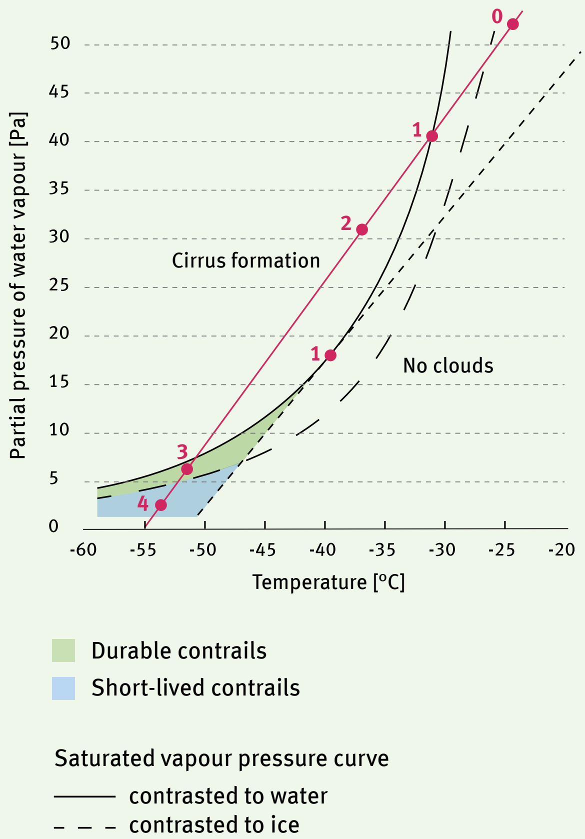


Figure 6

Contrails behind a A321

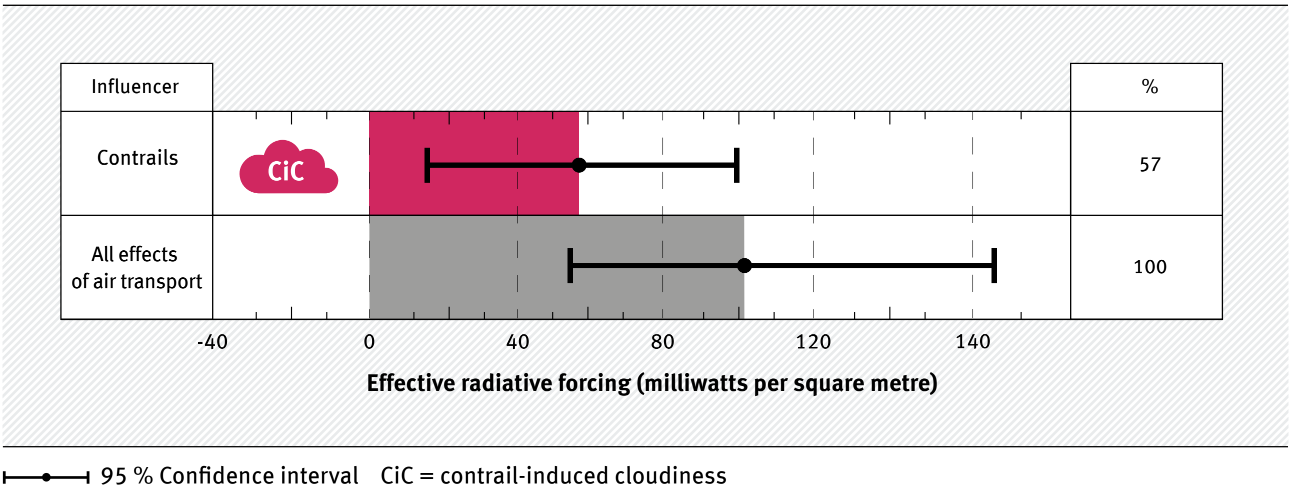
Source: image, DLR

While contrail cirrus are always warming at night because there is no solar radiation to backscatter, during the day the warming and cooling effects can partially offset each other. Averaged globally and throughout the day, contrail cirrus clouds lead to warming.

Globally, contrails form on average on only about 10 % of air routes, but still have a greater impact than CO_2 relative to the current radiative forcing of all historical aviation emissions (see figure 7) because they have a very strong regional and temporary effect on radiation.

Figure 7

CiC share of the total effective radiative forcing in 2018 from past air traffic



Source: own figure, DLR, based on data from Lee et al., 2021

Why don't contrails form everywhere?

Contrails can only form in sufficiently cold air and are only long-lived in moist air. Whether a contrail forms depends very much on where and when the aircraft's water vapour is emitted. Contrails form most frequently near the tropopause (altitude of about 8 kilometres at the poles and about 17 kilometres in the tropics), because it is both cold and humid enough there. At lower altitudes, it is usually too warm, while at higher altitudes, i.e., in the stratosphere, it is usually too dry. In addition, both the formation and the residence time of contrail cirrus depend on the weather situation. There are weather situations in which no contrails form if the air is too dry or too warm even at high altitudes. On the other hand, there are also weather situations in which there are hardly any natural clouds, but the sky is covered with a multitude of contrail cirrus.

Nitrogen oxides

As an undesirable by-product, nitrogen oxides (NO_x) are formed during the combustion of kerosene through the oxidation of atmospheric nitrogen at high combustion temperatures. The chemically reactive nitrogen oxides have only a very short residence time in the atmosphere and do not directly affect its radiation balance. However, they influence the concentration and residence time of greenhouse gases ozone (O_3) and methane (CH_4) in the atmosphere.

By interacting with a number of other gases, NO_x emissions from air transport further ozone production through photochemical reactions. At ground level, increased ozone concentration worsens air quality (smog). At altitudes where today's air traffic takes place (8-13 kilometres above sea level), however, ozone acts mainly as a short-lived greenhouse gas and the increase in concentration leads to a warming of the earth's surface. Since solar radiation is necessary for ozone production, the ozone production caused by NO_x emissions also increases proportionally to solar radiation at high altitudes.

The OH radicals produced by this reaction cause an increased decomposition of methane in the atmosphere. Since methane is a greenhouse gas, the reduction of the methane concentration leads to a cooling effect which lasts for about a decade (lifetime of methane).

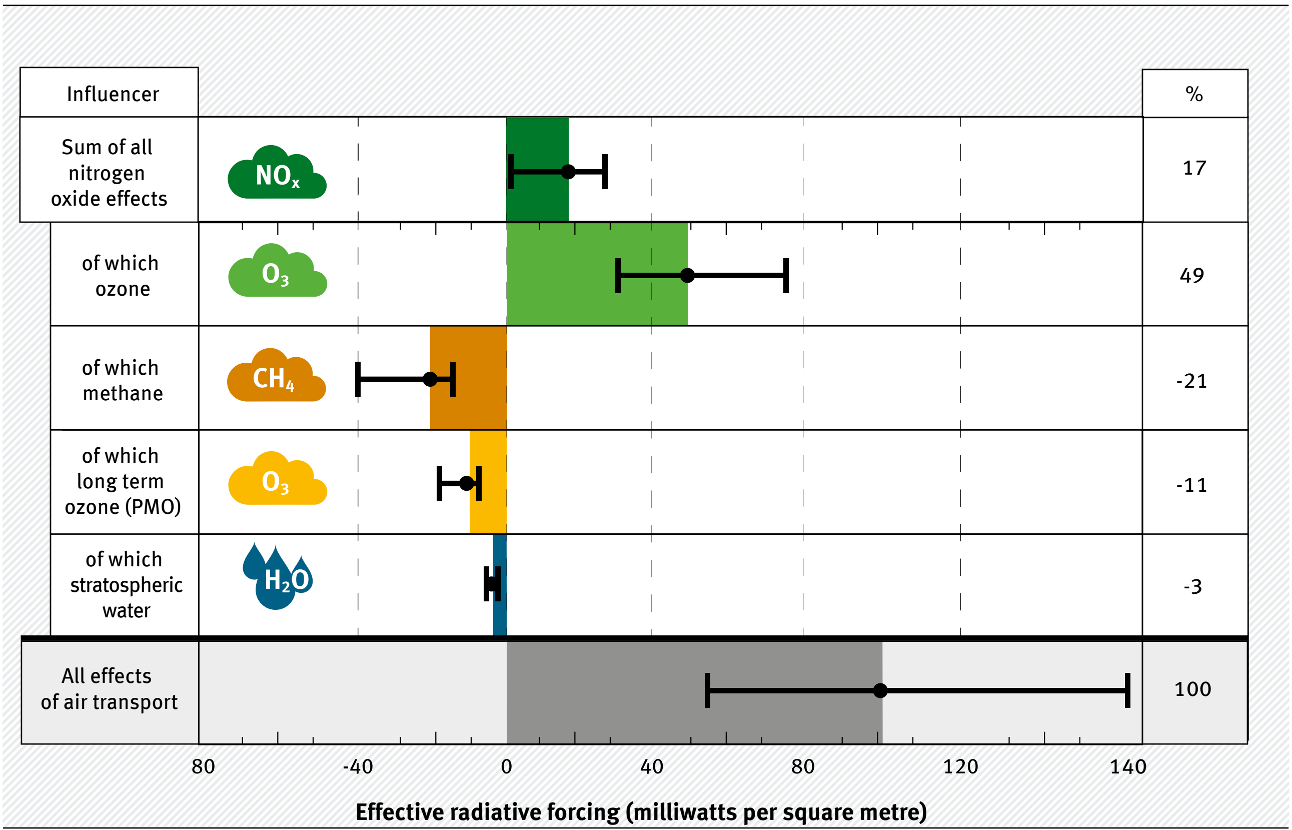
As a result of the reduced methane concentration, the “natural“ ozone production rate also decreases, resulting in a lower ozone concentration over time. This process occurs over the methane lifetime and results in cooling. However, the long-term reduction in ozone concentration is much less than the short-term increase in ozone concentration shortly after nitrogen oxide emission.

Another atmospheric greenhouse gas affected by the emission of nitrogen oxides is stratospheric[6] water vapour. Some of the methane that is transported into the stratosphere is oxidised there to carbon dioxide and water vapour. If less methane reaches the stratosphere due to the reduced methane concentration, less water vapour can form there. This process also takes place on the methane time-scale and leads to a cooling effect since water vapour is also a greenhouse gas.

If one considers all the processes mentioned here and their effects, which can be attributed to nitrogen oxide emissions from aviation, some of those effects offset each other. Overall, the emission of nitrogen oxides leads to a warming of the atmosphere when considered globally (also on longer time scales). The effect of nitrogen oxides on the effective radiative forcing of all historical aviation emissions is about 17 % of the total aviation effect (see figure 8).

Figure 8

Nitrogen oxides share of effective radiative forcing in 2018 from past air traffic



95 % Confidence interval

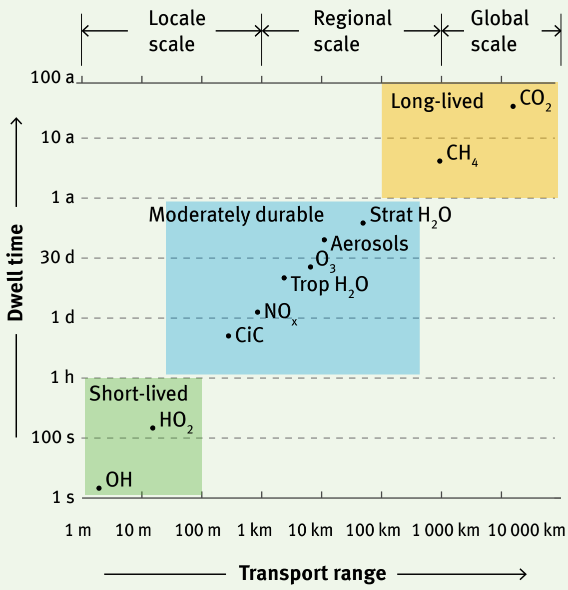
Source: own figure, DLR, based on data from Lee et al., 2021

6 The stratosphere is located above the troposphere at an altitude of about 15 to 50 kilometres.

Atmospheric residence time and transport range of trace substances.

The longer trace substances remain in the atmosphere, the further they are transported around the earth.

Carbon dioxide is particularly long-lived. Since it takes about 80 years for half of the emitted CO_2 to decompose again, CO_2 is distributed globally over this time. CO_2 thus affects the climate on a global scale. Particularly short-lived trace substances, such as NO_2, are transported only a few metres to kilometres. Their local climate impact is thus strongly dependent on local environmental conditions, such as weather phenomena.



Aerosols

Aerosols are heterogeneous mixtures of solid or liquid suspended particles in the air. They include, for example, soot, mineral dust or sulphate particles. Air traffic emits both aerosols (e.g. soot particles) and aerosol precursors (e.g. nitrogen and sulphur compounds), which can later form aerosols. Aerosols act in the atmosphere in two very different ways: on the one hand, directly by absorbing and reflecting radiation, and on the other hand, indirectly by influencing cloud formation.

The direct aerosol effect is strongly dependent on the optical properties of the respective particles. For sulphate particles, the reflection of short-wave solar radiation predominates, while the absorption of long-wave terrestrial radiation is rather low. Thus, sulphate particles lead to a cooling of the atmosphere. Soot particles, on the other hand, absorb a large part of the incoming solar radiation and thus lead to a warming of the atmosphere.

Besides the direct aerosol effect, aerosols can also influence the climate indirectly. Some aerosol species, e.g. sulphate and soot particles, can strongly influence the formation and properties of clouds. Aerosols emitted by aircraft, as well as aerosol precursors that are converted in chemical processes to sulphate- and nitrate-containing aerosols, can act as cloud condensation nuclei in the atmosphere. A larger number of cloud condensation nuclei, for example, leads to a larger number of cloud droplets which are smaller in size. For the same liquid water content, this leads to an increase in cloud albedo (cloud reflectivity) whereby more solar radiation is scattered back into space, and to a longer cloud residence time since smaller droplets rain out less quickly. This affects contrail cirrus as well as natural clouds.

In addition, similar to other natural or anthropogenic condensation nuclei, condensation nuclei from aviation can be transported far and wide and then, once the appropriate background conditions are present, allow new clouds to form.

Regarding condensation nuclei from air traffic, there are first estimates of the effect on low ("warm") water clouds and ice clouds.[7] According to these, these clouds lead to cooling.

7 E.g., Righi et al., 2013, Righi et al., 2021.

Because of the imprecise knowledge of the processes that aerosols undergo, estimates of the associated radiative forcing are very uncertain. Therefore, at present, the magnitude of the indirect aerosol effects of aviation is often not mentioned in the overall assessment of aviation climate impact.

Water vapour

Water vapour is one of the most important natural greenhouse gases and is responsible for about two-thirds of the natural greenhouse effect. The additional water vapour caused by air traffic leads to further warming of the atmosphere.

At low altitudes, the residence time of water vapour is very short, because water vapour condenses in clouds and rains out. In aviation, however, a large proportion of the water vapour is emitted at cruising altitude, i.e. between 8 and 13 kilometres above sea level. There, the air is many times drier than on the ground, and atmospheric residence time of water vapour is much longer. Therefore, air traffic makes a noticeable contribution to the total concentration of water vapour here. This effect is amplified at even higher altitudes, such as supersonic flights. Nevertheless, even for emissions in these regions, the residence time of a few days to a few weeks is too short to allow a homogeneous distribution of the additional water vapour. The impact of direct water vapour therefore also depends on the weather situation, in particular on the height of the tropopause and on the prevailing transport direction of the air masses.[8]

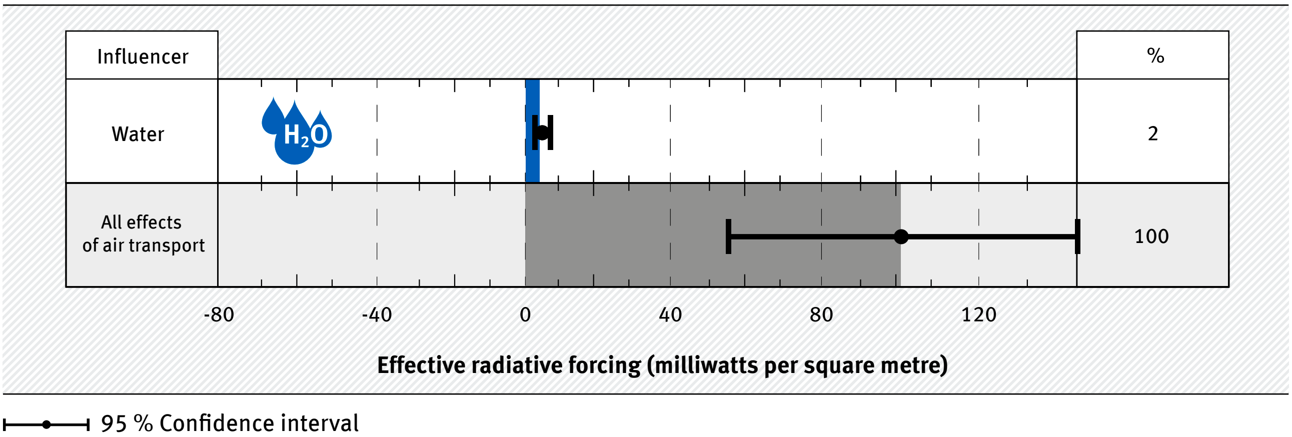
If the tropopause is at a lower altitude, water vapour is emitted to a greater extent in the stratosphere where the residence time is much longer and the effect is thus stronger. The current contribution of water vapour to the effective radiative forcing of all historical aviation emissions is only about 2 % of the total aviation effect (see figure 9).

What is the climate impact of water vapour emissions in the atmosphere?

Water vapour can affect the climate in several ways. First, water vapour is a greenhouse gas and thus warms the atmosphere. In addition, the emission of water vapour can lead to the formation of contrails. The more water there is in the turbine's exhaust stream, the greater the likelihood of contrails forming. However, increased water vapour concentration plays only a minor role in the further growth of the contrail, since the water that is needed for further growth comes predominantly from the atmosphere.

Figure 9

Water vapour share of total effective radiative forcing in 2018 from past air traffic



Source: own figure, DLR, based on data from Lee et al., 2021

8 The tropopause is the boundary between the troposphere and the stratosphere. It is about 17 kilometres high in the tropics and about 8 kilometres high at the poles.

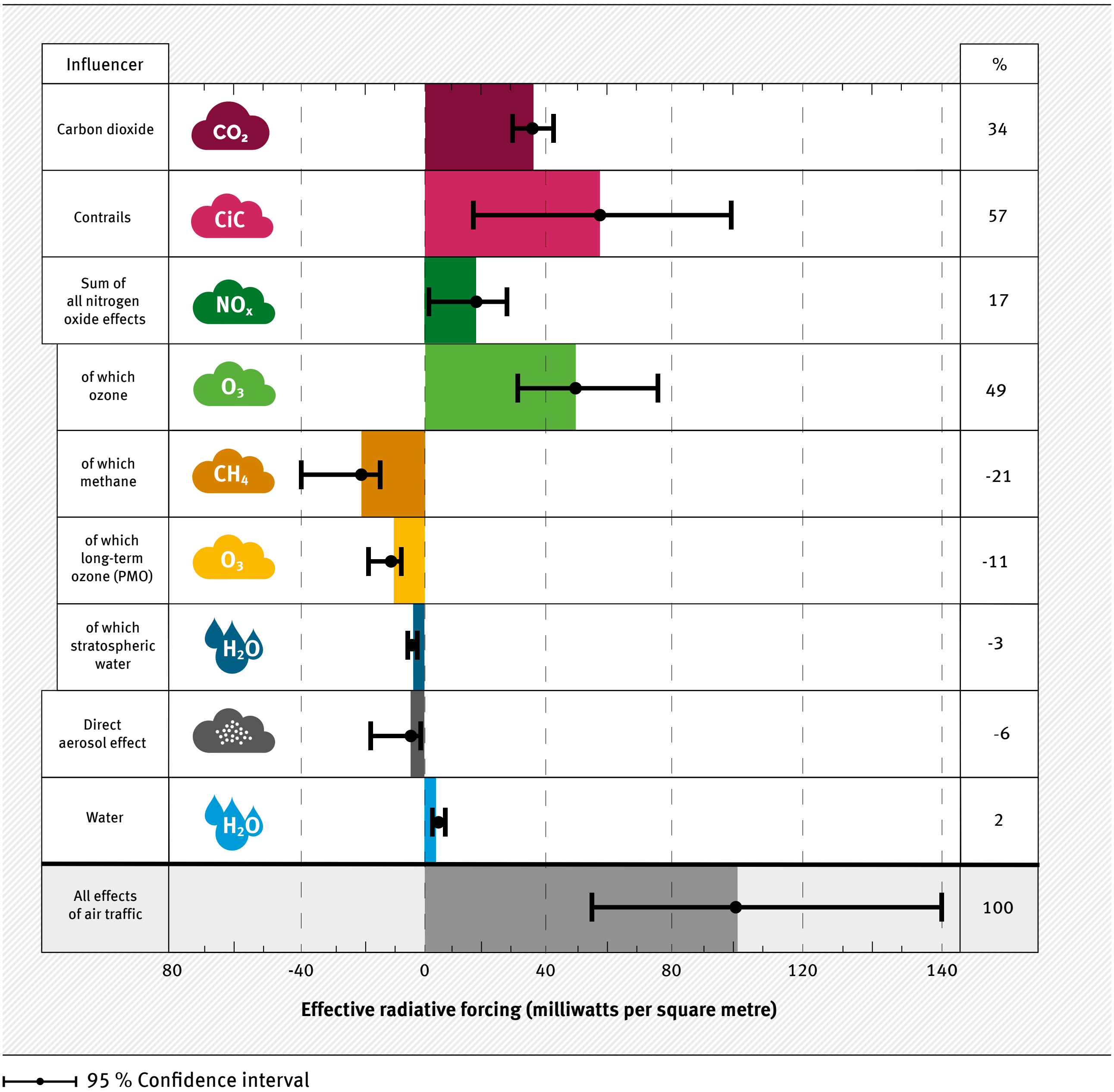
2.3 Resulting climate impact

The impact of historic global aviation emissions on the present-day radiative balance is shown in figure 10. Positive radiative forcing leads to warming, negative forcing to cooling. It can be seen that in addition to CO_2, the main effects on climate stem from contrail cirrus and nitrogen oxides.

The direct effects of water vapour and the direct aerosol effects play only a minor role. A potentially strong negative radiative forcing is caused by indirect aerosol effects, although very large uncertainties still exist here since small-scale processes in the exhaust jet cannot be resolved in the climate model.

Figure 10

Effective radiative forcing in 2018 from past air traffic



Source: own figure, DLR, based on data from Lee et al., 2021

The change in radiative balance leads to a change in the near-surface temperature. However, equal radiative forcing of different species does not necessarily lead to equal temperature changes. This is due to different climate sensitivities resulting from different spatial distributions and different feedbacks. These feedbacks can lead to an amplification, but also to a reduction of the effect. For example, ozone shows a higher climate sensitivity than CO_2, while contrail cirrus shows a much lower climate sensitivity. This is already taken into account in the effective radiative forcing.

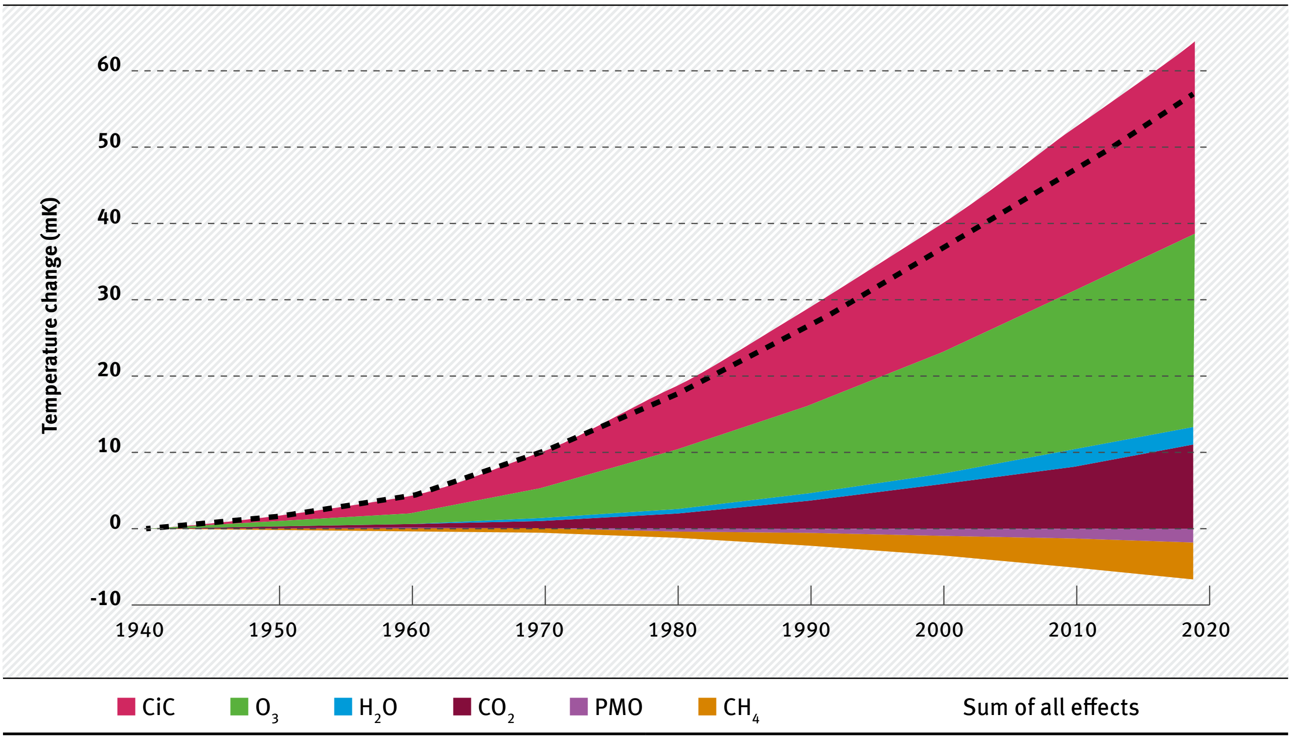
Figure 11 shows how historic aviation emissions affect temperature change in 2019 (excluding aerosol effects). By 2019, aviation had caused a change in ground-level temperature of about 57 mK (mK[9] = millikelvin). Assuming that the human-caused temperature change is about 1.1 K[10], aviation is currently responsible for about 5 % of anthropogenic climate change.

Why do non-CO_2 climate effects play a major role, especially in aviation?

Many of the non-CO_2 effects depend on the emission location. For example, contrails can only form in regions where it is moist and cold. This is especially the case at the altitudes of today's air traffic. But the regions of today's flight levels are also particularly unfavourable for climate effects due to the increase in ozone and water vapour concentrations. In addition, the temperature difference between the ground and the layer containing the clouds or greenhouse gases plays an important role. Since the atmosphere is colder at high altitudes, it radiates at a lower temperature than the ground. The radiation is therefore reduced. Near the ground, the temperature difference is small and so is the difference in radiation. For this reason, the non-CO_2 effects play a greater role in air transport than in road traffic, for example.

Figure 11

Time course of the temperature change of the individual trace substances of the present air traffic until the year 2019



Source: own figure, DLR

9 Temperature difference of 1 K corresponds to 1 °C temperature change.
10 IPCC, 2023.

Comparison of the climate impact

3

Comparison of the climate impact

For the climate impact of different sectors (e.g. road transport, rail transport), often only the effect of CO_2 is given. However, especially for air transport, the non-CO_2 effects are also particularly relevant. Therefore, it is important to aggregate the climate impact of all effects (CO_2 and non-CO_2) in order to find out the extent as to which certain measures affect the climate.

The climate impact of aviation is composed of the effect of a number of climate species[11]. These affect the radiation balance in different ways. In addition, they have different residence times, which means that their effects cannot be directly compared. Therefore, to evaluate the climate impact of different aviation scenarios or different trace emissions it is necessary to have a measure, or metric, available for comparison. Here, a metric represents the direct relationship between the emission and the effect under consideration (e.g., radiative forcing, temperature change, or damage).

Comparing the climate impact of different emissions is similar to comparing apples and oranges. There is no general metric that can be used to compare the two in all their characteristics. However, if one asks a specific question, for example, about the price of a kilogramme or vitamin content, it is very easy to compare apples and oranges. The problem with a metric for comparing climate impact is that the term 'climate impact' is not defined more precisely. It does not specify what effect is being studied (e.g., radiative forcing, temperature change), nor for what point in time or time period the effect should be considered. For a given question, e.g.: "What is the temperature change in 2100?", however, a unique metric can be specified.

Often, different climate effects are compared on the basis of their respective radiative forcing. By multiplying the radiative forcing by the climate sensitivity the globally averaged near-surface temperature change (dT) can be determined. However, the climate sensitivities of different climate species differ. For example, they are significantly lower for contrail cirrus than for ozone (see section 2.3).

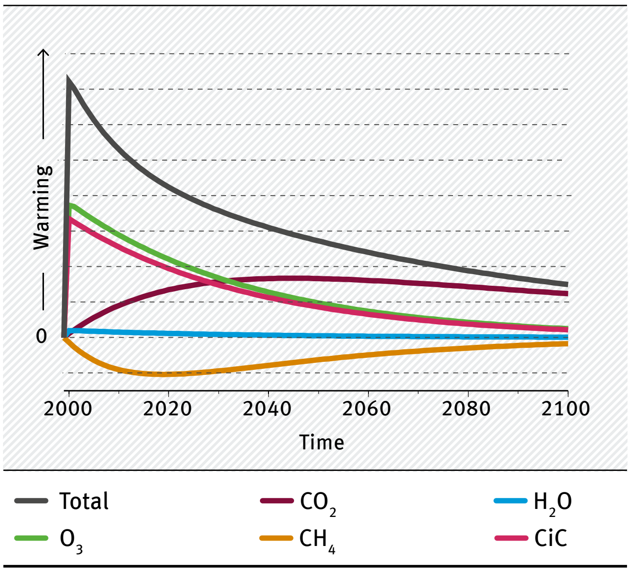
11 Climate species refers to the different components of climate impact, e.g., carbon dioxide, ozone, methane, contrails, and water vapour.

Furthermore, how large the impact of non-CO_2 effects is compared to the influence of CO_2 itself, depends on when the climate impact is analysed. As an example, figure 12 shows the temperature change due to emissions in the year 2000. CO_2 (dark red line) has very little effect on temperature in the early years. As it accumulates due to its long residence time in the atmosphere, the effect increases over time. The effect of nitrogen oxides on methane (light brown line) also shows only a small effect at the beginning, but increases over the next ten years and then decreases again. The temperature trajectories of contrail cirrus (CiC, purple line), ozone change caused by nitrogen oxides (light green), and H_2O (blue line) are very similar. The effect is very strong at the beginning, but then decreases over time.

In the first 30 years, contrail cirrus and ozone dominate the temperature change, i.e., the non-CO_2 effects, while CO_2 effects dominate thereafter. The ratio of non-CO_2 to CO_2 effects decreases, with the emissions of only one year shown here, from over 20:1 in the first years to about 1:4 after 100 years.

Figure 12

Time course of the temperature change of the different climate species for an emission in the year 2000



Source: data from Dahlmann et al., 2016

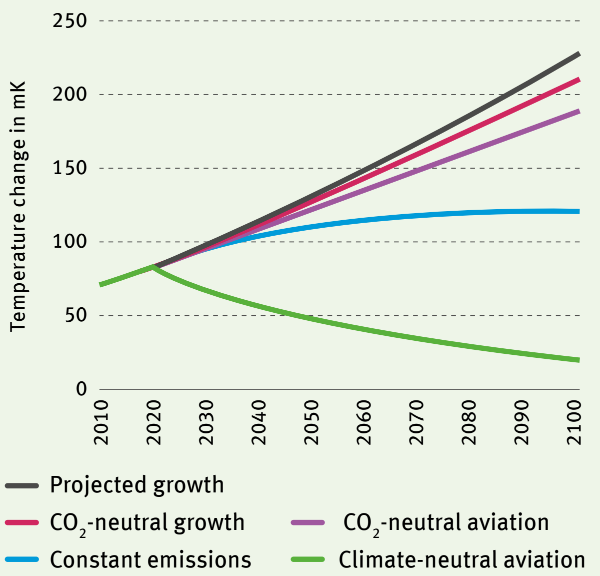
One way to reduce this dependence on the time period is to average or integrate over time, as is done, for example, for ATR[12] and GWP[13]. But again, the time period over which averaging is done affects the relationship between non-CO_2 effects and CO_2. A short time period puts the focus on non-CO_2 effects, while a long time period puts the focus on CO_2. When considering the effect of all historical aviation emissions relative to the current change in effective radiative forcing, the non-CO_2 effects (not including aerosol effects) cause about two-thirds of the effect.

Both the short and long time frames play a role in reducing the consequences of climate change. On the one hand, it must be ensured that the temperature does not rise too much in the coming decades, in order to avoid triggering irreversible tipping mechanisms in the earth's climate system. On the other hand, it must be ensured that climate change and related problems are not simply passed on to the next generations by reducing the short-term effects now, but thereby accepting the long-term climate-damaging effects. One example of a middle ground is therefore to use an integrating or averaging metric with a long time horizon, as then both the short-term and long-term effects are taken into account. For example, a metric that accounts for both short-term and long-term temperature change would be the ATR_{100}.

How does temperature evolve in the future for different emission scenarios?

Temperature change caused by aviation is largely determined by the quantity emitted and the spatial and temporal distribution of all climate-relevant emissions. The location and quantity of emissions depend on the global volume of traffic, the choice of fuel and the efficiency of the aircraft types used.
If, as in recent decades, air traffic growth exceeds the reduction in fossil fuel consumption, emissions and thus the temperature change caused by air traffic continue to increase (black curve). If the amount of emitted CO_2 remains the same we call this **CO_2-neutral growth.**

For **CO_2-neutral aviation**[15], one assumes that CO_2 net emissions are zero (purple curve). Both could be achieved through efficiency improvements, alternative fuels, or even off-sets. However, due to increasing non-CO_2 effects and CO_2 accumulation, temperature also increases in these scenarios. If in the future, in addition to CO_2 emissions, the emission amount of all trace substances remains the same, we call this **constant aviation emissions** (blue curve). As a result of the inertia of the atmosphere and the accumulation of CO_2, this also only leads to a slowdown in warming. For **climate-neutral aviation**, all emissions would have to be avoided or compensated (green curve).



Source: own figure, DLR

12 Average Temperature Response, averaged ground level temperature change over a period of time.
13 Global Warming Potential, radiative forcing of a species summed over a period of time relative to that of CO_2.
14 Under the simplified assumption that the spatial distribution of emissions does not change.
15 In the literature, the terms CO_2-neutral or climate-neutral aviation are used differently and sometimes as synonyms.

Measures to reduce the climate impact of aviation

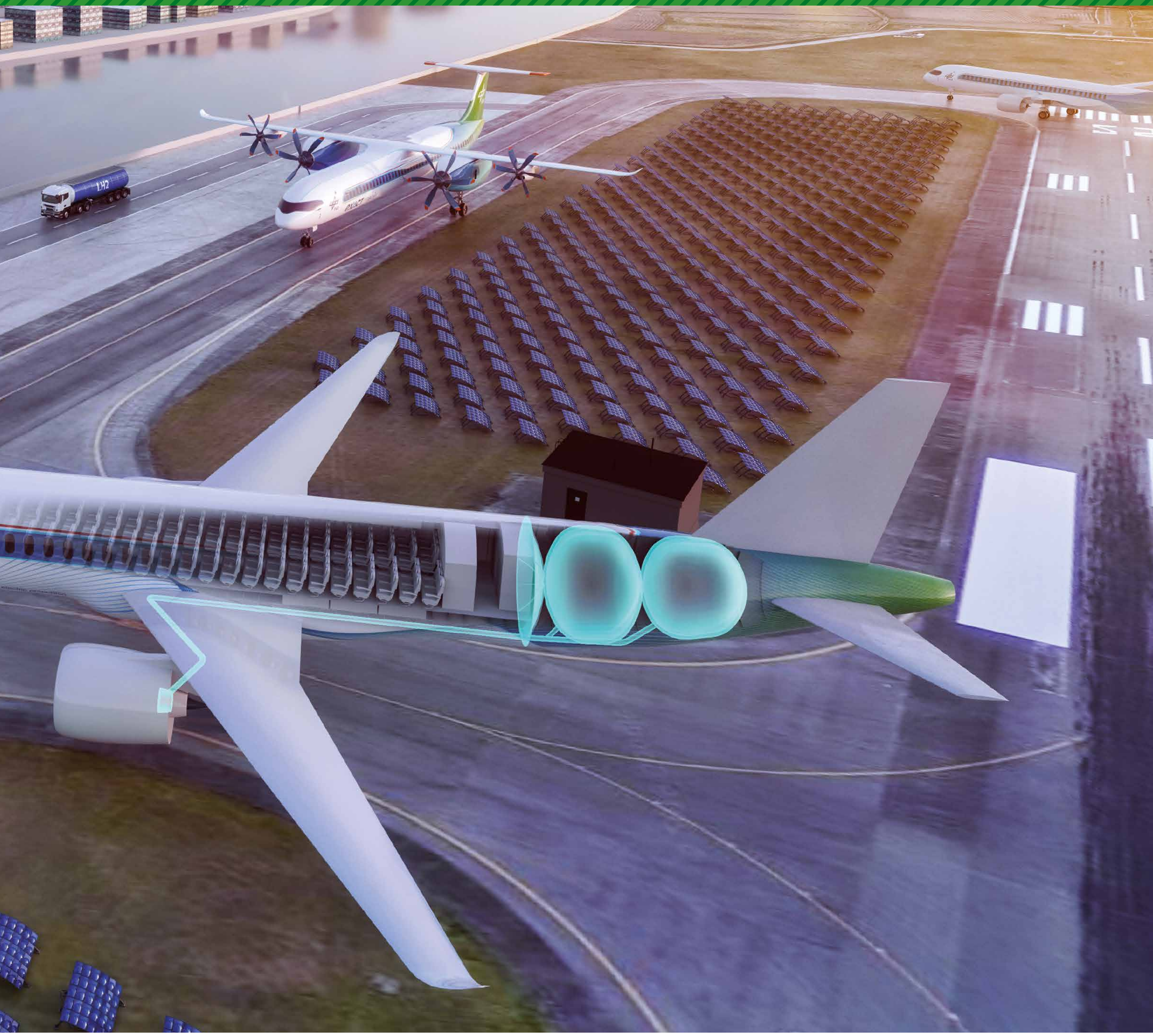
4

Energy-efficient aircraft

Low-emission propulsion

Alternative fuels

Reduced-emission air transport system



Measures to reduce the climate impact of aviation

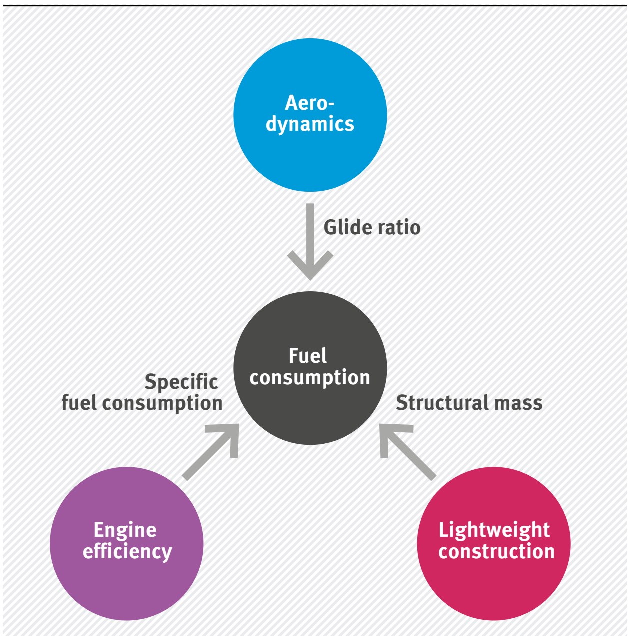
As a result of the strongly different modes of action of CO_2 and non-CO_2 effects, measures need to be researched and implemented that reduce the overall climate impact of all effects.

Under the simplified assumption that the spatial and temporal distribution of emissions does not change, the following applies: the fewer emissions are emitted per flight, the lower the resulting climate impact. However, if individual flight routes are considered on different days, individual measures can also be contradictory to each other: if, for example, flights have to be re-routed to avoid the formation of contrail cirrus clouds, this is often only possible with increased fuel consumption and rising emissions. In these cases, the reduced climate impact of contrail avoidance must be balanced against the warming effect of additional CO_2 emissions in order to determine the resulting climate impact. When selecting suitable measures it is therefore important to consider the climate impact of all climate-relevant aviation emissions and their indirect atmospheric chemical and microphysical effects together and to optimise them holistically. Particularly promising measures are discussed on the following pages. In addition to alternative aviation fuels, these include, on the technological side, low-emission aviation engines and energy-efficient aircraft, and, on the operational or regulatory side, an emission-reduced air transport system. These measures are flanked by digitisation, which is seen as a key driver for accelerated implementation of the measures.

How zero-emission aviation can be achieved in the future has been published by DLR, among others, in its Aviation Strategy for the European Green Deal[16].

Figure 13

Ways to reduce fuel consumption



Source: own representation, DLR

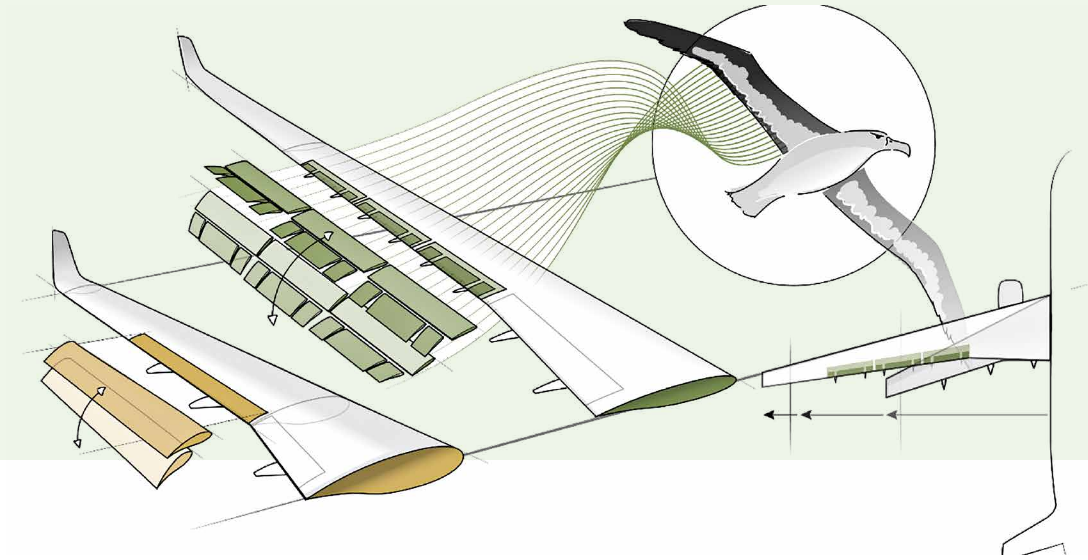
4.1 Energy-efficient aircraft

On the technology side, the amount of emissions per flight – especially CO_2 – can be reduced through continuous improvements in aerodynamics, aircraft structure and engines (see figure 13). The transition to new types of energy sources such as SAF (sustainably produced kerosene), hydrogen or batteries will have a significant impact on the configuration of an aircraft, its range and transport performance, and the possibilities of using new technologies.

16 DLR, 2021.

New, finely segmented control surfaces for highly stretched wings of the future

Nature often serves as a model for technical innovations. The effortlessly gliding Albatross, for example, demonstrates how aerodynamic drag can be further reduced by stretching the wings to a particularly slim shape. If the airplane flaps in use are also replaced by more finely divided control surfaces, it is hoped that this will result in particularly high aerodynamic performance.



Drag reduction

Aerodynamic improvements to aircraft aim to improve the glide ratio, which is the quotient between lift and drag on an aircraft: the higher, the glide ratio, the lower the energy consumption for the same transport performance (range, payload). A high glide ratio is achieved at a certain speed, which depends on the flight altitude. At lower altitudes, with higher air density, it is necessary to fly more slowly in order to operate the aircraft in the optimum glide ratio.

Another lever is the flow around the wings and fuselage. If airflow around airfoils is largely turbulent, as is the case today, this increases drag, fuel consumption and emissions. Laminar airfoils are designed to ensure that the flow around the wing is as smooth and turbulence-free as possible over long distances. However, this requires very smooth surfaces, which makes the production of a wing significantly more complex and expensive and requires frequent cleaning.

Weight reduction through lightweight construction

Improved aircraft structure attempts to reduce the empty weight of an aircraft whilst maintaining the same load capacity. This is of particular importance in aviation since the weight of the aircraft must be supported by aerodynamic lift, unlike ground-based vehicles where the weight is borne by the ground.

Systematic lightweight design with integrated systems is therefore necessary in order to take full advantage of all technological improvements to the aircraft. Every kilogramme of weight that can be saved reduces the required lift, thus drag and ultimately fuel consumption. If less fuel is consumed, less must be refuelled, further reducing weight. Technologies directly related to reducing overall aircraft weight include novel materials, production and maintenance technologies.

Control of stability and load as well as optimisation of the on-board systems

Load reduction technologies aim to reduce the forces acting on the aircraft structure by means of precisely calculated control pulses, thus enabling even lighter designs. Such systems are necessary, for example, to take full advantage of the aerodynamic benefits of a high aspect ratio wing and not to jeopardise them by excessive wing mass. Appropriate electrical flight control systems and sensors ensure that an adaptive compliant wing is used optimally.

Integration of new propulsion technologies and required systems for new fuels

The use of new energy sources, such as batteries or hydrogen, also opens up opportunities to make aircraft more emission-efficient. For example, the introduction of distributed electric drives or hybrid powertrains is being discussed. Developing and testing new refuelling systems is one of the tasks required for hydrogen to be used as an energy source. Storing hydrogen in gaseous form requires a lot of space; keeping it liquid at minus 253 °C costs energy and requires good thermal insulation and a safety concept. Likewise, cooling concepts are needed for the use of fuel cells and electrical systems.

What is the average service life of individual aircraft types?

Individual aircraft types are often produced over many decades (in the case of the Boeing 747, for example, over 50 years) and are constantly being adapted to the advancing state of the art with new variants. With appropriate maintenance, delivered aircraft can be operated economically for around 30 years. In direct comparison to other sectors, such as the automotive industry, the renewal of the operating fleets is therefore a slow process.

Configurations

The challenge in the development of new aircraft is to combine the above technologies in a meaningful way, to identify suitable aircraft configurations and to realise optimised overall aircraft designs taking into account the technologies, in particular the alternative propulsion concepts.

In order to specifically reduce the non-CO_2 effects of aircraft as well, further conceptual approaches consist of integrating the findings of atmospheric research directly into aircraft design. If future aircraft are explicitly designed for more climate-friendly (slightly lower) flight altitudes and cruise speeds, efficiency losses that occur when operating aircraft at lower flight altitudes can be better compensated. Implications for air traffic management and travel times must be kept in mind.

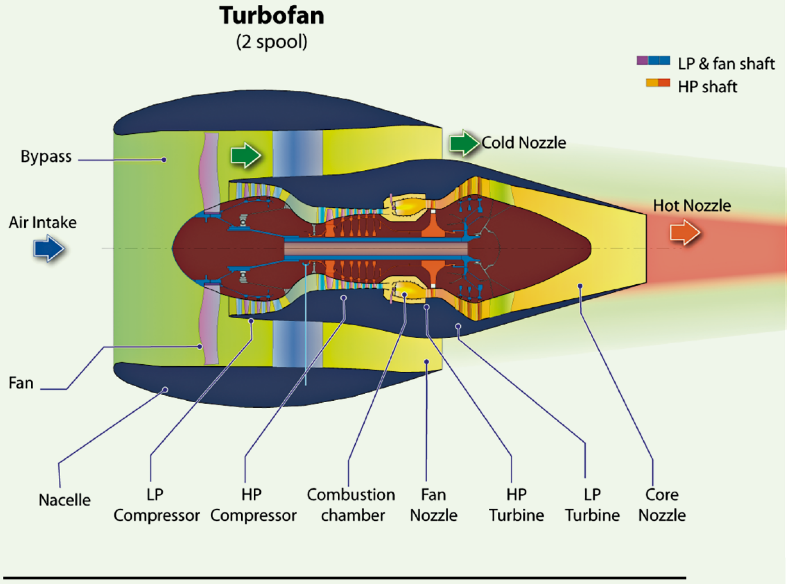
However, due to relatively long product cycles in aviation, the introduction of completely new types of aircraft is not expected within the next 10 years.

In order to achieve the EU's climate targets ("Green Deal"), future aircraft would have to be improved to such an extent that only half of today's propulsion power would be required by 2050. Current studies show that this could be achieved by reducing aerodynamic drag by more than 40 % and reducing the total weight of the aircraft by 10 %. In order to be able to integrate the technologies required for this in an aircraft concept in the best possible way, they must be taken into account right from the start of development work.

How a jet engine works

All modern jet engines consist of an engine core in which the combustion of fuel takes place with a small portion of intake air to produce propulsion energy. The larger portion of intake air flows around this engine core in an outer annular duct, called a bypass, and is compressed and accelerated only by the engine's first blade wheel, called a fan. This acceleration of the air creates a propulsive force called thrust, which is what propels the aircraft.

The energy to drive the fan is supplied by the engine core. The ratio of the air mass flow through the bypass and through the core is called the bypass ratio and reaches a value of 10 and higher in modern engines.



Source: Wikipedia, 2023, CC BY-SA 3.0

4.2 Low-emission propulsion

A reduction in CO_2 emissions from aircraft engines can be achieved by reducing fuel consumption or by using fuels with a lower carbon content (e.g. SAF or hydrogen, see section 4.3).

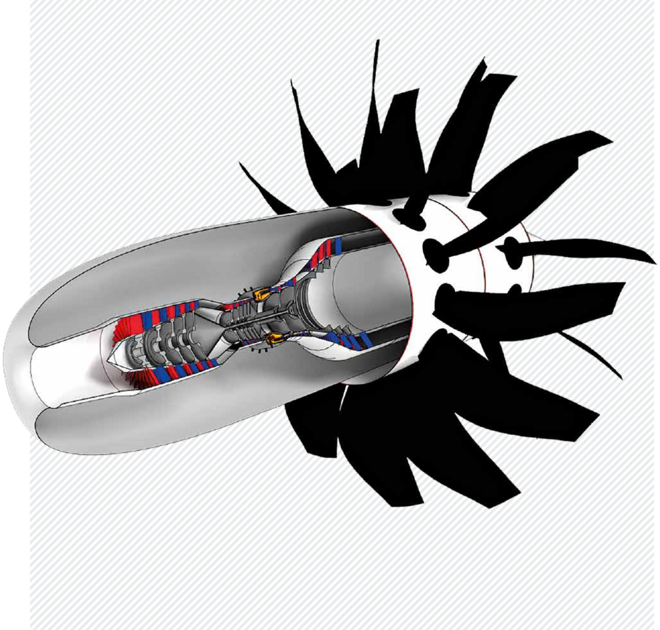
Turbo engines

In the field of conventional turbo engines, fuel consumption – and thus CO_2 emissions – can be reduced by improving the overall efficiency of the jet engine. This concerns the thermal efficiency of the energy conversion in the engine process and the propulsion efficiency. Any improvement in the efficiency of aircraft engines must target one or both of these efficiencies. Additionally, the weight (lightweight design) and the engine diameter (aerodynamics) are relevant for the overall efficiency of an aircraft, as both contribute to the aircraft's aerodynamic drag.

The thermal efficiency of energy conversion in the engine core is determined by its maximum temperature, its overall pressure ratio and the efficiencies of the engine's compressor and turbine components. The achievable maximum temperature and the overall pressure ratio are limited by physical constraints. For example, peak temperatures in modern engines lie well above the melting temperature of the materials used, which therefore have to be protected by sophisticated cooling techniques and thermal barrier coatings. Here, research is being conducted into new, high-temperature-resistant materials and advanced cooling technologies to enable further efficiency improvements. Control of NO_x formation is also becoming more difficult due to pressure and temperature increases; thus the full potential of CO_2 reduction technologies may not be realised.

Figure 14

Concept of an open rotor engine



Source: own representation, DLR

Propulsive efficiency is a measure of how efficiently the work done on the engine's working medium (=air) is converted into propulsive power (=thrust). This efficiency can be improved by reducing the speed of the propelling jet. To achieve this, the air mass accelerated by the engine must be increased to generate the same thrust. This requires an increase in the bypass ratio (see infobox) and is associated with a larger engine diameter and increased weight, which affects the overall efficiency of the aircraft. This can be countered in part by innovative composite materials and optimised components. High engine core power density can also partially offset this effect, but in turn requires higher process pressures and temperatures, which lead to challenges in controlling NO_x emissions. An extreme case of this development is the propeller engine, where there is very little difference between airspeed and speed of the propelling jet. However, this also means that propeller aircraft are generelly slower than jets. So-called open rotor engines (figure 14) represent a compromise in this respect, although research work still needs to be done here.

Further improvements in the field of turbo engines are technically limited by the requirements for integrating the engine into the aircraft. Progressively larger engines can no longer be installed under the wing and may require completely different aircraft configurations.

As possible alternatives to this, so-called distributed propulsion systems are being discussed for short-haul and regional aircraft, in which either an engine core drives several smaller fans distributed over the wing or these fans are driven by their own electric motors (see figure 15). These concepts are significantly more complex in technical implementation and probably also heavier than conventional engines, which has implications for the overall aircraft design.

Electrical components, fuel cells and hybrid-electric drives

In order to be able to realise such distributed electric propulsion systems, for example, hybrid-electric propulsion concepts are currently being researched using hydrogen in fuel cells and the utilisation of the electric current in high-performance electric drives. Challenges here include power and power density as well as system weight, which is why the technology is not yet mature enough to be able to operate larger civilian commercial aircraft with it. Additional batteries can be used to meet higher power requirements in the short term during critical phases of flight (especially takeoff, climb and "go-around"). The potential of further battery-electric applications is being investigated for increasingly larger aircraft and for more extended flight missions.

Revolutionary gas turbine drives

In addition, technologies aimed at reducing the non-CO_2 effects of classic gas turbine engines are also being researched. These include, for example, lean-burn combustion (see section 2.1), but also revolutionary concepts such as water injection in the combustion chamber (Water-Enhanced Turbofan, WET), which primarily aim to significantly reduce NO_x emissions. Novel combustor concepts also provide further levers due to the reduction of soot particles (see section 2.1), which can influence the climate impact of contrails.

Figure 15

Example of an aircraft concept with distributed drives, electric components, fuel cells and hybrid electric drives

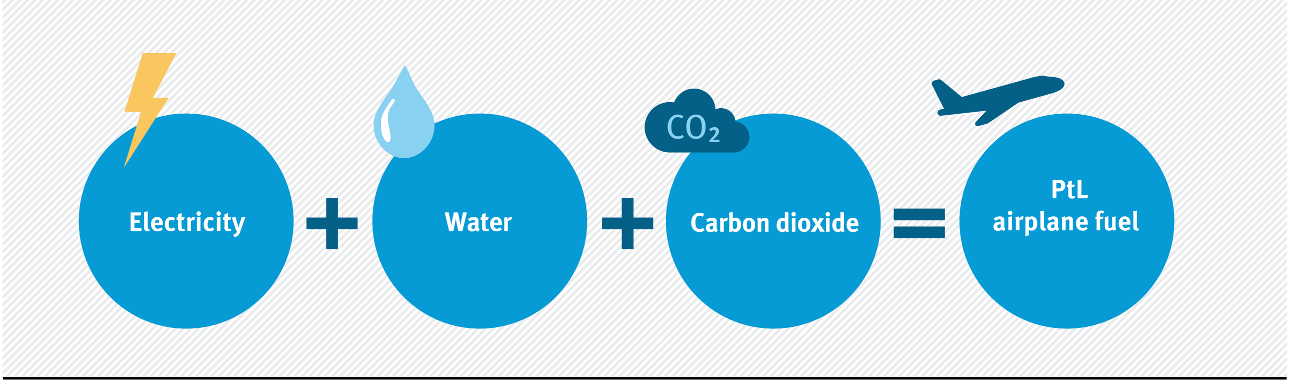
Source: o wn representation, DLR, CC-BY 3.0

Hydrogen technology and sustainably produced kerosene (SAF)

The use of hydrogen as an energy carrier in the engine requires systematic research and development of safe, reliable and low-polluting hydrogen combustors, as well as safe handling and control of hydrogen and an increased water vapour content in the hot gas range. The combustion of SAF with a modified chemical composition also requires further research and development if 100 % SAF should be used as fuel.

Figure 16

Principle of power-to-liquid (PtL) fuels



Source: BHL and LBST, 2021

4.3 Alternative fuels

While conventional kerosene is produced on the basis of crude oil, kerosene can alternatively be produced synthetically from biomass (agricultural waste products, household waste, plants grown in-house) or with the help of electricity from renewable energies ("power to liquid", PtL)[17] (figure 16). In PtL production, hydrogen is first produced (electrolysis) and then combined with CO_2 in a chemical process. However, hydrogen or methane (natural gas) can also be used directly as fuel.

What are the non-CO_2 effects if aircraft flew on hydrogen instead of kerosene?

The combustion of hydrogen emits more water vapour than the combustion of kerosene. As a result, the effect of the water vapour is greater and the probability of contrails forming increases. On the other hand, significantly fewer particles are emitted which could reduce the climate impact of contrails, as both the residence time decreases and optical properties change. In addition, the lower emission of aerosols also reduces the direct and indirect aerosol effects. The extent to which hydrogen combustion reduces the emission of nitrogen oxides is still uncertain.

In the case of alternative fuels, a distinction is made between so-called drop-in fuels, which can be used with the existing infrastructure and in today's existing aircraft and engines without major modifications, and non-drop-in fuels, for which a separate supply infrastructure would have to be installed and new aircraft and/or engine types developed. It stands to reason that the latter can only be introduced after a transition period of several years, as the fuels and associated infrastructure have to be made available globally at a sufficient number of airports. Drop-in fuels, on the other hand, can be and are already being deployed without much preparation. Drop-in fuels include all blends of hydrocarbon compounds from different sources that meet the currently applicable fuel specification for jet engines. To date, only blends of these fuels with kerosene from fossil sources have been permitted, as synthetic kerosene generally does not contain aromatic hydrocarbon compounds. Aromatics cause the seals used in older engines to swell, so their absence could cause leaks. However, the absence of aromatic hydrocarbons also has advantages: for example, aromatic hydrocarbons are involved in the processes that create soot particles, and fuels that do not contain these compounds produce significantly fewer particles during combustion. Since drop-in fuels can be used immediately, their potential for reducing particulate emissions from aviation can be realised comparatively quickly.

17 PtL fuels are also called e-kerosene or electricity-based kerosene.

Non-drop-in fuels include both liquid hydrocarbon mixtures that do not meet the currently applicable fuel specification for jet engines and compressed or liquefied gases, in particular methane and hydrogen. On the one hand, methane and hydrogen contain little to no carbon, but on the other hand they require a completely new airport infrastructure and also new aircraft concepts, among other things because the volume of these fuels for the same energy content is considerably larger than for liquid hydrocarbons. This is particularly the case for hydrogen. A hydrogen aircraft of similar dimensions to an Airbus A320 or a Boeing B737 could only transport about half as many passengers, and even that only at reduced range[18].

Generally, alternative fuels can only enable largely CO_2-neutral operation of aircraft if the fuel is produced with renewable energy from sustainable sources.

Moreover, if gaseous fuels are used in jet engines instead of liquid fuels, technologies for low-emission combustion can be implemented more easily. Soot particles are not produced at all during the combustion of hydrogen and can probably also be largely avoided with methane. However, it is not yet possible to make a reliable forecast of nitrogen oxide emissions when switching to methane or hydrogen as an aviation fuel at the present time.

4.4 Reduced-emission air transport system

In direct comparison to technological improvements, operational measures can be realised much more quickly, and can usually be applied not only to future aircraft types, but also to existing ones. For example, current aircraft can already be operated more efficiently (e.g., more direct, higher utilisation) or target altitudes and trajectories that minimise not only the amount of fuel but also the resulting climate impact.

Measures to increase the efficiency of flight operations

Fuel and emission volumes can be reduced operationally by all procedures aimed at increasing efficiency in flight operations. Improvements in horizontal and vertical flight efficiency can be achieved, for example, through more direct flight guidance (free route airspace) or through newer, direct approach and departure procedures. Flight planning using improved weather forecast data already plays a role here, allowing efficient consideration of wind (e.g., exploiting tailwinds, avoiding headwinds).

One way of reducing the fuel consumption of long-haul flights is to divide them up into several, shorter legs ('multi-stops'). Since additional fuel is required for each additional kilogramme transported, so-called snowball effects lead here to a disproportionate reduction in efficiency as the range increases.

Figure 17

Formation flight: the rear aircraft "surfs" on the airflow of the wake vortex

Source: own representation, DLR

18 Görtz and Silberhorn, 2022.

However, efficiency-enhancing measures do not necessarily reduce the climate impact. The altitude at which aircraft achieve their maximum fuel efficiency increases as aircraft mass decreases. If, as a result of stopovers, (lighter) aircraft are operated in a fuel-optimal manner at higher and more climate-sensitive altitudes, the climate impact may increase despite decreasing CO_2 emission levels, since non-CO_2 effects generally increase with altitude. Accordingly, it is easy to create undesirable disincentives if measures focus exclusively on reducing the climate impact of individual trace substances (e.g., CO_2 minimisation). However, if 'multi-stop' flights are operated at lower altitudes, as recent studies show[19], both fuel consumption and the climate impact of non-CO_2 effects could be reduced. However, multi-stop flights lead to additional takeoffs and landings, which in turn can have an impact on aircraft structure and engine but also on flight safety. Furthermore, the additional takeoffs and landings increase noise and exhaust pollution at the airports concerned.

Another way to reduce fuel consumption is to introduce formation flying along the lines of migratory birds. By having the second bird "surf" on the lift vortex of the bird ahead, the birds save a lot of energy. The same principle also works for airplanes and has already been demonstrated in various flight tests. Initial studies for a formation of two aircraft show that – if formation flying were introduced between major international airports – it could save about 5 % of fuel requirements and about 24 % of climate impact per flight on global level[20]. However, a number of technical and operational issues currently stand in the way of systematic use of formation flying. For example, turbulence is to be expected in the formation, making this initially suitable only for cargo flights.

Climate impact-optimised flight trajectories

Operationally, it is not only possible to reduce the quantity of emissions, but also to mitigate the location- and weather-dependent effects of many trace substances. For example, commercial aircraft fly at cruising altitudes between 10 and 15 kilometres, where a particularly large number of chemical and micro-physical processes take place. Today, the optimal cruising altitude for a flight is calculated separately for each flight and is purely an economic trade-off between fuel and flight time-dependent costs. However, the choice of cruising altitude may also take climatological effects into account. Although that a reduction in cruising altitude leads to an increase in fuel consumption as a result of increasing air resistance, and thus to increased CO_2 and H_2O emissions, but it also reduces both the contrail coverage and the residence time of ozone in the atmosphere. Overall, this shows a decrease in the climate impact for lower flight altitudes[21].

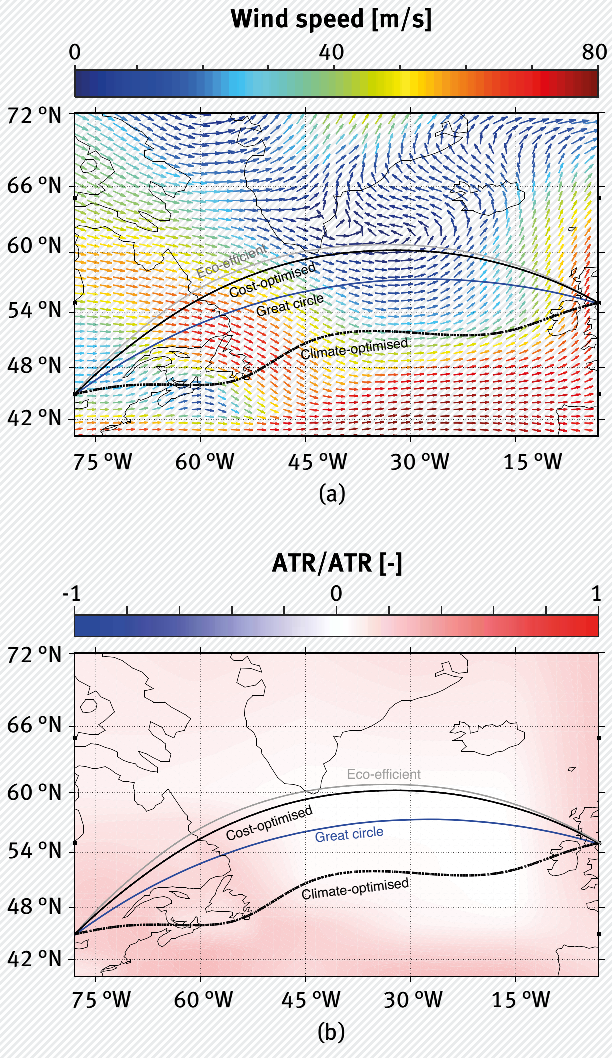
Climate-optimised flight planning is even more efficient. For example, many non-CO_2 effects can be avoided by re-routing flying around highly climate-sensitive regions (red areas in figure 18 below). This is a particularly efficient way of avoiding the formation of contrail cirrus clouds, since a temporary change in flight altitude of a few hundred metres is often sufficient. In these approaches, current weather and traffic forecasts are not only used, as is currently the case, to deploy aircraft on the most economical route (black solid line in figure 18), but also in a more climate-friendly way. Since purely climate-optimised flight planning (dotted line) often involves significant additional costs and increased fuel consumption, eco-efficient routes (dashed lines) are often a good compromise. All of this requires robust prediction of climate impact.

19 Linke et al., 2017.
20 Marks et al., 2021, Dahlmann et al., 2020.
21 Dahlmann et al., 2016, Matthes et al., 2021.

With today's aircraft, it must therefore be weighed up whether to accept the additional fuel consumption for the reduction of the overall climate impact. If new engines, climate-optimised aircraft designs or alternative fuels are used as well, CO_2 consumption can also be reduced when re-routing flights around highly under climate-sensitive regions.

Figure 18

Climate-optimised flight guidance



Source: Lührs et al., 2016

Policy measures

5

Aircraft design measures

Measures for alternative fuels

Policy measures for climate-friendly air transport

Overarching measures

Policy measures

The previous chapter presented options for reducing the climate impact of aviation. Most of these measures result in increased investment (e.g., purchase of new aircraft) or increased operating costs due to a larger fuel consumption with alternative route planning, higher fuel costs for SAF, or longer flight times. Policy measures can create an incentive to develop and implement new technologies and operational measures in a timely manner, thereby reducing the climate impact of aviation.

Possible trade-offs between the short-term and relatively strong non-CO_2 climate effects and the very long-lasting CO_2 can be a particular challenge. Measures that only aim at CO_2 emission reductions can be counterproductive from a climate perspective. Against this background, it is important to give equal consideration to non-CO_2 and CO_2 emissions.

Aircraft design measures

The permissible levels of certain trace substances in aircraft engine exhaust are regulated globally by ICAO emission standards, which are provided by Annex 16, Vol. II to the Convention on International Civil Aviation. In addition to carbon monoxide and unburnt hydrocarbons, these standards also define limits for nitrogen oxides and non-volatile particulate matter (nvPM). These standards are mainly aimed at air quality in the vicinity of airports and therefore only consider local emissions. Nevertheless, it has been shown that a reduction of local emissions also leads to a reduction of cruise level emissions of the same magnitude. The International Civil Aviation Organization (ICAO) periodically commissions a review to determine whether this relationship still exists.

While the **ICAO standard for nvPM** is relatively new, emissions were first limited in the early 1980s **(NO_x standard)**. The standards have been tightened several times since then, always taking technical feasibility into account. Nevertheless, as a result of these tightening measures, engine manufacturers have invested substantially in research into new, low-NO_x combustion concepts, which have ultimately also been used in some of the latest products.

Furthermore, ICAO issued a CO_2 standard for aircraft several years ago, with different limits for already certified and new aircraft types. This is described in Volume III of Annex 16. For this standard, however, not only CO_2 emissions are measured and evaluated, but a metric is determined that represents a measure for an aircraft's transport efficiency. This is to ensure that aircraft with the same level of efficiency, but different transport capacities, are rated by the same in the CO_2 standard.

Measures for alternative fuels

Sustainable aviation fuels (SAF), as a substitute for fossil fuel kerosene, play a key role in reducing climate relevant emissions. However, few of these alternatives are 100 % drop-in-capable because they lack jet engine certification. Approval processes are underway.

Further hurdles must be overcome to bring SAF into the market. Due to higher production costs compared to fossil kerosene, these fuels do not automatically enter the market on a sufficiently broad scale. Measures have been and are being established to ensure the usability of SAF as well as to stimulate production and sales.

Certification of fuels

Before new fuels can be used, their safe use under all operating conditions must be proven. ASTM testing and approval is extensive and takes years. A number of alternative fuels are currently in the certification process.[22]

22 See details in BHL and LBST, 2021, section 2.2.

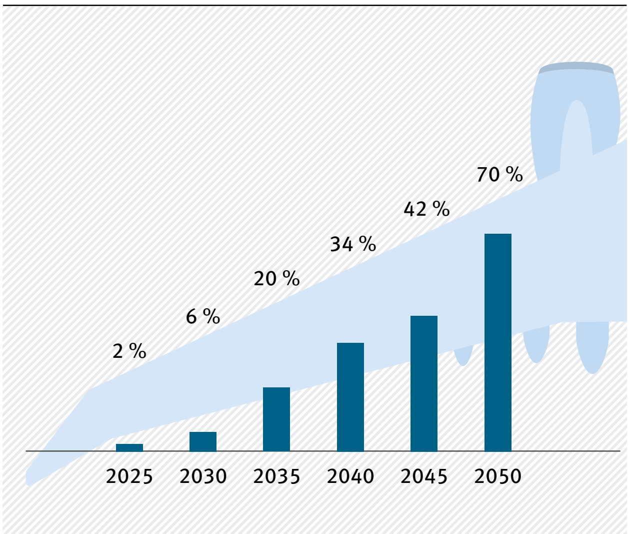
Demand incentives

One of the legislative initiatives of the European Commission's Fit for 55 package is **ReFuel EU Aviation**[23]. This initiative was negotiated between the European institutions – Commission, Parliament and Council – and will come into force in 2025.

It prescribes a minimum blending quota for alternative fuels (SAF) for each aircraft refuelling in the EU. Aircraft fuel suppliers at EU airports will have to gradually increase the share of SAF, starting at 2 % in 2025 and reaching 65 % in 2050 (figure 19). Airports will be required to provide the necessary supply, storage, and refuelling infrastructure for sustainable aviation fuels. In addition to the general blending quota for SAF, a gradually increasing sub-quota for PtL is included.

Figure 19

Share of SAF according to ReFuel EU Aviation regulation



Source: own representation, DLR, based on EU-Commission (2021)

For flights departing Germany, a minimum PtL blending quota in aviation was already enshrined in law in 2021. From starting at 0.5 % in 2026, this share will gradually increase to 2 % in 2030.

Policy measures for climate-friendly air transport

In 2020, the European Aviation Safety Agency (EASA) proposed the **'avoidance of ice-saturated regions in the airspace'** and the introduction of a so-called **'climate charge'** as measures to avoid non-CO_2 emissions through climate-compatible air traffic management as part of a study on behalf of the European Commission[24]. Both measures would provide incentives for climate-friendly flight route planning. The aim of the first measure is to optimise individual flight routing during flight planning so that climate-sensitive regions in the atmosphere are avoided as much as possible. In particular, this could reduce the formation of contrail cirrus clouds. In contrast, a 'climate charge' would address all non-CO_2 effects simultaneously. Overall, the proposed instruments could thus provide effective incentives to avoid non-CO_2 effects. EASA sees a number of open questions that should be investigated before introducing these instruments in order to reduce scientific uncertainties, especially in the field of atmospheric science. EASA estimated in 2020 that measures to avoid climate-sensitive regions of the atmosphere would be more likely to be introduced in the medium term (in 5 to 8 years). A climate charge would only be implemented in the long term (in more than 8 years) due to currently still open questions.

23 European Commission, 2023.
24 European Commission, 2020.

Another possible instrument for climate-compatible flight routing are so-called **'climate charging zones'.** This instrument, developed by DLR, could also provide incentives for more climate-compatible air transport[25]. The aim is to calculate the climate impact at the individual flight level, depending on the current weather situation prior to the respective flight. Depending on how strong the climate impact of the flight is, the aircraft operator has to pay more or less climate charge for flying through predefined 'climate charging zones'. The aircraft operator can then decide individually whether to fly around climate-sensitive regions and thus pay less climate charge or to accept the additional costs and fly through this region. This could provide an economic incentive for climate-friendly flight planning and operation, so that non-CO_2 effects in particular are reduced.

Another frequently discussed instrument would be the introduction of a **flight altitude restriction.** This would reduce non-CO_2 effects in particular. As with the above-mentioned measures, which lead to a longer flight path, flying lower is also likely to lead to a slight increase in aviation-related CO_2 emissions, since there is increased air resistance at lower flight levels, which increases kerosene consumption. Thus, a so-called trade-off problem arises between the reduction of non-CO_2 and CO_2 emissions. In addition, it can be assumed that limiting flight altitude in heavily frequented airspace, such as in Europe, will be difficult to implement and will set incentives for detours in flight planning.

Overarching measures

Since 2012, so-called market-based measures have been introduced to limit climate-relevant emissions from aviation. However, these measures have so far focussed on reducing aviation-related CO_2 emissions.

In Europe, CO_2 emissions from aviation in the European Economic Area (EEA) have been covered by the EU Emissions Trading Scheme (EU ETS) since 2012, i.e. airlines must surrender an emission allowance for each ton of CO_2 emitted. Figure 20 illustrates the basic principle of CO_2 emission trading. The emissions cap for aviation was 95 % of the average ETS-relevant CO_2 emissions from 2004 to 2006, until 2020. Since 2021, the cap has been reduced by 2.2 % annually, and from 2024 and 2028, the annual reduction will be 4.3 % and 4.4 %, respectively. There is an option to purchase emission allowances from other sectors of the economy participating in the EU ETS, which, due to the relatively high abatement costs in aviation, means that CO_2 emission reductions are more likely to take place in other sectors than aviation.

In May 2023, regulations for aviation within the ETS-Directive were tightened significantly at EU-level[26]. In particular, the 'cap' and the amount of emission allowances allocated free of charge will be further reduced, with the consequence that from 2026 all emission allowances will have to be purchased. According to the EU Commission, revenues from the auctions are to be used for research and development for climate protection. In addition, the use of SAF is to be promoted. Non-CO_2 emissions from aviation are to be monitored and reported by all aircraft operators on a flight-by-flight basis from 2025 in accordance with MRV (monitoring, reporting and verification) rules that have yet to be drawn up (by 2024). In addition, starting with 2028 at the latest, rules for the full inclusion of non-CO_2 effects, i.e. rules with an obligation to surrender emission allowances also for the non-CO_2 species such as contrails and contrail cirrus (whose climate impact was first converted into CO_2 equivalents for this purpose), are to be presented.

25 E.g. Niklaß et al., 2019.
26 European Union, 2023.

At the global level, the introduction of a global market-based CO_2 offsetting measure for international aviation (Carbon Offsetting and Reduction Scheme for International Aviation, CORSIA) was adopted for the first time in 2016 in ICAO Resolution A39-3.

Under CORSIA, certain CO_2 emissions from international aviation are offset, i.e. emission credits ('offsets') from verified projects for CO_2 reductions must be purchased and cancelled. This will apply in the time frame 2021-2023 for emissions above 2019 levels. From 2024, the baseline is then 85 % of 2019 emissions. CORSIA is applicable from 2021 to routes between voluntarily participating countries. From 2027, CORSIA will be mandatory for all major aviation states.

However, CORSIA is significantly less ambitious in terms of CO_2 reduction targets than the EU ETS for aviation. This is mainly due to the fact that CORSIA aims at CO_2-neutral growth from 2020 onwards, whereas the currently applicable EU ETS already starts at the total CO_2 emissions of the years 2004-2006 and reduces them.

Unlike at the European level, there are currently no concrete plans at ICAO level to include non-CO_2 emissions from aviation in CORSIA.

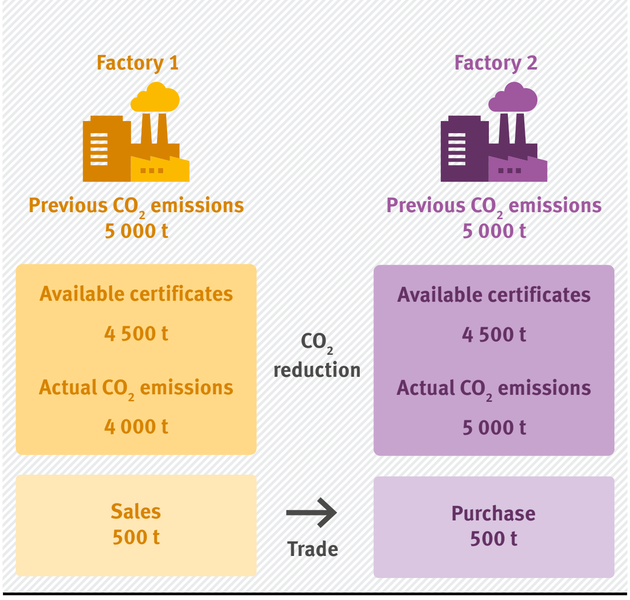
As a further measure, the EU Commission proposed the introduction of a kerosene tax in summer 2021 as part of the so-called Fit for 55 package. It is to be introduced in stages, with a maximum of € 0.45 per kilogramme of kerosene in 2033. The tax would be levied on all intra-EU flights (with the exception of pure cargo flights). Currently, kerosene for commercial air transport and international flights is not subject to taxation. The kerosene tax would provide an economic incentive to save aviation fuel and thus indirectly also to avoid CO_2. However, the introduction of a new EU energy tax as proposed by the EU Commission requires the unanimous approval of all EU member states. Against this background, the future of this Commission proposal remains to be seen[27].

In principle, it should be noted for all overarching aviation-related measures aimed exclusively at avoiding CO_2 emissions that there is also the trade-off problem mentioned above, i.e. a conflict of objectives between avoiding CO_2 and non-CO_2 effects in aviation. Thus, focussing on CO_2 emissions can lead to strategic evasive responses by airlines, such as flying longer at higher flight levels where the climate impact is higher.

In order to effectively limit all climate-relevant emissions from aviation, policy measures should therefore address both CO_2 and non-CO_2 effects of aviation in equal measure.

Figure 20

Basic principle of CO_2 emissions trading



UBA, 2022

27 European Commission, 2021.

Possible actions of the travellers: what can each individual do?

6

Possible actions of the travellers: what can each individual do?

Travellers can contribute to reducing the climate impact of air transport. However, the heterogeneous impact of non-CO_2 and CO_2 effects poses some challenges for travellers. This applies in particular to the compensation of flight emissions when non-CO_2 effects are not considered by providers.

According to a representative survey of the German-speaking resident population in 2018, 43 % of respondents had flown in the previous two years[28]. This represents a large population group whose actions could potentially have significant influence on the climate impact of aviation.

Providing consumers with information about emissions of individual travel decision is a necessary condition to reduce the climate impact. Therefore, travellers should have the opportunity to inform themselves about the climate impact of different airlines and alternative means of transport. For example, when choosing an airline, attention could be paid to the use of modern aircraft, alternative fuels or operational mitigation measures. According to the Federal Environment Agency, on short routes and short feeder flights, both tourists and business travellers could, if necessary, use more climate-friendly means of transport such as trains or buses[29].

Tourists could pay more attention to the overall climate impact of their travel activities. Companies are already partially replacing business trips with video conferencing. Avoiding emissions is preferable to offsetting the climate impact.

If flight behaviour cannot be adjusted, flight emissions can be compensated voluntarily by emission reduction credits (so-called certificates or offsets). In this case, credits corresponding to the climate impact of a trip are purchased from climate protection projects that reduce greenhouse gas emissions or remove them from the atmosphere (e.g. wind power plants or reforestation projects in developing countries). This option is already offered by numerous airlines during the booking process. On behalf of the passengers, the airline cooperates with an offset provider and purchases offsets corresponding to the CO_2 emissions of the booked flight. Alternatively, air travellers can also purchase offsets directly from a variety of providers. Often, such providers offer tools on their websites that can be used to calculate the expected CO_2 emissions of a flight. Non-CO_2 effects are often not yet considered. However, air travellers could voluntarily purchase double or triple the number of offsets, for example, to compensate for them approximately. Alternatively, providers such as Atmosfair or Klima-Kollekte offer calculation tools for non-CO_2 effects of individual flights.

Unfortunately, a great abundance of offset providers exists but no legal minimum standards. The market is therefore flooded with extremely cheap offsets, some of which have ambiguous ecological and social properties.

What needs to be considered when comparing the climate impact of different transport modes?

When choosing a means of transport (e.g. bus, train, car, plane), emissions must be considered over the entire (product) life cycle. In addition to operation, emissions also occur during production and disposal of the means of transport, as well as during construction and maintenance of the infrastructure (e.g. road, rail, airport). Depending on how the system boundary is drawn in the process, the carbon footprint of each mode of transportation differs. For example, the distance from the place of residence to the airport is partly assigned to the mode of transport used (e.g. bus, train, car) and partly directly to air transport, which also uses ground infrastructure for the feeder. Furthermore, unplanned inefficiencies in operations due to congestion, detour, holding patterns and accidents affect the climate impact.

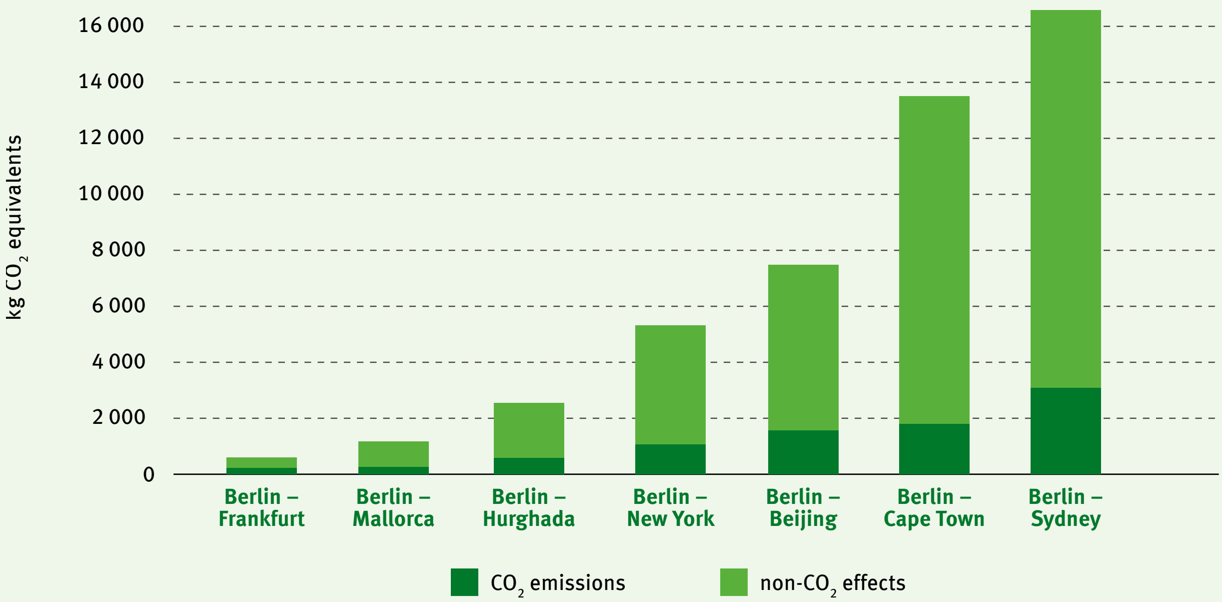
28 BDL, 2018.
29 UBA, 2020.

Why do the prices of offsets vary so much?

The quality and type of a carbon offset project strongly influence the price. Expensive does not necessarily mean climate-friendly, as production costs can vary greatly depending on project size, region or type. Therefore, offset prices can vary substantially even within a certification standard, although the same requirements are met. Airlines face the same problem for voluntary offsets, but may have already gained experience with the offset market through CORSIA. In addition, the programmes/standards approved under CORSIA are subject to minimum requirements designed to protect against abusive providers. The standards with the largest offset volume are the Clean Development Mechanism, the Verified Carbon Standard, and the Gold Standard. Travellers can purchase certified offsets either directly from these standards on their homepages or by paying attention to these standards when purchasing through third-party vendors.

CO_2 equivalents for individual flights

The following table shows the CO_2 equivalents for various flights. These were calculated on the basis of the DLR Simplified CO_2e Estimator for outbound and return flights in the ATR100 metric[30]. For comparison, the German per capita greenhouse gas emissions are about 10 340 kilogrammes CO_2 equivalents per year[31]. Annual CO_2 emissions per passenger car, at a mileage of 13 600 kilometres, are about 2 045 kilogrammes. For road traffic, the non-CO_2 effects play only a minor role. The climate impact of a single long-distance flight per person can already be higher than the annual emissions of a car. It should be noted that this comparison does not take life cycle emissions into account, but only emissions during the journey.



30 A preliminary version can be found under https://gmd.copernicus.org/preprints/gmd-2023-126/ UBA plans to publish the DLR Simplified CO_2e Estimator on their homepage by the end of 2023.
31 UBA, 2023.

Summary

In addition to CO_2 emissions, non-CO_2 climate effects play a special role in aviation. These effects include the formation of contrail cirrus, the effect of nitrogen oxide emissions on ozone and methane concentrations, direct and indirect aerosol effects, and water vapour effects. All of these affect the radiation balance of the atmosphere in different ways and differ significantly in their residence time. As a result, they can only be compared using climate metrics that represent the direct relationship between the emission and the effect under consideration.

When selecting suitable measures to reduce climate impacts, it is therefore important to consider all climate-relevant aviation emissions and their indirect atmospheric chemical and microphysical effects together and optimise them jointly. Considering the various climate effects on an individual flight level opens up the potential to reducing the overall climate impact significantly through optimising flight trajectories.

On the technology side, energy-efficient aircraft can be achieved through drag and weight reduction, control of stability and load, optimisation of onboard systems, integration of new propulsion technologies and systems for new fuels. Furthermore, engine technologies aimed at reducing non-CO_2 effects are being researched. In addition to improvements in turbo propulsion, distributed propulsion concepts and electric components as well as fuel cells and hybrid-electric propulsion systems are being researched.

7

Instead of conventional kerosene, synthetic fuels produced from biomass or with the help of electricity from renewable energy can also be used. If only the amount of CO_2 previously removed from the atmosphere by plant growth or technical processes is emitted, these CO_2 emissions are considered climate-neutral. If fewer soot and sulphate particles are emitted, the radiative forcing of contrails is also reduced.

In addition to technological changes, climate impacts can also be reduced through operational measures. These include both efficiency-enhancing measures (more direct flying, higher load factors) and climate-optimised flight routing, in which non-CO_2 effects, especially contrails, are reduced by selectively flying around climate-sensitive regions. Many of these operational measures can be applied not only to future aircraft types, but also to existing ones. In order for those measures to be introduced in a timely manner, international frameworks, especially in-flight planning and air traffic control, must be adjusted.

Policy measures can create an incentive to develop and implement new technologies and operational measures faster to reduce the climate impact of aviation. Individuals can also make travel decisions with more information and offset the remaining climate impact through compensation payments.

Thus, overall, there are a number of possible measures to reduce the climate impact of air transport. The faster and the more extensive these measures are introduced and supported by research, the more climate-friendly air traffic will become. This requires a joint approach by politicians as well as representatives from industry, business, research and aviation organisations.

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