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EXECUTIVE SUMMARY

This report corresponds to D7.1 Spatial and temporal distribution characteristics of aviation emissions. The work reported is related to WP7.1 Scientific description of the impact of aviation emissions to climate change.

WP7.1 is organized in three different tasks:

- Task 7.1.1 State-of-the-art review on aviation environment impact
- Task 7.1.2 The spatial and temporal distribution characteristics of aviation emissions
- Task 7.1.3 Aviation emissions impact on the environment

Deliverable D7.1 includes the work performed in Task 7.1.1 and Task 7.1.2. The work performed in Task 7.1.3 will be part of D7.2 Report on description of aviation emissions impact on the environment.

The information contained in this report provides the first input to characterize the scientific description of the impact of aviation emissions to climate change, which is the objective of the first WP of MWP7. The results of the tasks corresponding to the state-of-the-art review on aviation environment impact and the spatial and temporal distribution characteristics of aviation emissions are reported.

These results, together with the investigations on the remaining task of WP7.1, related to the Aviation emissions impact on the environment, will provide the necessary inputs to continue the work in this MWP7 and begin the next WP7.2 Development of an evaluation methodology for environmental impact, which is the work planned for the next 12 months.

No major issues or deviations are to be reported.

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1. INTRODUCTION

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2. WORK PERFORMED

2.1. INVESTIGATIONS AND RESULTS ON ACTIVITY 7.1.1. STATE-OF-THE-ART REVIEW ON AVIATION ENVIRONMENTAL IMPACT

The interest on the environmental impact of civil aviation started in the middle 60s with the introduction of the first commercial jets. The noise around the airports increased in a substantial manner and incentivize the research on technical and regulatory solutions. First noise certification regulation was developed in United States by the Federal Aviation Administration (FAA). The Federal Aviation Regulation (FAR) Part 36 entered into force in 1969, followed by other rule with similar content but global reach: the International Civil Aviation Organization (ICAO) Annex 16 Volume I in 1971. Both regulations were updated, and gradually brought together, with an increased stringency entering into force in 1977, another in 2006 and the last one until now in 2020.

A second step was to control local air quality around commercial airports. Engine certification rules, limiting emissions of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx) and solid visible particles (Smoke) during their operation close to the airport (during a Landing Takeoff Cycle LTO, with the aircraft below 3.000 ft over the airport runway) were introduced in ICAO Annex 16 as Volume 2, in 1980.

While fast commercial engine technology progress made practically irrelevant the initial CO, HC and Smoke limits, NOx emissions continued being a problem, and further updates were applied to its regulatory limits in the following years by the ICAO Committee on Aviation Environmental Protection (CAEP). As a particular feature of NOx limitations, new stringency regulations for new design engines were followed by other rules applicable to in-production engines for avoiding the persistency of the old technology engines production.

The effects of civil aircraft activity on climate change became object of study since the initial work on atmospheric warming in the 80s that led towards the signature of the United

Nations Framework Convention on Climate Change (UNFCCC) in 1988. One of the most relevant agreements in that Convention was the creation of a permanent scientific group, the Intergovernmental Panel on Climate Change (IPCC), with the mission of collecting all the available information on Climate Change and keeping it updated through periodical revisions.

Evaluation of the aviation emissions is relatively straightforward close to the ground, but it gets more complicated at altitude, because engine emissions interact in different atmospheric layers with variable physical and chemical properties. A first, and for the time being the most ambitious, intent of getting together everything known about this problem, was published in 1999 by the IPCC as the book Aviation and the global atmosphere. This work made an exhaustive review of all the elements related with civil aviation, having some relevancy for the atmospheric evolution. The baseline taken for the analysis was the situation in the year 1992 and the results were projected in a few scenarios until the year 2050, according to some projections of world economy and civil aviation activities.

This publication listed the effects of the products emitted by aircraft engines as result of the kerosene combustion, evaluating their respective impact in terms of instantaneous Radiative Forcing (RF), using Watts/square meters (Wm-2) as measurement unit, and indicated the levels of confidence of the quantifications, according to the knowledge of the atmospheric perturbations and the amount of available data. The list can be seen in Table 7.1. The result shows that aviation contribution to climate change was 0.050 Wm-2, approximately 3.5% of the total anthropogenic RF in that year. Positive RF values mean an increase of atmospheric warming and negative ones indicate a cooling effect.

Even with this small participation figure in the total anthropogenic climate change emissions, the high rate of growth forecasted for commercial aviation for the next decades, made reasonable to devote research efforts in a better evaluation and reduction of the aviation responsible effects. The above referred publication developed a number of future scenarios, concluding that aviation share might become 6-7% in year 2050, in the most likely projection.

Table 7.1 Radiative forcing of civil aviation in 1992 (*Source: Aviation and the global atmosphere, 1999*).

Type of emission	RF (most likely value) W/m2	Scientific knowledge level
Carbon dioxide	0.019	Good
NOx (Ozone creation)	0.022	Fair
NOx (Methane destruction)	-0.015	Poor
Water vapour	0.002	Poor
Condensation trails	0.021	Fair
Cirrus clouds	Not defined	very poor
Direct Sulphate	-0.002	Fair
Direct soot	0.003	Fair
Total (without cirrus clouds)	**0.050**	

The analysis of each one of the components showed very different precision levels. The best defined one was the CO_2, the only direct greenhouse gas (GHG) in the list, chemically very stable and with a direct relationship with the quantity of consumed kerosene: the combustion of 1kg of kerosene produces 3.15 kg of CO_2 (the EU uses a factor of 3.15 while ICAO generally applies 3.16).

While several emitted nitrogen oxides, commonly identified as NOx, are not greenhouse gases, in the high levels of the atmosphere produce a dual effect on ozone and methane, these being greenhouse 5ases. NOx emissions activate the creation of ozone and increases RF, and cause destruction of methane diminishing RF. The resultant of both effects is positive (warming). NOx emissions depend on the technology of engine combustors and their working regime, therefore, is relatively simple of calculating. Water vapour itself has a small RF increase effect and is also easy to calculate as it is emitted with a ratio of 1.239 kg per 1 kg of burned kerosene. Direct sulphate depends on the sulphur content of the kerosene, that is regulated by fuel specifications, and direct soot is a consequence of the combustor efficiency, being reduced as the fuel and the air mix improves its quality.

The formation of condensation trails (usually mentioned as contrails) is more complex because depends on the physical conditions of the atmospheric region where the flight is being performed. Humidity, temperature and, to a certain extent, wind are influential. However, it can be calculated with an acceptable accuracy. A more difficult task is to evaluate the effect of aerosols from aircraft on the microphysical and radiative properties of clouds. In certain conditions, contrails may evolve and generate cirrus clouds with a powerful warming effect. This was the most uncertain element in 1999 and is still today.

Six years later the IPPC study was updated, taking the aviation activity of year 2000 as baseline. The calculation was performed in two different ways: the first one assumed that the 1992 values from the original study were correct and extrapolate them to the conditions of the higher aviation activity in the year 2000; the second one was a totally new calculation, taking advantage of the better scientific knowledge of the moment. The results can be seen in Figure 7.1.

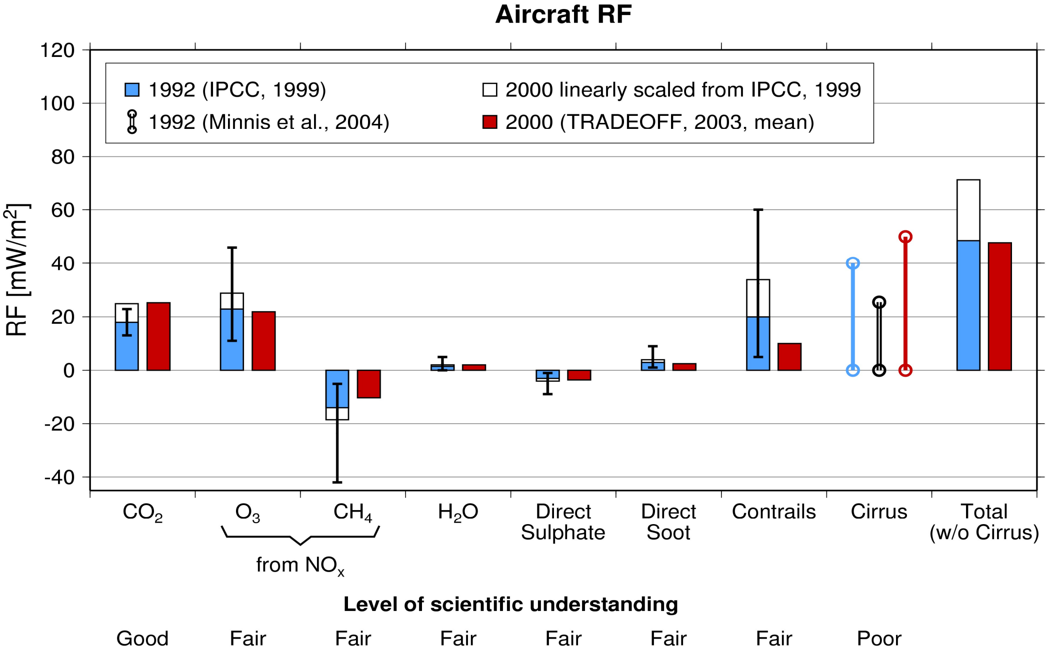


Figure 7.1. Aviation impact on climate change (*Source: Sausen, R. I. et al. Aviation radiative forcing in 2000: An update on IPCC (1999), Meteorologische Zeitschrift 14, 2005*)

Basic conclusions indicate that original calculations were accurate for the CO_2 values, and reasonable for all the other emissions apart from contrails, the importance of which appeared to be much lower than previously assumed. The formation of cirrus clouds remained difficult to evaluate and was not included in the total computation. The conclusions of this analysis was that year 2000 aviation effect was more or less of the same magnitude than the previously calculated for the year 1992, in spite of an aviation growth close to 45% in those eight years.

The next step ahead appeared four years later, performing a new evaluation of the aviation impact, taking year 2005 as a baseline (*Lee D. S. et al. Aviation and global climate change in the 21st century. Atmospheric Environment 43, 2009*). The conclusions were very similar with respect to CO_2, particles, soot and sulphur effects, but substantially increased water vapour and contrails warming potential. The conclusions, quantified in terms of Radiative Forcing, suggested that aviation was responsible of 6.5% of the overall net anthropogenic forcing. CO_2 emissions were responsible of 1.59% and the other elements took the rest. Figure 7.2 shows a schematic compilation of the results. As it can be seen, some elements show large levels of incertitude, including water vapour and the repercussions of NOx emissions, previously considered as less subject to erroneous calculations.

A separate evaluation was provided by the results of the FAA Aviation Climate Change Research Initiative (ACCRI), started in 2008. Phase I of the program was focus on the identification of the key uncertainties and the needs for improvement in areas of chemistry and transport processes, aerosols, microphysics, climate impacts of contrails, induced cirrus clouds and metrics. The research scheme can be seen in figure 7.3.

Based on these recommendations, Phase II was launched with the purpose of studying the climatic consequences of aviation non-CO_2 emissions and reduce the uncertainties of their effects. There were two temporal scenarios: actual 2006 and forecasted 2050 data. The modelling work of the different elements was divided among ten Universities and Research Organizations and the reference for comparisons was the 2009 Lee D. S. et al. results. Final figures needed to be corrected because ACCRI was using total aviation data (civil and military), while the reference counted only commercial aviation flights.

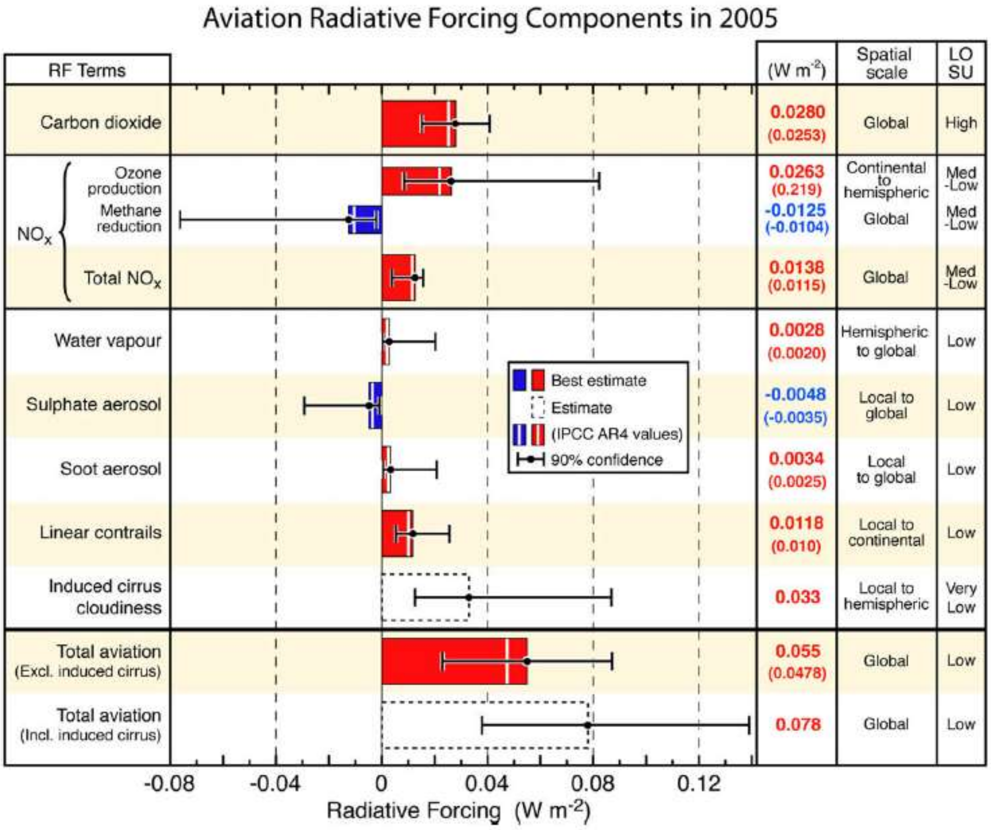


Figure 7.2. Aviation impact in climate change at 2005 levels (*Source: Lee D. S. et al. Aviation and global climate change in the 21st century. Atmospheric Environment 43, 2009*)

The contribution of this program was important to improve the scientific understanding of aviation climate impacts, particularly in accounting its interactions with the climate system. It reduced incertitude in the calculation of some emissions RF values, specifically in the estimation of aviation-induced cirrus cloud climate forcing, increasing the level of scientific understanding from "very low" to "low". It also identified some additional factors not previously taken into account, like long-term ozone, the change in stratospheric water vapor due to the change in methane caused by NOx emissions, the nitrate aerosol effect, and the direct and indirect effects of soot and sulphate aerosols.

Global quantitative results were similar to those in the reference paper, but ACCRI work investigated in regional effects as well, considering that aviation emissions were mostly concentrated on North Hemisphere flight corridor regions. Additional work was done in the refining of the definition and the use of different metrics, like RF, Global Warming Potential (GWP), Global Temperature change Potential (GTP), and Regional Temperature Potential (RTP). As a result of those works, it seems that GWP is a relatively robust, transparent and policy-relevant emission metric (*Peters et al.: The integrated global temperature change potential (iGTP) and relationships between emissions metrics Environmental Research Letters nº 6, 2011*), to be used in future aviation and climate change evaluations. An exception would be those gases with atmospheric lifetimes less than one year, where uncertainties may be larger. The analysis made using GWP use to take a period of 20, 50 and 100 years (GWP_{20}, GWP_{50} and GWP_{100}, respectively) because the emission with the longest life, CO_2, has an average of 100 years life.

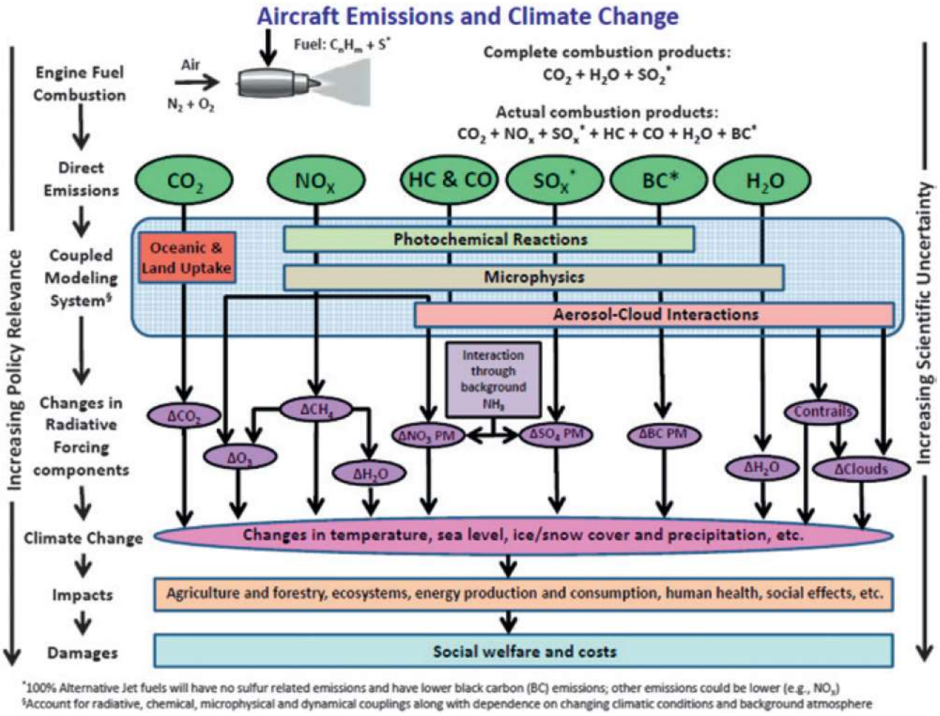


Figure 7.3 Basic diagram for ACCRI work (*Source: Brasseur et al. Impact of aviation on climate: FAA´s Aviation Climate Change Research Initiative (ACCRI) Phase II.* Bulletin of the American Meteorological Society 97, 2016)

More detailed studies on the high incertitude emissions effects previously identified were performed in the 2012-2015 period. In the case of the water vapour, it was demonstrated (*Wilcox L. J., Shine K. P., Hoskins B. J.: Radiative forcing due to aviation water vapour emissions. Atmospheric Environment 63 (2012)*) that marked differences in stratospheric deposition and accumulation, are both contingent in the trajectories of the flights and the position of the tropopause in the latitudes in which aircraft operate. The consequence is a seasonal cycle in the accumulated emissions in the stratosphere, with annual maximum values in April, 70% higher than the minimum value in July. The application of this technique to the year 2006 (base year for CCRI work) gives some results about 33% of those calculated in Lee et al. (2009), and incertitude standard deviation 15 times smaller.

In the case of the NOx emissions, the effects are produced by the chemical mechanism NOx-O_3-CH_4, with emitted NOx increases the formation of atmospheric ozone, but accelerates the destruction of methane, both of them being GHGs. The magnitude of those effects varies according to the total NOx concentration in the flight zone. Then, latitude becomes an important variable, resulting in RF increases higher in lower latitudes and lower in northern areas, all of them, for the same amount of NOx emitted by a flight or a group of flights (*Köhler, M. O., Rädel, G., Shine, K. P., Rogers, H. L., Pyle, J. A.: Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics. Atmospheric Environment 64 (2013)*). The differences appear not only in total RF but also in the respective ozone and methane outputs. In the majority of the conditions, the net RF is positive (warming effect) but some research papers achieve small negative results in some specific areas (cooling effect). Chati Y S et al. (*Chati Y S, Balakrishnan H. Analysis of aircraft fuel burn and emissions in the landing and take-off cycle using operational data. International Conference on Research in Air Transportation*

(2014)) used the data from Flight Data Recorders (FDR) to estimate the operational values of NOx emission indices for 12 aircraft-and-engine combinations. These operational values are statistically compared to those reported in the ICAO Engine Exhaust Emissions Databank. In most cases, the operational values are found to differ from the ICAO databank values in a statistically significant manner. The ICAO databank is found to typically overestimate the values of LTO cycle fuel burn and emissions, as it is using certification limits, measured at maximum engine thrust for takeoff. Huang Y et al. (*Huang Y, Zhou G L, Wu S S. A preliminary investigation on the inventory of NOx emitted from CAAC flights over China[J]. ACTA SCIENTIAE CIRCUMSTANTIAE (2000)*) estimated the NOx emissions and distribution of civil aviation aircraft over China for the first time.

As both products (CH_4 and O_3) have different life duration, the global effect, measured in terms of GWP or GTP are generally positive for the whole world, but the same amount of emitted additional NOx may be reflected in a GWP_{100} value of 25 if it is emitted over Europe (a region with high NOx concentration), or in a figure of 115 in the North Atlantic area, with much lower NOx content (*Skowron A., Lee D. S., De León R. R.: Variation of radiative forcing and global warning potentials from regional aviation NOx emissions. Atmospheric Environment 104 (2015)*). The consequence is that in geographical areas with low NOx concentrations, like remote desertic or oceanic regions, additional quantities of emitted NOx often constitute a significant relative increase. Ozone (O_3) is a reactive oxidant gas playing a key role in photochemical air pollution and in atmospheric oxidation processes. Ozone is associated with decrements in respiratory function and death from respiratory causes (*Jerrett M, Burnett R T, Pope III C A, et al. Long-term ozone exposure and mortality. New England Journal of Medicine, (2009)*). Although in the upper atmosphere it acts as a barrier for ultraviolet radiation, in the lower troposphere is a secondary air pollutant generated through a series of complex photochemical reactions involving reactive hydrocarbons, solar radiation and NO_2 (*Seinfeld J H, Pandis S N. Atmospheric chemistry and physics: from air pollution to climate change (2016.)*).

Other scientific improvements dealt with the main evaluation parameter Radiative Forcing (RF). The basic definition of RF is an energy imbalance imposed on the climate system externally (volcanic phenomena, solar eruptions) or by human activities (emissions of GHG, change of land use, aerosols). The unit is watts per square meter (W/m^2), averaged during a selected period of time. The initial evaluations were done using an instantaneous value, and it is an easy tool to compare the effect of different sources.

However, the effects of the RF change slightly at different atmospheric layers and the induced temperature changes are also different. The original calculations were done assuming that no atmospheric adaptation happened between troposphere and stratosphere and temperature changes do not depend on altitude. The name applied to this approach is Instantaneous Radiative Forcing (IRF) and uses to be the one most used for direct comparisons among different type of emissions.

A second possibility is accepting that this only happens in the troposphere (approximately up to 15 km altitude as average), while stratosphere is capable to adjust itself to the new gas composition created by emissions. The tropospheric temperature becomes the reference magnitude. This calculation receives the name of Stratospherically adjusted Radiative Forcing (RF).

The third scenario is allowing rapid tropospheric adjustments in conjunction with the stratospheric ones, leaving the ground temperature as the reference one. This is known as Effective Radiative Forcing (ERF), and it is the one receiving more scientific support in recent times. Figure 7.4 represents graphically these three approaches, where TOA means Top of Atmosphere.

All those developments intensified the search for an optimum indicator, representative of the present climate change situation, that could be used as a policy-making tool towards a desirable objective. This indicator must be a good evaluator for the aviation impact on climate change and, at the same time, be compatible with similar evaluators used in other activity sectors with relevant climate change influence.

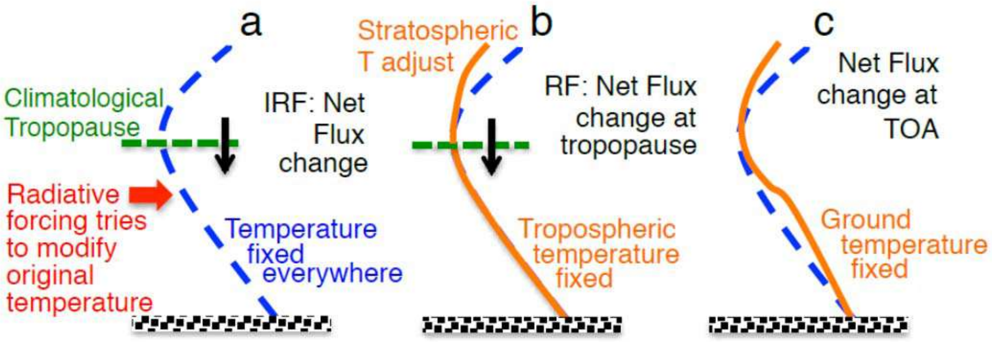


Figure 7.4 Scheme of the three different RF calculations a) Instantaneous Radiative Forcing (IRF), b) Stratospherically adjusted Radiative Forcing (RF), c) Effective Radiative Forcing (ERF) (*Source: IPPC AR5, 2013*)

The basic approach has been, since the first IPCC evaluation, the use of Global Warming Potential (GWP), that integrated the RF during a certain period of time, taking CO_2 RF as reference and transforming other emissions RF in their equivalent CO_2 values that can be added directly to the CO_2 emissions.

Main GWP problems come from the differences in lifetimes of the emissions and the effects in the lower and high atmospheric layers. As CO_2 is the only factor that can be calculated with total accuracy, the quantification of the global impact is easier including all other emissions in a non-CO_2 group, represented by a factor multiplying the CO_2 IRF. A recent paper (*Jungbluth, J. and Meili, C.: Recommendations for calculation of the global warming potential of aviation including the radiative forcing index. International Journal of LCA 24, 2019*) reviews the up to now developed approaches, dividing them in five categories for the GWP calculation purposes:

- a) Consider aircraft CO2 as a part of the general GHGs emissions and treating this element as the only climate change important element from aviation. This might be acceptable for the carbon footprint calculation, but it is not adequate to represent the global aviation impact in atmospheric warming
- b) Include all aviation emissions effects, but the cirrus clouds formation that is considered to be too uncertain. This approach can be used if it is understood that represent a cautious and conservative calculation of the global effect
- c) Applying a IRF factor between 2.7 and 3.0 only to the CO2 emitted in the higher atmosphere. The rest of the CO2 emissions get a factor of 1.0. It is a not very often used approach and difficult to compute properly. Main users are some companies calculating carbon offsettings for passenger tickets
- d) Applying a IRF factor between 1.7 to 2.0 to all CO2 emissions from aviation, that will be equivalent to use a factor between 3.9 and 5.2 for emissions in the higher atmosphere. Most modern papers are using this approach with more or less modifications

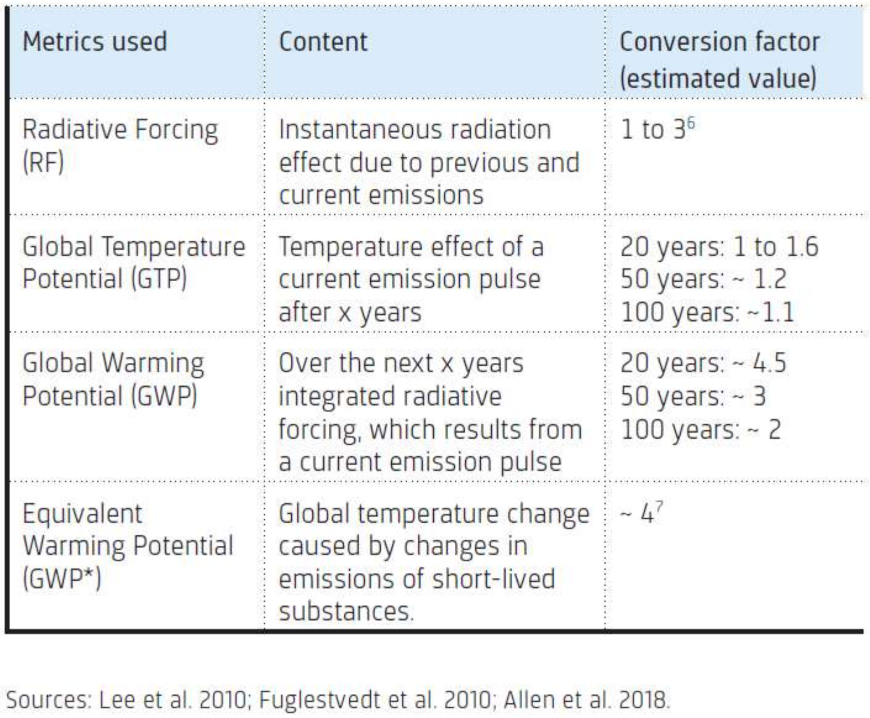
- e) Applying a IRF factor between 2.7 and 2.8 to the total CO2 emitted by the aircraft. This will represent a higher atmosphere emissions IRF between 8.1 and 8.5, generally considered as being too high. Like in the case c) is used mainly for offsetting calculation purposes

The debate on whether GWP is the right indicator for measuring emissions effects on climate change has provided a promising discussion area. A paper presented in CAEP12 WG3-5 compares the use of RF, GTP, GWP and GWP* (see Table 7.2), quantifying the different conversion factors to be applied to the effect of CO_2 alone.

The selected metric must be in agreement with the type of problem to be applied to. IRF is an instantaneous measure, not adequate to compare effects of today's emissions to the future. GWP does that work, integrating the IRF over a given period time, generally quantify in 20, 50 or 100 years according to the type of emissions. It also takes into account the short life emissions effects, integrated them along the selected time.

If the main interest is the variation in Earth surface temperature, Global Temperature Potential GTP) calculates the change in temperature at a determined date in the future caused by a single emission source. When the future date selected is far ahead enough (i. e. 50 or 100 years), this metric does not capture the effect of short-lived emissions. Then, if warming effects are studied in the next 20 years, the importance of those short-lived emissions is overweighted. Otherwise, periods of 50-100 years give more relevancy to the long-lived ones.

Table 7.2 Metrics comparison, including the conversion factor applied to the CO_2 IRF (*Source: Neu, U.: The impact of emissions from aviation on the climate. Swiss academies communications Vol. 15 nº 9. 2020*)



Metrics used	Content	Conversion factor (estimated value)
Radiative Forcing (RF)	Instantaneous radiation effect due to previous and current emissions	1 to 3[6]
Global Temperature Potential (GTP)	Temperature effect of a current emission pulse after x years	20 years: 1 to 1.6 50 years: ~ 1.2 100 years: ~1.1
Global Warming Potential (GWP)	Over the next x years integrated radiative forcing, which results from a current emission pulse	20 years: ~ 4.5 50 years: ~ 3 100 years: ~ 2
Equivalent Warming Potential (GWP*)	Global temperature change caused by changes in emissions of short-lived substances.	~ 4[7]

Sources: Lee et al. 2010; Fuglestvedt et al. 2010; Allen et al. 2018.

The last option is the use of Equivalent Warming Potential (GWP*) which takes into account that short-lived effects no longer cause temperature changes if emissions remain constant. Then, if short-lived emissions increase, GWP* is positive and becomes negative when that emissions decrease, being relatively independent of the time scale.

An example can be seen in figure 7.5, from the same reference, showing comparative impacts of a one-time emission, calculated using GWP_{20} and GTP_{20}. Long live emission reference is CO_2. When standard kerosene is the used fuel, the factor to multiply CO_2 IRF decreases with time. It is interesting to note that the use al Sustainable Aviation Fuels (SAF) may decrease Life Cycle CO_2 emissions but not necessarily contrails or cirrus clouds, what leads to an increase in the IRF factor. The lack of sulphur in many biokerosene composition would improve local air quality, but at the same time eliminates emissions with cooling effects in altitude. Finally, if fuel is partially or totally decarbonized, like the potential use of hydrogen, CO_2 is eliminated but water vapour increases, as probably do contrails and the formation of cirrus clouds. Boucher et al. (*Boucher O. Seeing through contrails. Nature Climate Change, (2011)*) found that the contrails formed by aircraft may cause a more serious greenhouse effect than all CO_2 emissions. Wang et.al (*Wang Z, Yong T, Wan L, et al. Progress in the Study of Environmental Impacts of High Altitude Flight. Environmental Protection Science (2017)*) summarized harms of high altitude flight .It was concluded that CO2 emission and contrails formation are the most important direct pollution causes of the greenhouse effect and the corresponding atmospheric warming. The, the image of a hydrogen propulsion aircraft as a zero-emissions vehicle is certainly misleading.

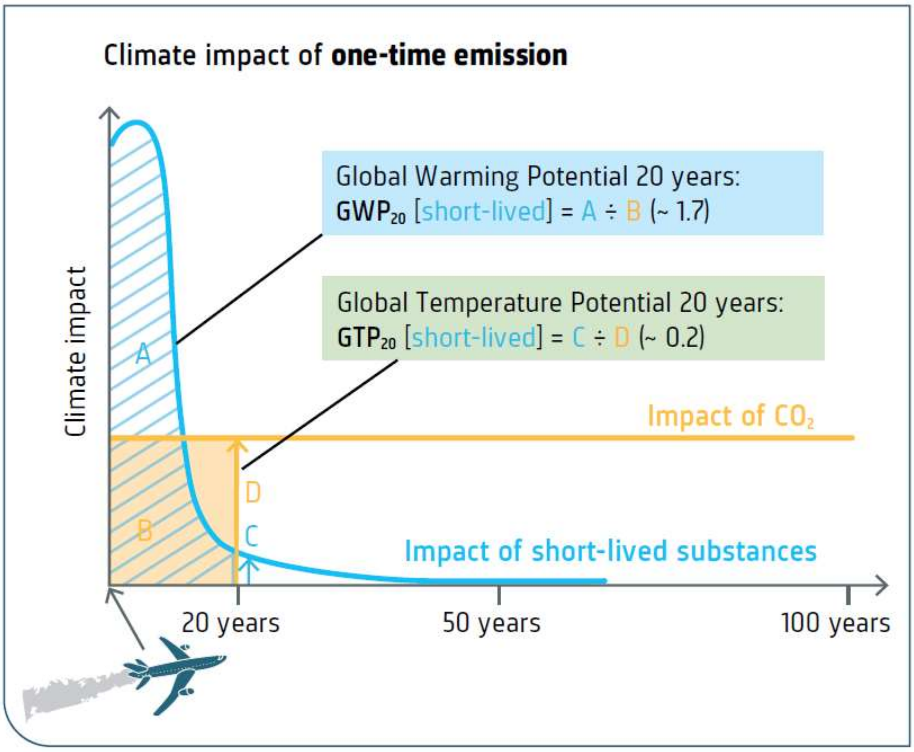


Figure 7.5 Comparison of the calculation of one-time emission effects in climate change using GWP_{20} and GTP_{20} (*Source: Neu, U.: The impact of emissions from aviation on the climate. Swiss academies communications Vol. 15 nº 9. 2020*)

The complication of the non-CO_2 emissions effects simulation has fostered the search for Simplified Climate Models (SCM) capable of achieving good approximate results. Khodayari et al. (2013) examined six of the most used ones: Aviation Environmental Portfolio Management Tool (APMT) from Federal Aviation Administration, CICERO-1 and CICERO-2 from the Center for International Climate and Environmental Research in Oslo, Integrated Science Assessment Model (ISAM) from Livermore National Laboratory, the simple Linear Climate response model (LinClim) and the Model for the Assessment of Greenhouse-gas Induced Climate Change version 6 (MAGICC6) from MAGICC organization.

The conclusions confirm that the model selection depends on the type of application and the availability of the needed parameters for that particular type of problem. For example, calculations of surface temperature changes are better done if the model has a function for calculations of the energy exchange with the deep ocean. Other conclusions were that, when calculating all aviation impacts it is important that all processes were adequately represented. A decisive element in the final selection could be the model capability to provide a possible range of future aviation-induced climate responses. The capability to calculate future economic impacts of aviation is an important additional value.

In the year 2020, a very comprehensive resume of the present knowledge on this issue was presented in the CAEP Steering Group, held in October, and published subsequently by Atmospheric Environment. The graphic scheme of the study field is shown in figure 7.6.

The paper was calculating RF and ERF for the years 2000-2018. The results show that the combination of linear contrails and the cirrus cloudiness arising from them is the highest positive effect in terms of ERF, followed by CO_2 and NOx emissions, while sulphate aerosol provides a small cooling effect. As a group, non-CO_2 emissions would produce more than half of the total ERF (66% in 2018).

The contribution of aviation to the world anthropogenic ERF was evaluated for the year 2011, as a 3.5%, with a small error margin between 3.4 and 4.0% values. This is very similar to the original estimation for the 1992 year, meaning that the very high growth of aviation (superior to most of industrial and commercial activities) was partially compensated by a sizeable improvement in energy use efficiency. Other interesting element, confirmed by the study, was that the calculation of non-CO_2 emissions effects contributes 8 times more to the incertitude of the calculations than CO_2 effects.

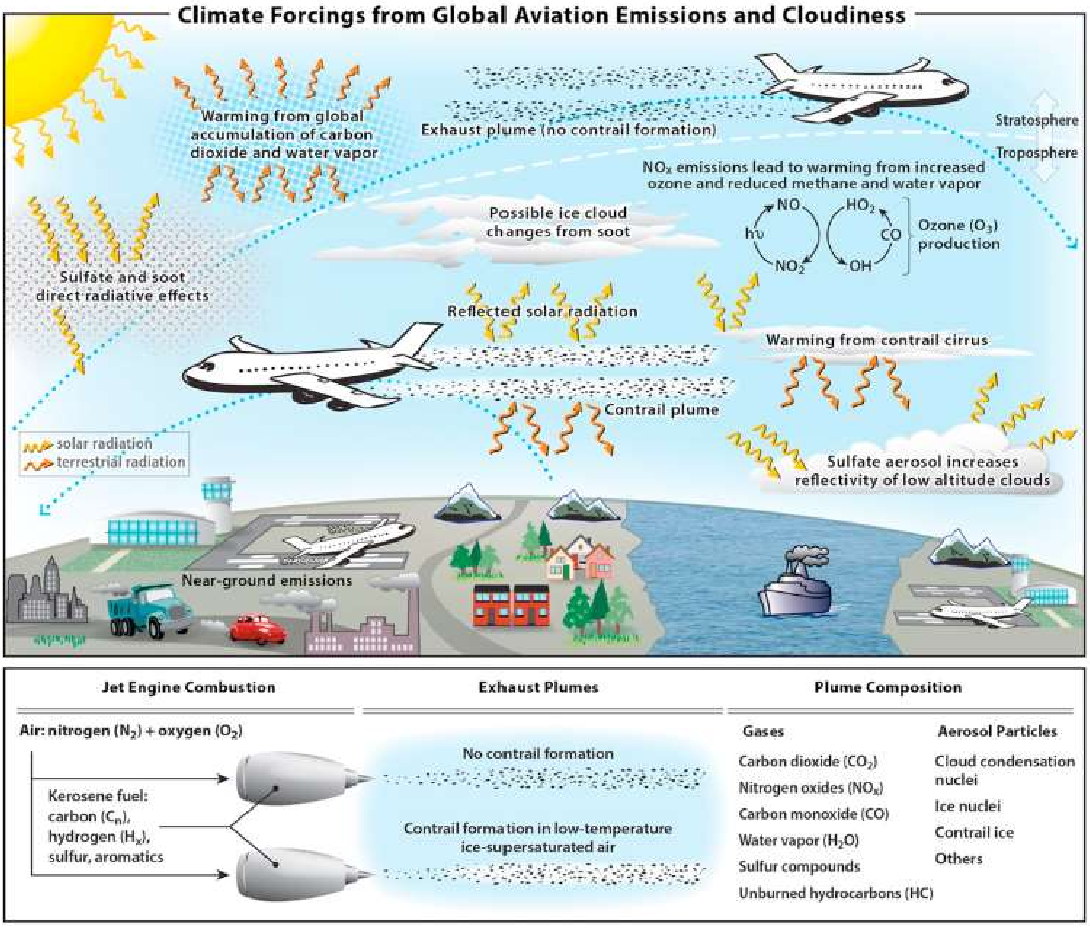


Figure 7.6 Aviation emissions and climate change: a schematic description (*Source: Lee et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment 244, 2021*)

Figure 7.7, from the same source, presents a global calculation of the aviation climate forcing terms from 1940 to 2018, quantified both in ERF and RF values. Red bars indicate warming effects and blue ones, cooling. The symbol (1) means that no estimate is available yet. Close to most likely values, in brackets, appear the 5%-95% confidence intervals.

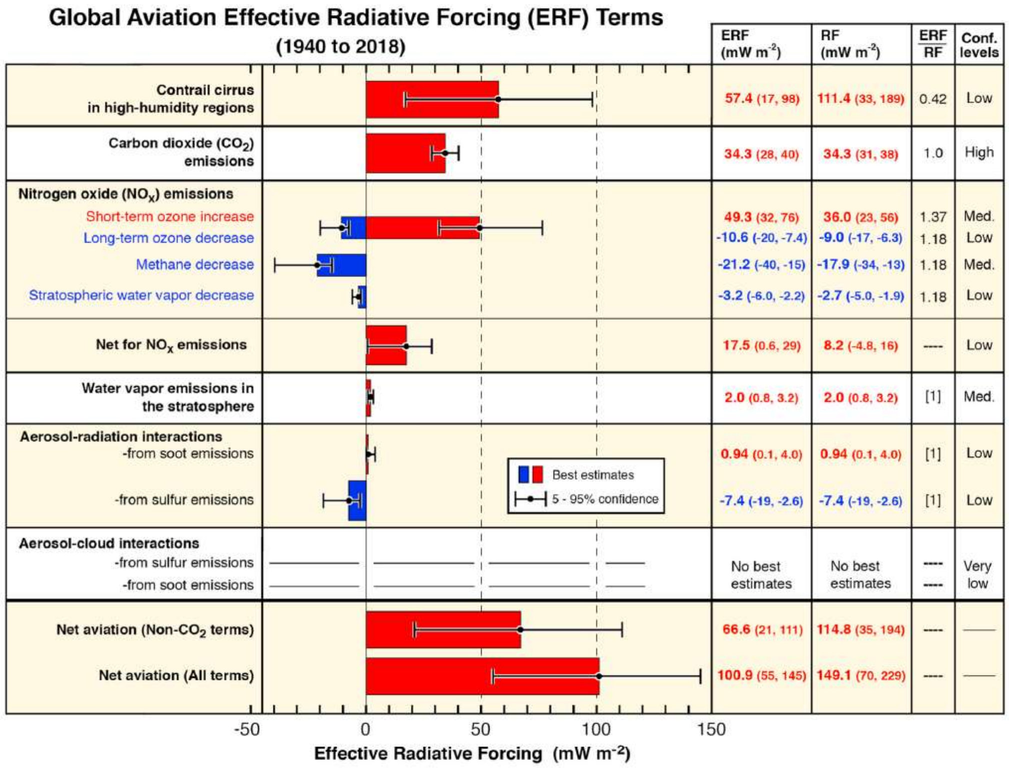


Figure 7.7 Global aviation impact in climate change in the 1940-2018 period (*Source: Lee et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment 244, 2021*)

Aviation sector CO_2 emissions are heavily regulated as it was previously indicated, but non-CO_2 emissions are not presently covered by any official legislation as they are not GHGs. However, as part of the 2015 Paris Agreement decisions, IPCC was invited to publish a study on the possibilities and required actions to reach the goal of not more than 1.5º average temperature increase in the Earth. One of the Summary for Policy Makers (SPM) conclusions in the document (*IPCC: Global Warming of 1.5ºC. Cambridge University Press, Cambridge, UK, 2018*) stated:

"Reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scale"

Considering these two conditions, in the case of aviation there is a need for decarbonization of the sector, achieving net zero CO_2 emissions, and a reduction of the non-CO_2 RF. An additional possibility would be receiving net negative emissions from other economic sector through some kind of Market Based Measures (MBM) mechanism.

Actions in these two areas should not be considered independently. In most case, the emissions to be dealt with have a high degree of interdependency. For example, lower cruise flight altitudes may reduce the contrail formation at the cost of increasing fuel consumption and the corresponding CO_2 emissions. Combustion technology developments to improve the air-kerosene mix efficiency and reduce the consumption (less fuel and less CO_2) use to increase combustion chamber temperature and, as a result, produce more emitted NOx. Trade off analysis between CO_2 and non-CO_2 emissions should be very careful, considering the life differences among the products.

2.2. INVESTIGATIONS AND RESULTS ON ACTIVITY 7.1.2. THE SPATIAL AND TEMPORAL DISTRIBUTION CHARACTERISTICS OF AVIATION EMISSIONS

As it was indicated in the previous chapter, there is a significative difference between the effect on the climate change from CO2 and non-CO2 aviation emissions. Carbon dioxide is a very stable chemical substance and in the Earth's atmosphere conditions does not easily combine with other elements, achieving molecular lives around 100 years average. In addition, it has a high diffusion power in the different atmospheric layers and geographical regions, reaching homogeneous concentration levels very fast. All these properties allow to treat CO2 as a single magnitude in terms of climatic change impact, independently of the emission place and of the conditions of the surrounding air.

The non-CO2 have different and diverse characteristics, with average lives much shorter and stability depending on the chemical and meteorological conditions where they are emitted. At the same time, many of them react with atmospheric components producing different types of substances. These chemical reactions may be strongly dependent on the emissions concentration. Then, the geographical point of emission and the amount of concentration of each one of the substances have a relevant role in the resultant Effective Radiative Forcing (ERF). As a consequence, the air space zones with the highest traffic (generally in the middle latitudes of the North Hemisphere) have different conditions than other less frequented areas and the months of the year with more flights (in this hemisphere the summer period) get higher pollutant concentrations.

A first step in the knowledge of the pollutant diffusion into the atmosphere is the study of the interaction of the engine exhaust and the surrounding atmospheric flow, perturbed by the wake flow of the aircraft. Figure 7.8 shows a simplified scheme of the interaction of the wingtip vortex and the engines exhaust.

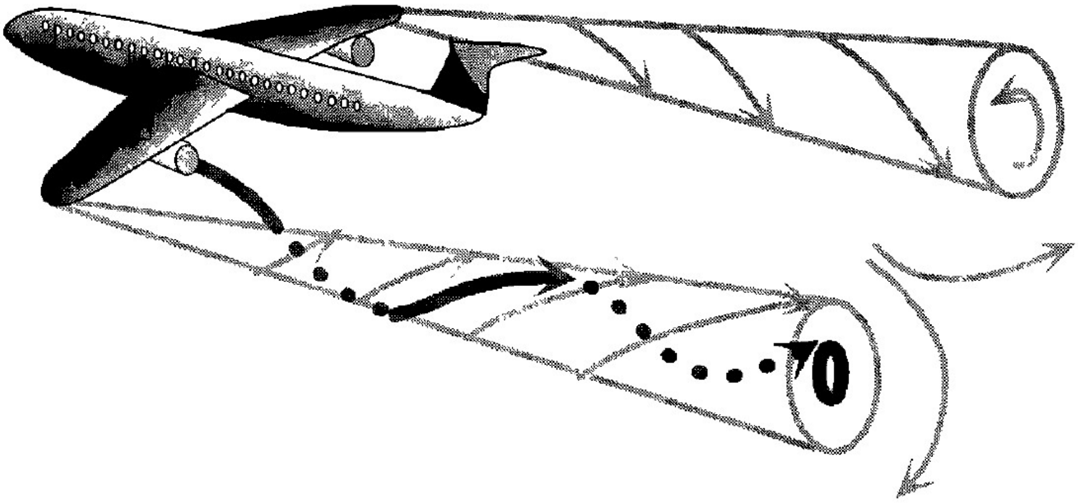


Figure 7.8. Early wake dynamics behind an airplane (Source: Gerz, T. et al. Transport and effective diffusion of aircraft emissions. Journal of Geophysical Research, vol.103 pp.169-187 (2020)

According to that analysis, an exhaust plume disperses due to the combined effects of advection, turbulent diffusion, and molecular diffusion, resulting in an effective diffusion. The process has three different temporal stages: the “jet” regime, before wingtip vortex and exhaust mix; the “vortex” regime, when engine exhaust is captured by wingtip vortex, and the “dissipation” regime, when vortexes break up and their energy dissipates into the atmosphere. If the atmosphere itself presents a non-stable regime, for example, with a sizeable amount of wind shear, the mixing rate increases, and horizontal dispersion gets stronger.

The study distinguishes between “primary wake” originated by the two wingtip vortices and the “secondary wake”, when about 10 to 30% of the exhaust mass that has sank and separated from the main flow. Vortices collapse into aircraft turbulence in about 2 to 3 minutes. Under typical cruise flight conditions, the plume extension may reach up to 20 km horizontally and 0.3 km vertically. The dilution of exhaust products to the background concentration levels can take between 2 and 12 hours, depending on the atmospheric turbulence levels, giving time enough to be mixed with the products of other flights flying in the same airway.

According to the Gerz study, the maximum emission concentration in the primary wake is five times higher than the one in the secondary wake in steady state, with the difference being reduced by an increase in the atmospheric turbulence. Differences between primary and secondary wakes are relevant for the chemical reactions of pollutants. For example, the ratio NO2/NOx is three times higher in the secondary wake, probably due to a higher presence of atmospheric O3 (a greenhouse gas).

The chemical effects of injecting emissions in the turbulent regime previously described have been (and will be) subject of a great number of studies. From the climatic change perspective, the most important issue is the interaction between commercial flights emissions and the atmosphere in the cruise phase of the flight, where the aircraft operates in the upper troposphere and the lower stratosphere (UTLS).

A good synthesis of some of the problems in understanding and modelling of atmospheric chemistry in the UTLS was provided by the American Meteorological Society (Toohey, W. D., McConnell, J., Avallone, L. and Evans, W: Aviation and Chemistry and transport process in upper troposphere and lower Stratosphere. Bulletin of the American Meteorological Society, pp. 485-489 (2010)). The NOx and water vapour emitted by the engines react with the atmospheric fluids, creating a series of nitrogen and hydrogen products, normally designated as NOy and HOx the amount of which modifies the ozone creation (warming effect) and methane destruction (cooling effect). In every case, air conditions (temperature, turbulence) and concentration of pollutants are key factors that change with geographical position and traffic density.

It should be noticed that the contribution to the climate change is the most important but not the only environmental effect of aviation emissions, that can be classified in three categories (Van Pham, V., Tang, J., Alam, S., Lokac, C. and Abbass, H. A.: Aviation emission inventory development and analysis. Environmental Modelling & Software, vol. 25 pp. 1738-1753 (2010)):

- Wide range contamination, covering all the effects at long distance from the pollution source. An example will be the acid rain, partially caused by NOx and SOx emissions, not only coming from aviation but from other industrial and agricultural activities.
- Effects of the NOx emissions on the ozone layer. When emitted over the tropopause, NOx destroys ozone. This is a major concern for supersonic flights flying at very high altitudes. On the other hand, below tropopause, NOx emissions induce reactions for ozone formation. Ozone is a GHG and contributes to atmospheric

warming but, at the same time, ozone layer is needed to protect the Earth from excessive ultraviolet radiation from the sun. The emission of ozone depleting substances has been damaging the ozone layer. But through domestic and international action (in September 1987 the Montreal Protocol on Substances that Deplete the Ozone Layer was signed), the ozone layer is healing and should fully recover by about 2065. Although the tropopause altitude changes with the latitude, a majority of present flights are below, and their NOx emissions create ozone.

- Greenhouse effect, mainly due to the emitted CO2 and water vapour absorbing infrared radiation and warming the atmosphere. Other emitted substances, like NOx, SOx, soot and particles have also minor warming and cooling effects.

A very complete analysis of the state of the art in spatial and temporal distribution of emissions was provided by the Federal Aviation Agency (FAA) Aviation Climate Change Research Initiative (ACCRI) that used a combination of atmospheric models, surface and satellite observations, and laboratory experiments for quantifying climate impacts of aviation emissions (Brasseur, G.P., Gupta, M., Anderson, B. E., Balasubramanian, S., Barrett, S., Duda, D., Fleming, G., Forster, P. M., Fuglestvedt, J. et al.: Impact of aviation on climate: FAA´s Aviation Climate Change Research Initiative (ACCRI) Phase II. Bulletin of the American Meteorological Society 97 (2016). The results, far still to be definitive, pointed out the need of studying more in detail the spatial and temporal distribution of emissions, not only for a more accurate assessment of each one importance, but also to define better mitigation procedures.

While CO2 effects can be accurately calculated on global basis, individual component-based ERF to temperature relationships for non-CO2 aviation emissions vary significantly on both global and regional geographic and temporal scales. Changing atmospheric and climatic conditions at cruise altitude will affect some of the most important non-CO2 elements, as formation of persistent contrails and cirrus clouds, along with cloud-aerosol interactions. Global observation datasets should complement the model results and progressively reducing the incertitude levels of the ERF calculations.

An example of the achieved results can be seen in figure 7.9, showing the calculation of the net Cloud Radiative Forcing (CRF) from aviation contrails during the year 2006 in daytime and nighttime hours. The distribution reflects the density of traffic, higher in the Northern Hemisphere, and the differences in the time of the flights. Climate radiative effects of contrails are determined by the background radiation field and some contrail properties, as extension, lifetime, temperature, optical depth, particular shape, and ice crystal effective diameter. Background radiation is quite different day and night. At daytime long and short wave forcing are cancelling each other, something that does not happen at night. Then CRF is higher by night.

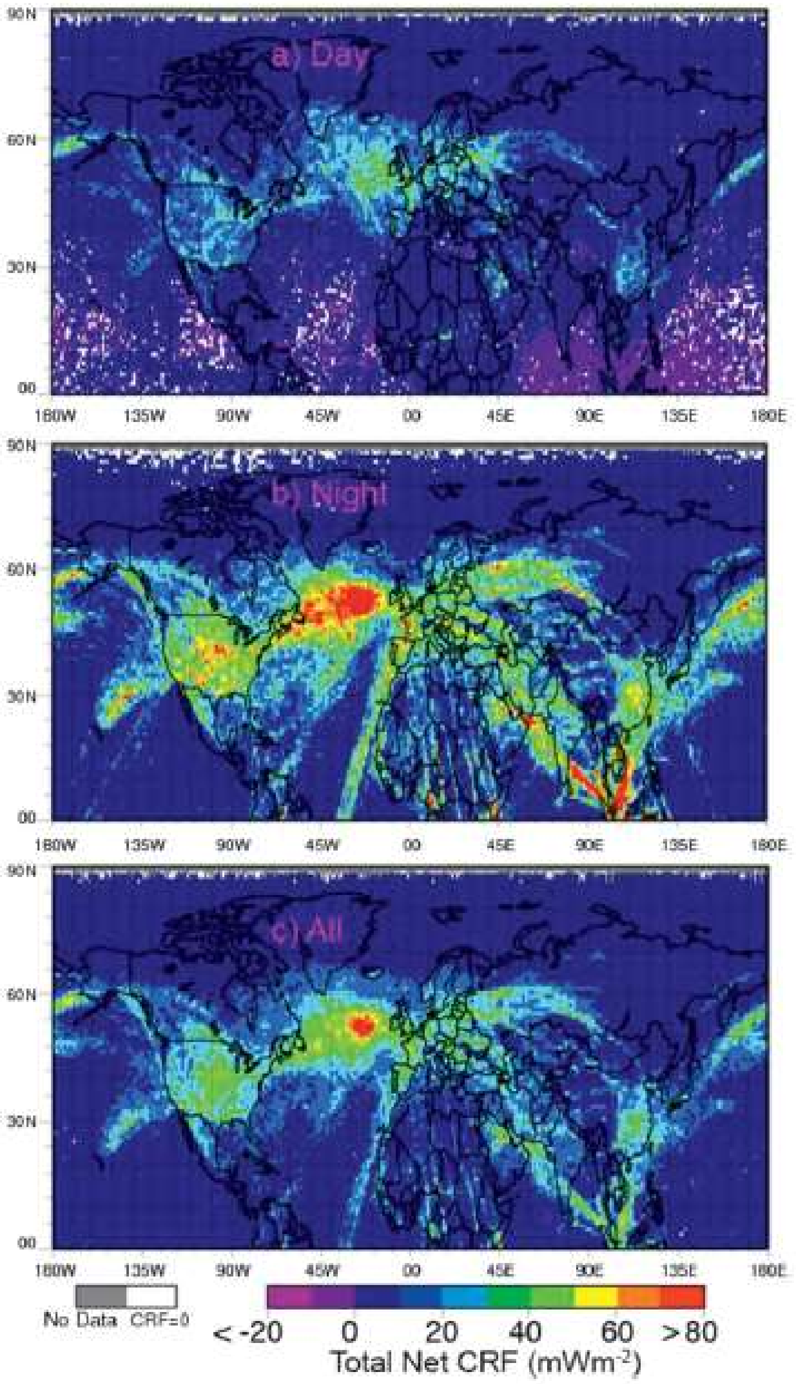


Figure 7.9. Mean 2006 net contrail RF from Aqua MODIS data: (a) daytime, (b) nighttime, and (c) all data (NASA Langley) (Source: Brasseur et al. Impact of aviation on climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II. Bulletin of the American Meteorological Society 97, 2016)

2.2.1. EMISSIONS SPATIAL DISTRIBUTION

The emissions spatial distribution is highly dependent of the flight range and trajectory. In a typical commercial jet aircraft, the amount of emissions and their type of characterisation change in the different flight phases due to their duration and the engine regime. In addition, the flight path determines the geographical area where these emissions are ejected and the flight profile the emissions altitude.

A typical distribution of flight phases and their associated emissions can be established in this schematic way:

- Airport taxi-out: the phase duration depends on the airport size, the level of airport congestion and the operation procedures. Engines run at low thrust emitting comparatively high quantities of CO and HC, some non-volatile particulate matter (nvPM) and smaller amounts of solid carbon and NOx.
- Take-off and climb out: short phase of a few minutes duration with engines at high thrust. High levels of emitted NOx
- Climb: a 20–30 minute phase with relatively high thrust. High NOx emitted and water vapour.
- Cruise: this phase duration and altitude depend on the length of the flight. Engines run at 30–40 % of maximum thrust and the aircraft moves in an area where emissions may have a great impact in climatic change by reacting physical and chemically with the high atmospheric layers (UTLS).
- Descent and approach: similar duration than climb but with engines at low thrust. Moderate emissions.
- Landing and airport taxi-in: similar to taxi-out but with lower level of emissions because in many occasions is done with one engine out.

Airport related emissions are typically computed as those produced by flights below 3,000 ft of height over the runway, with the addition of those produced by service vehicles and airport facilities. The emissions coming from the aircraft operation are mixed with those generated by the different facilities in the airport and around, many of them difficult to compute or modelized.

A detailed analysis of the GHG emitted by the airport (CO2, N2O, CH4 and H2O) operations in the years 2009-2010 was made by the National Research Foundation of Korea (Song, S. K. and Shon, Z. H.: Emissions of greenhouse gases and air pollutants from commercial aircraft at international airports in Korea. Atmospheric Environment, vol. 61 pp. 148-158 (2012)), covering the four largest airports of South Korea (Incheon, Gimpo, Gimhae and Jeju), with 90% of the flights in that country. Other pollutants, like NOx, CO, HC, and particulate matter were also calculated using the Emissions and Dispersion Modelling System (EDMS).

The results of the analysis showed that, in absolute terms, the largest GHG emissions happened in the taxi-out phase, followed by climb-out, approach, taxi-in and take-off. For the other pollutants, CO and HC were the highest during taxi-out, while NOx and particulate matter dominated take-off, climb out and approach modes. A curious result was that the values of CH4 were negative, as part of the atmospheric methane was consumed by the engine. In any case, the total quantity of emitted GHG in the airport area was very small compared with the total flight.

Copenhagen Airport has developed a very complete analysis of the pollutants with the highest effect in local air quality, as NOx and particulate matter (mass and number of particles), using 2009 traffic data. The study was including emissions of the main engines, Auxiliary Power Units (APU) and handling equipment needed for the commercial flights' turnaround, following with great accuracy the aircraft movement in the airside of the airport, as can be seen in figure 7.10, providing a useful method for both spatial and temporal calculation.

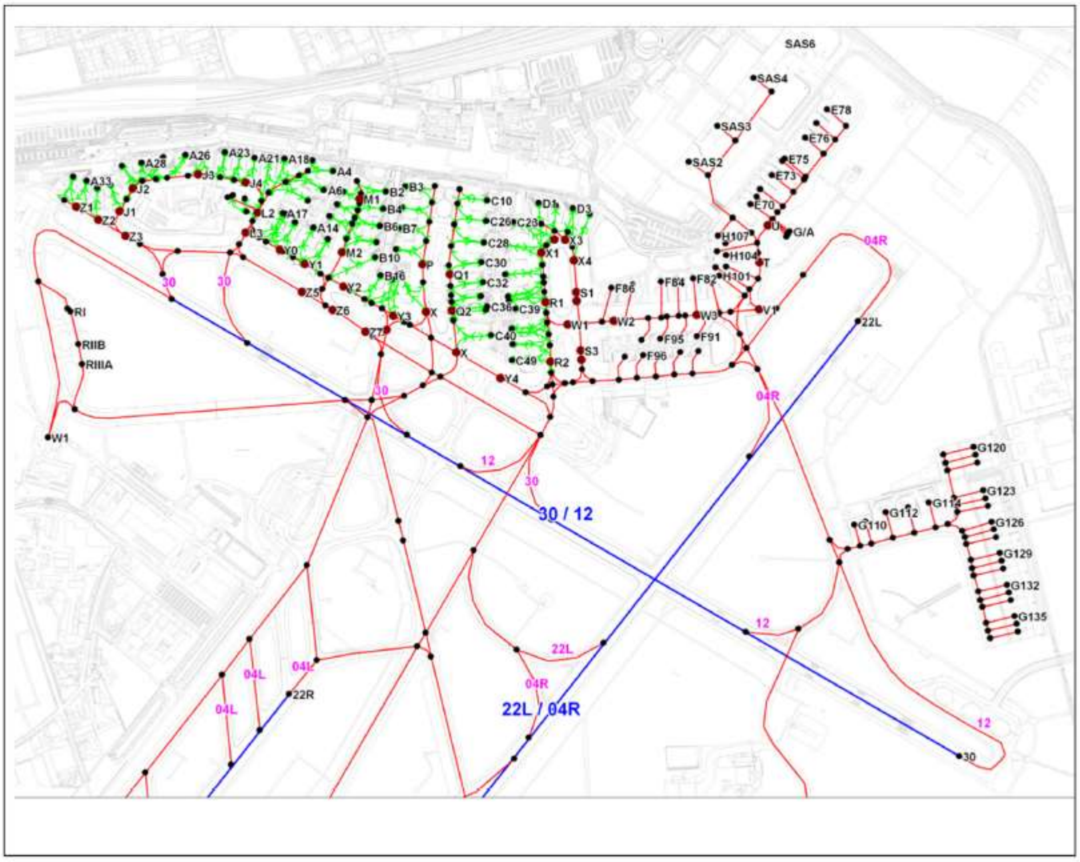


Figure 7.10 Map of Copenhagen airport: Black dots are terminal gates, Brown dots indicate main engine start-up, red and green lines are aircraft taxiways and blue lines indicate sectors of the runways (Source: Winther, M., Kousgaard, U., Ellermann, T., Massling, A., Nøjgaard, J. K. and Ketzel, M.: Emissions of NOx, particle mass and particle numbers from aircraft main engines, APU's and handling equipment at Copenhagen airport. Atmospheric Environment, vol 100 pp. 3,605-3,631 (2015))

The results were compared with some available data, provided by other airports, as shown in Table 7.3, indicate that main engines are the most important source of NOx (between 87 and 93% of total) and particulate matter mass (between 55 and 75%). Not enough particulate number data were available, but Copenhagen data supports the hypothesis of a more than 90% are coming from main engines. It is interesting to notice that Handling equipment is responsible of a non-negligible amount of the particulate mass (between 6 and 33%), what underline the importance of replace this equipment by a more environmentally friendly one.

The study, however, does not cover other airport emission sources not directly related with the aircraft movements. Size and configuration of this airport are relatively open and free of interferences with non-aeronautical activities. In other larger airports, like Heathrow or Charles de Gaulle, the emissions from road traffic and industrial activities reach magnitudes comparable with the aircraft ones.

Table 7.3. Percentage share of NOx, PM, and PN by the different airport sources (Source: Winther, M. et al. as figure 7.10)

Airport	Source	NOx	PM	PN
Copenhagen	Main engines	87	61	94.8
	APU	4	8	5.0
	Handling	9	31	0.2
Brisbane	Main engines	91	-	-
	APU	9	-	-
	Handling	-	-	-
Heathrow	Main engines	87	55	-
	APU	7	12	-
	Handling	6	13	-
San Diego	Main engines	92	75	-
	APU	3	19	-
	Handling	5	6	-
Zurich	Main engines	93	74	-
	APU	2	6	-
	Handling	5	20	-

The analysis of airport contaminant quantities can be made at large scale, like the study of LTO cycle in the largest 217 airports in China, recently published by the Ministry of Environmental Protection of that country. Figure 7.11 provides a glimpse of the size of the work, the great number of airports and the different contaminants considered.

The conclusions of the study marked NOx emissions as the most important emitted substance from aviation, in terms of both pollutant amount and environmental impact, while fine particulate matter PM2.5 (particles with less than 2.5 micrometres of diameter) generated an extensive influence. The effects on air quality were moderated (although this should be reconsidered if traffic continues growing at the high path in China), and it was only relevant in airports serving important economic areas or popular tourist spots. Grouped by provinces or municipalities (a total of 31 in China), NOx, SO2 and PM2.5 emissions were easy to adjust to a linear regression versus each zone GDP, except Beijing and Shanghai, areas with several big airports, with showed much higher emission concentrations.

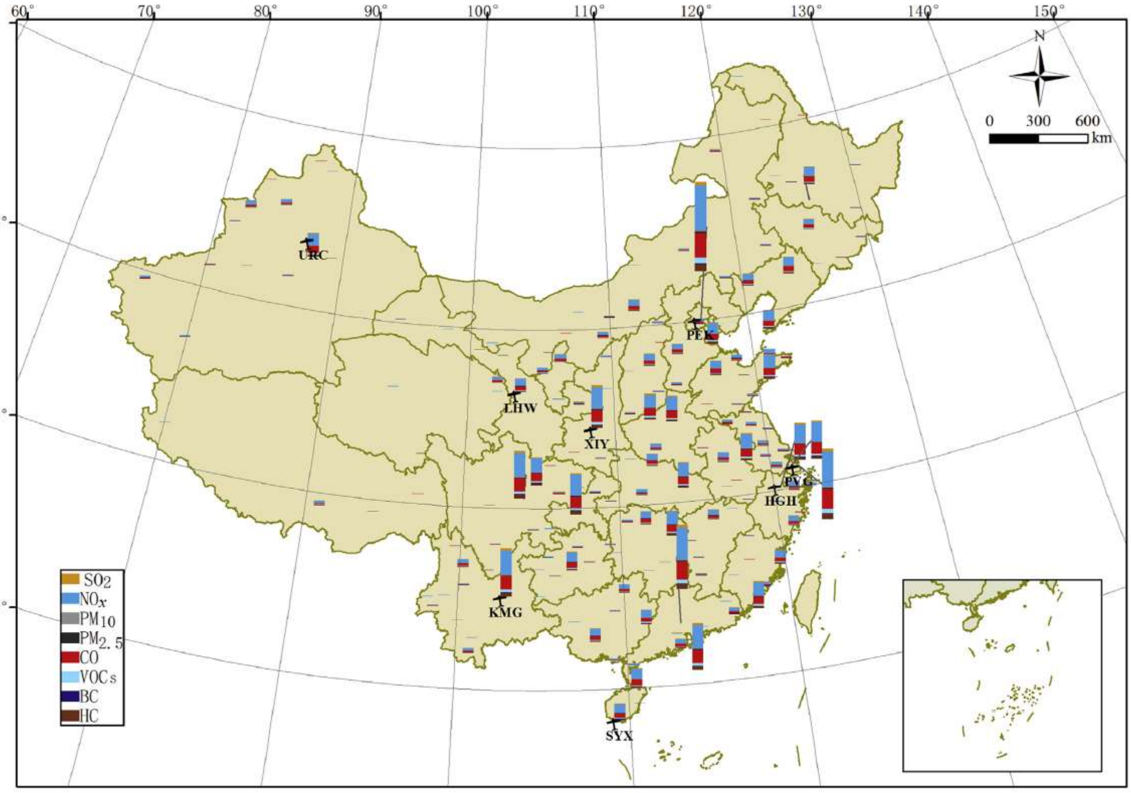


Figure 7.11 Estimated aviation emissions at 217 airports in China (year 2016) (Source: Bo, X., Xue, X., Xu, J., Du, X., Zhou, B. and Tang, L: Aviation's emissions and contribution to the air quality in China. Atmospheric Environment, vol. 201 pp.121-131 (2019))

Most of the airport operation emissions studies directly apply ICAO Annex 16 Volume II LTO cycle emission rules, which provides engine emissions below 3,000 ft under certification rules. This implies new engines operated at maximum certified thrust in standard conditions. In real life, engines operate in the prevailing conditions of the airport and have suffered certain performance deterioration levels, depending on their age and historical operating conditions.

With respect to NOx, being the most important pollutant at the high thrust conditions, predominant during take-off and climb, a comparison between ICAO data and real operative conditions was made by Turgut, E. T. et al., using CFM International CFM56-7 engines of two variants: -7B and -7B3.

The results, shown in Table 7.4, indicate that ICAO data globally underestimate NOx emissions in a range between 1.0 and 10.7%, with an average value of 4.6%, but this margin was not homogeneous. In the case of the -7B variant, the error range was 1.0–3.5% and the average 2.3%, while for the -7B/3 it was 5.6-10.7% with an average of 8.0%.

Table 7.4 Comparison between take-off and climb NOx emissions (Source: Turgut, E. T., Usanmaz, O. and Rosen, M. A.: Estimation of vertical and horizontal distribution of take-off and climb NOx emission for commercial aircraft. Energy Conversion Management, vol. 76 pp. 121-127 (2013))

Flight	Engine type	Altitude at take-off beginning (m)	End of climb altitude (m)	Emitted NOx (kg)	ICAO figure NOx (kg)	Difference (%)
1	7B	73	9,759	28.39	27.41	3.5
2	7B/3	100	10,371	21.90	19.92	9.0
3	7B	21	9,760	30.33	29.61	2.4
4	7B	9	10,361	29.96	28.91	3.5
5	7B/3	16	10,362	24.65	22.97	6.8
6	7B	110	9,147	25.89	25.63	1.0
7	7B	39	7,313	22.80	22.41	1.7
8	7B	145	9,142	30.98	30.42	1.8
9	7B/3	79	8,535	21.85	19.51	10.7
10	7B/3	139	9,146	22.37	21.11	5.6

There are several analyses about the geographical distribution of commercial aviation emissions around the world. One of the first and more complete one was published in 2010 by Wilkerson, J. T. et al., using 2004 and 2006 data provided by the Volpe National Transportation Systems Center and the FAA's Aviation Environmental Design Tool (AEDT).

Taking the year 2006 data, 92.5% of the total fuel was burned in the North Hemisphere, 74.6% at altitudes higher than 7 km and 69% in the space placed between 30o and 60o parallels. More than half of the total was emitted flying over ground (25.5% over the USA, 14.6% over Europe and 11.1% over East Asia). A graphical representation of the commercial aviation geographical distribution can be seen in figure 7.12. were more reddish areas indicate higher CO2 emissions, in terms of kg emitted per km2. The lateral latitude graphic allows to analyse the latitudinal distribution, with peaks about 30o, 40o and 50o North. A similar graphic below provides the analysis of the longitudinal distribution, with peaks over the three continents above mentioned.

From the same source, figure 7.13 provides a graphic view of the CO2 emissions distribution in altitude and in latitude. The analysis considers that short range flights (less than three hours) produce 39.65% of the total CO2 emissions, medium range (between 3 and 6 hours) emit 22.65% and long-haul (those lasting more than 6 hours), 37.70%. The great majority is emitted in cruise, over 7 km of altitude. As it is shown in that figure, there are two dominant corridors: North Atlantic and North Pacific. They are different in emissions concentration, because North Atlantic has mainly long range, all emissions over 7 km altitude, in a relatively narrow group of airways. Then, emissions concentration is much higher than in the North Pacific, wider and with more short-range flights.

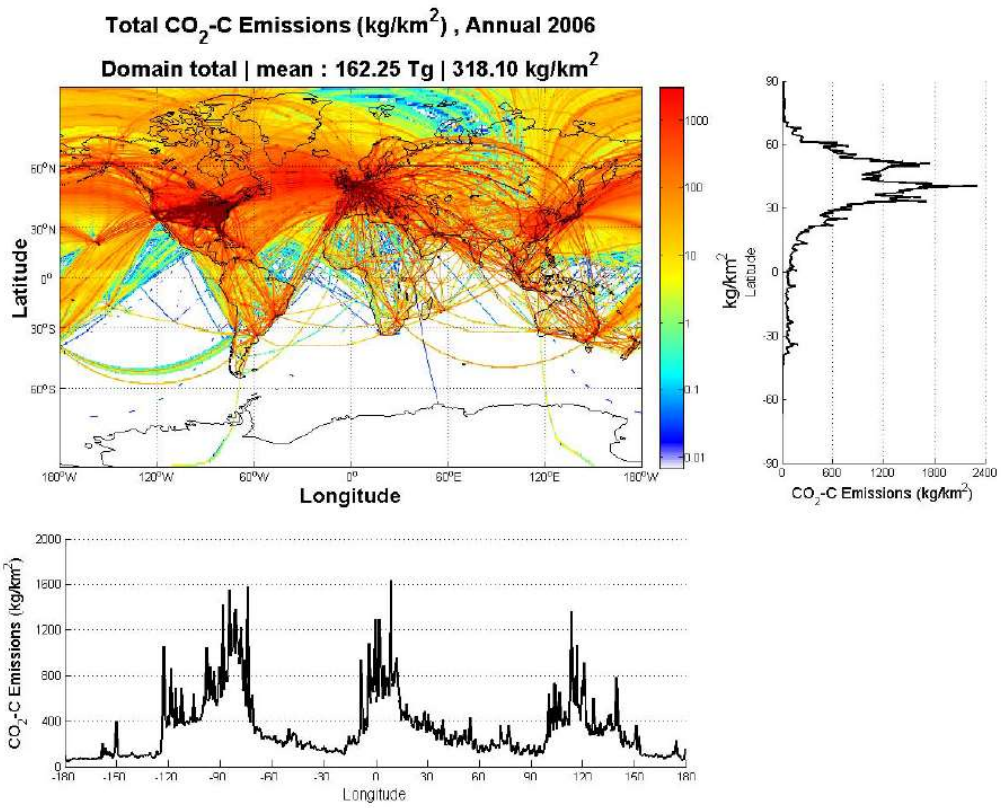


Figure 7.12 Commercial aviation CO2 emissions in 2006 in kg per km2, represented by surface, by latitude and longitude (Source: Wilkerson, J. T. et al.: Analysis of emission data from global commercial aircraft: 2004 and 2006. Atmospheric Chemistry and Physics, vol. 10 pp. 6,391-6,408 (2010))

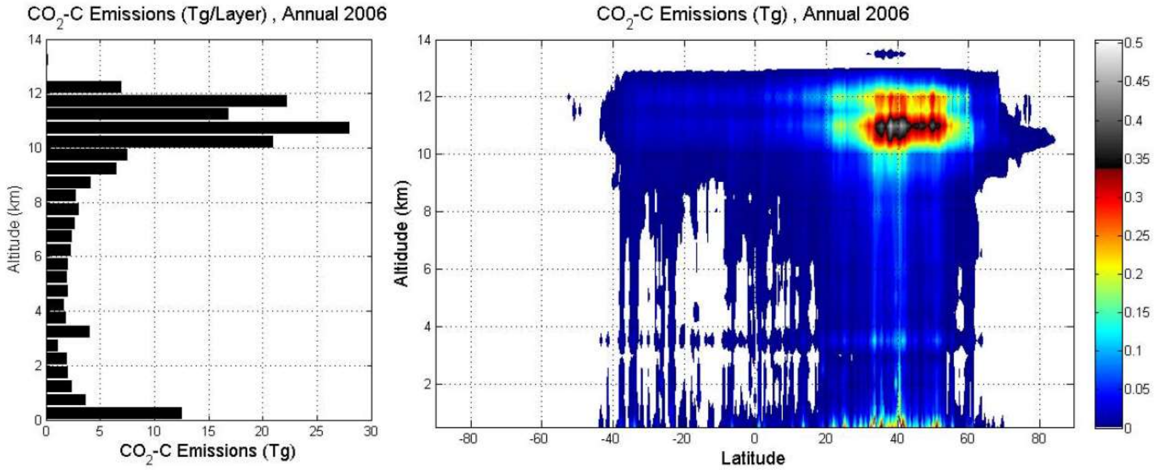


Figure 7.13 Altitude distribution of 2006 commercial aviation CO2 emissions. On the left, total quantities; on the right, latitudinal distribution (Source: Wilkerson et al. as Figure 7.12)

An area of particular interest is the Artic region. Although emissions per km2 are a small fraction than those in other corridors, they have a longer residence time there, because

95% of them are emitted in high altitude, at a latitude where the limit between troposphere and stratosphere is lower and the emission area has very stable conditions. In addition, typical wind patterns push emissions from the North Atlantic to the north, towards the polar region. This produces a relatively high emissions concentration, in stable conditions, and the potential climate change effects are relevant, in spite of being a low emission area.

The fact that commercial aviation is the most abundant direct source of black carbon and other climate-relevant pollutants over the Artic has indicated the convenience of rerouting cross-polar flights, even if this can produce longer flights, an additional fuel consumption and more CO2 emissions. The analysis of 2006 flights over the Artic (Jacobson, M. Z., Wilkerson, J. T., Balasubramanian, S., Cooper, W. W. and Mohleji, N.: The effects of rerouting around the artic circle on artic and global climate. Climatic Change vol. 115 pp. 709-724 (2012)) seemed to favour such action. Fuel use increased 0.056%, with a cost of about 100 MUSD, at that moment fuel price, but the emissions were removed faster because were injected over lower latitude, in atmospheric conditions of greater precipitation and lesser stability that in the Artic region, what helped to reduce pollutant lives. This cost is calculated to be 50 times less than the benefits for less climate warming, just in the United States.

Other analysis, like Pagoni, I. and Psaraki-Kalouptsidi, V.: Calculation of aircraft fuel consumption and CO2 emissions based on path profile estimation by clustering and registration. Transportation Research Part D, vol. 54 pp. 172-190 (2017) covering the 100 routes with more traffic in the domestic United States market, arrives to similar emissions distribution. In this case, CO2 emissions are led by coast to coast routes that, in exchange, offers the best figures in terms of emissions per Available Seat Mile (ASM) because the higher length of the flights and the greater size of the operated aircraft.

The mechanism of interaction between aircraft emission and the surrounding atmosphere is very changeable depending on the atmospheric composition and the concentration of emissions. Between November 1994 and July 1995 and from August to November 1997 the Project POLINAT (The Pollution from Aircraft Emissions in the North Atlantic Flight Corridor) used an equipped Dassault Falcon, operated by DLR, to measure exhaust emissions from a Swissair B747 flying between Switzerland and United States at altitudes between 6 and 13 km in different flight phases.

POLINAT showed (Schumann, U. et al.: Pollution from aircraft emissions in the North Atlantic flight corridor: Overview on the POLINAT projects. Journal Geophysical Research, vol. 105 pp. 3,605-3,631 (2000)) that aircraft emissions contribute measurable NOx concentration changes until many hours after the flight and, under certain meteorological conditions, NOx concentration in high traffic corridors can accumulate during a few days, being as high as 2.5 ppbv (particles per billion), with lower levels in summer than in winter. Ozone increases of 3 to 6% in this zone of latitude 30o N, but on the contrary than NOx, the values are higher in summer than in winter. A very important finding was the importance of humidity level in the formation of persistent contrails. Higher water vapour concentration, through ice supersaturated air masses in the autumn period, favoured the creation of contrails and their persistence.

This delicate balance in the mechanism of ozone formation and methane destruction because of aviation NOx emissions has been subject of different regional analysis because results may be very different depending on the prevalent atmospheric conditions and the pollutant concentrations in the area.

In 2013 Köhler, M. O. et al. made some chemical transport model experiments with regional perturbations to aircraft NOx emissions in four regions: USA, Europe, India, and China, simulating the addition of a fixed 0.036 Tg(N)/year amount of pollutant at different aircraft cruise altitudes. The predominant factor for the resultant net RF was the flight cruise level, but it was not homogeneous at different latitudes due to the tropopause altitude, that is lower at high latitudes. When emissions are ejected below tropopause, the creation of ozone is higher and RF greater.

Figure 7.14 compiles in three graphs the study results by region and along the different altitudes. The upper one shows the net RF increase (black cross) with its three components (short lived ozone production, reduction of methane lifetime and methane induced ozone decrease). The effect is higher in less dense traffic areas as China and India than in USA and Europe. The middle one indicates the ozone RF variation with latitude, with peaks between 15o and 30o for China and India and 25o to 40o in USA and Europe. The bottom panel quantifies the methane lifetime reduction (cooling effect), greater in China and India as well.

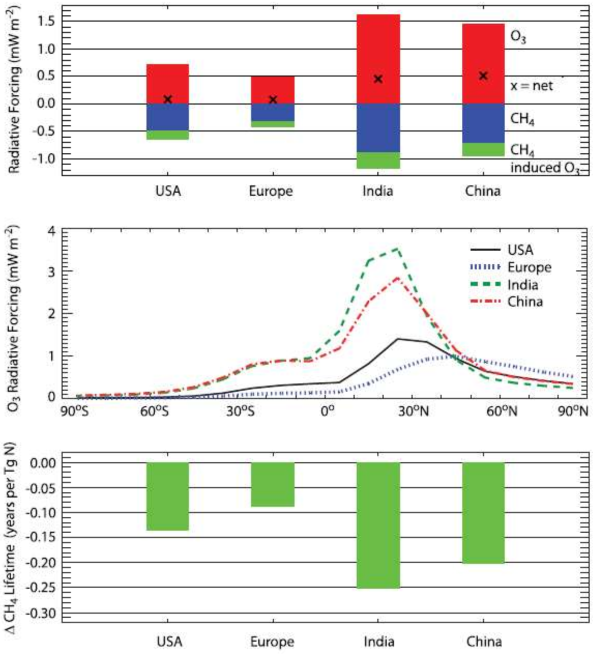


Figure 7.14 Regional latitude effects on ozone formation (Source: Köhler, M. O., Rädel, G., Shine, K. P., Rogers, H. L., Pyle, J. A.: Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics. Atmospheric Environment, vol. 64 pp. 1-9 (2013))

The possibility of reducing climate change impact by changing cruise altitude has been explored in the paper Søvde, O. A. et al.: Aircraft emission mitigation by changing route altitude: A multi-modal estimate of aircraft NOx emission impact on O3 photochemistry. Atmospheric Environment, vol. 95 pp. 468-479 (2014). At standard cruise long range levels below tropopause, a 2,000 ft movement upwards increases RF due to gaseous photochemistry by about 2 ± 1 mW m-2 and a downward shift reduces it in the same quantity. This should be compared with the decrease/increase of CO2 emissions from the change in fuel consumption that is reduced by increase the flight altitude, in the order of ≤ 1%.

A wider and more detailed study appeared two years later by Skowron, A. et al., comparing the results, in terms of RF and, GWP100 of small and large injection of NOx in five different world areas, starting from a uniform concentration level of this pollutant. A global chemistry transport model, MOZART-3 CTM was used for the simulation.

The RF results can be seen in table 7.5, where Net NOx accounts for short term O3 RF, CH4-induced O3 RF and CH4 with Shortwave RF. Aircraft NOx emissions injected into several world areas affect in a different way the compensating balance between ozone and methane. The difference between ozone creation to the same NOx injection can reach 54%, with dense NOx areas like Europe being the lowest and less crowded ones, like Australia, the highest.

As an important conclusion for the climate change impact of NOx emissions, it seems that the effects of aircraft NOx in the regional RF and GWP values is dependent on the relative global emission pattern and pollutant concentration. Then, same emissions can produce different effects if they are injected in different regions and, consequently, these effects can vary in the same region if its pollutant background changes.

Table 7.5 Net NOx RF (Radiative forcings) in different world areas and their variation with emission increases (Source: Skowron, A., Lee, D. S., De León, R. R.: Variation of radiative forcing and global warning potentials from regional aviation NOx emissions. Atmospheric Environment, vol. 104 pp. 69-78 (2015))

World Region	Net NOx RF (mW m^{-2} / Tg(N) yr^{-1})		
	0.035 Tg(N) yr^{-1}	**5% (N) yr^{-1}**	**100% (N) yr^{-1}**
World	5.51	5.51	4.89
North Hemisphere	5.31	5.32	4.76
South Hemisphere	6.45	9.02	6.42
Europe	2.32	2.90	1.97
North America	3.73	5.07	3.52
Southeast Asia	5.33	5.26	5.25
North Pacific	9.22	23.73	9.53
North Atlantic	10.21	14.06	10.38

Some studies are devoted to the emissions distribution in some specific part of the world, focusing on aviation or taking the complete industrial system with all fossil-fuel (coal, gas, petroleum) CO2 emissions. At world scale, fossil fuels are the origin of 80% of anthropogenic CO2 emissions. The study made by Gregg, J. S. et al. (Gregg, J. S., Losey, L. M., Andres, R. J., Blasing, T. J. and Marland, G: The temporal and spatial distribution of carbon dioxide emissions from fossil-fuel use in North America. Jour 7.4nal of Applied Meteorology and Climatology, vol. 48 pp. 2,528-2,542 (2009)) covered the North America continent (Canada, United States and Mexico) in the 1990-2007 period. The small aviation part was relatively uniform, growing without discontinuities with the increase of the traffic.

A complete analysis of the Chinese domestic aviation emissions in the 1980-2015 period was made by Huanjia Liu et al. The study results, covering 299 domestic routes among 208 Chinese airports, and all flight phases emissions, are resumed in figure 7.14, and the conclusions are aligned with the Xin Bo et al. study on airport air quality emissions. Central and Eastern regions of China, with high population density, large economic volume, and good airline connections, have the largest share of emissions, in comparison with north-eastern and western regions.

Even with a high number of short and medium range flights, cruise emissions are dominant for CO2/SO2/Heavy Metals (92% of the total), PM2.5 (89%) and NOx (81%), while LTO cycle emissions ranking is headed by CO (76% of the total) and HC (71%). The figure 7.15 shows this distribution as well as the growth in each one of the different emissions compared with GDP and GDP per capita increase, all of them following similar patterns.

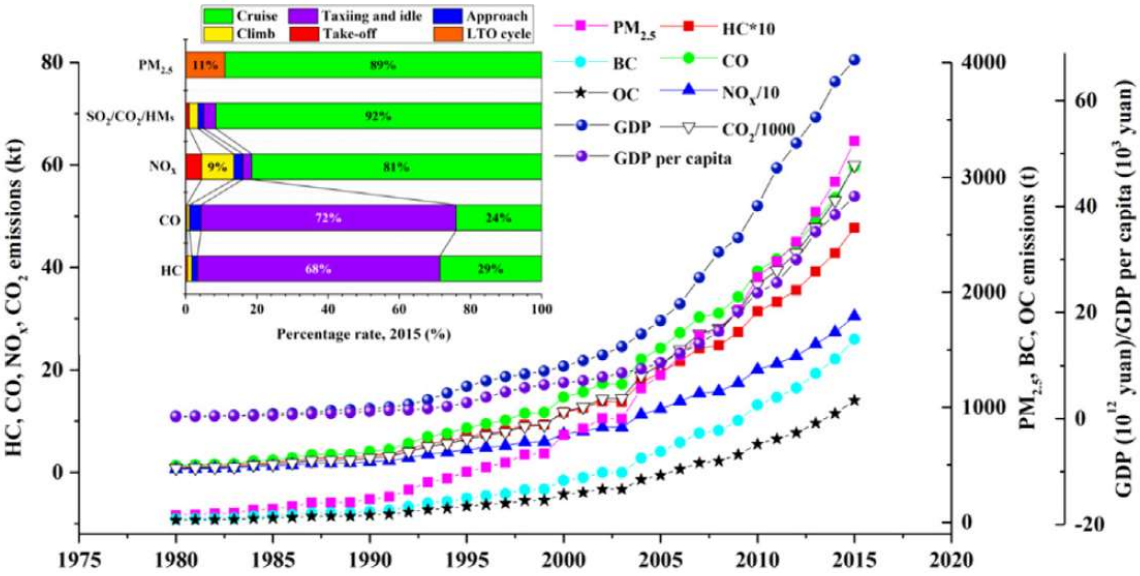


Figure 7.15 Evolution of the main commercial aviation pollutants in China domestic market and percentage of these emissions in each one of the flight phases (Source: Liu, H. et al.: Atmospheric emission inventory of multiple pollutants from civil aviation in China: Temporal trend, spatial distribution characteristics and emission features analysis. Science of the Total Environment, vol 648 pp. 871-879 (2019))

The other key climate change issue, in addition of the NOx-O3-CH4 balance mechanism, of the spatial distribution of the flights is the formation of persistent contrails and cirrus clouds that, according to the present scientific knowledge, would be the climate warming factor with the largest RF. While the formation of a contrail is relatively easy to simulate thermodynamically, if meteorological and aircraft/engine parameters are known, the persistent contrail life cycle mechanism is more complex and covers a long time. Under certain meteorological conditions ice particles are formed in the exhaust jet (timing between 0.1 and 20 seconds). They spread and downwash with the wake vortices forming behind the aircraft (see figure 7.8, in 1 to 20 minutes), make a transition into wide-spread cirrus clouds and weaken and disappear (between 1 hour and some days)

The modelization of the process by Schumann (Schumann, U.: A contrail cirrus prediction model. Geoscientific Model Development, vol. 5 pp. 543-580 (2012), known as Contrail Cirrus Prediction Tool (CoCiP) is a Lagrangian Gaussian model widely used for the forecast of contrails formation by individual flights and for aggregated evaluation of a flight program. An interesting case is the trade-off between CO2 and contrails to minimize RF in long-range routes. Figure 7.16 showed tha results of using CoCiP in a Paris-Beijing flight by Lim, Y. et al. The used weather data includes wind fields, temperature, pressure, and relative humidity with respect to water. Cruise altitude is 34,000 ft and day and night periods were considered as well, trying to avoid as much as possible areas with positive RF. This policy leads to some twisted trajectories, probably not acceptable for ATC.

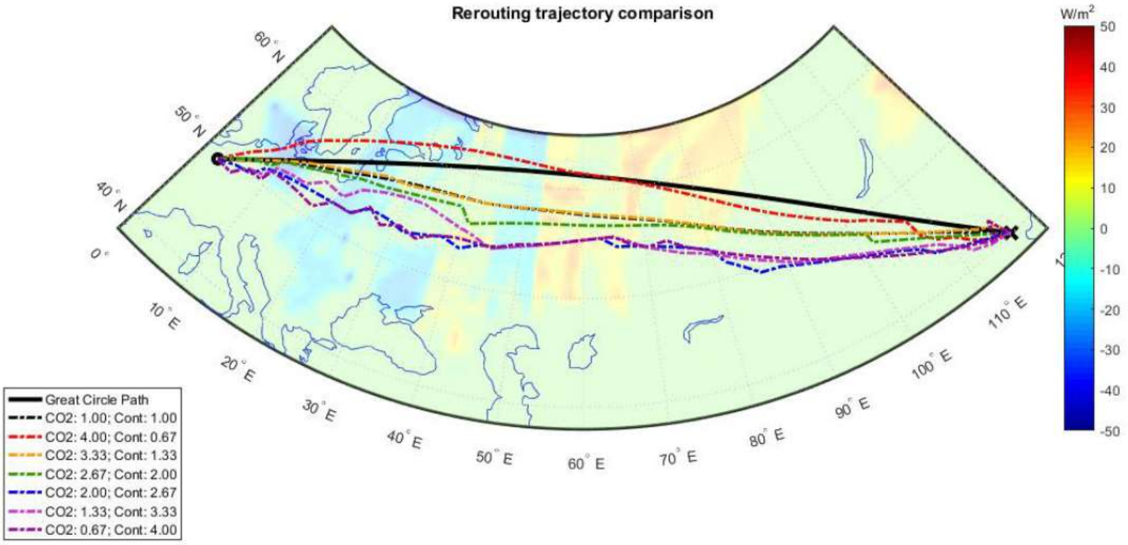


Figure 7.16 Minimum RF route optimization with different CO2 and contrails RF values (Source: Lim, Y., Gardi, A. and Sabatini, R.: Optimal aircraft trajectories to minimize the radiative impact of contrails and CO2. Energy Procedia, vol. 110 pp. 446-452 (2017))

A more complex trajectory optimisation is given by the use of a multiphase mixed integer optimal control problem (MIOCP), where several optimisation variables, like passenger travel time, fuel cost, CO2 emissions and contrail-based costs are taken into account (Soler, M., Zou, B. and Hansen, M.: Flight trajectory design in the presence of contrails: Application of a multiphase mixed-integer optimal control approach. Transportation Research Part C Emergency Technologies, vol. 48 pp. 172-194 (2014)).

The accuracy level of contrail predictions is still a matter of debate. A recent review of the state of the art (Gierens, K., Matthes, S. and Rohs S.: How well can persistent contrails be predicted? Aerospace, vol. 7 pp. 169-187 (2020)) concludes that both pure weather prediction and climate model in specified dynamics mode make reliable predictions of thermodynamic conditions for contrail formation. However relative humidity and in particular frequency and degree of ice supersaturation use to be underestimated and produce low reliability in the contrail persistence forecast. Then, up to now, the capability for estimating contrail formation along a real-world aircraft trajectory is still limited.

Deuber, O., Sigrun, M., Robert, S., Michael, P. and Ling, L: A physical metric-based framework for evaluating the climate trade-off between CO2 and contrails – The case of lowering aircraft flight trajectories. Environmental Science & Policy, vol. 25 pp.176-185 (2013) made a different approach to the problem, assuming that, for a certain flight, the reduction of climate change impact needs to have a temporal horizon, assuming that some pollutants have a shorter live. Then, an improvement of climate change impact in the short term will not have the same action pattern than the same improvement in the long term. The temporal point in which both solutions have the same effectivity value is named "turning point". Among different possible applications, the cruise flight level (long life CO2 versus shorter life contrails) is an excellent example.

2.2.2. EMISSIONS TEMPORAL DISTRIBUTION

The temporal distribution of emissions depends on several elements, most of them related with the air transport demand in the different regions:

- During the year, summer and holiday seasons attract more passengers. In the North Hemisphere, where 90% of commercial traffic is performed, this is the June-September period, with a peak mid-July to mid-August. In addition, there are some additional worldwide festivities like Christmas and some local ones like Chinese New Year, Thanksgiving in the USA, Eastern in some parts of Europe, that create additional demand. Holiday resorts with good weather in winter, like Florida, Caribbean or Maldives Islands are good examples of traffic attraction poles.
- During the week, Monday and Friday use to have more traffic in business markets and Friday to Sundays for holiday places.
- During the day, passenger traffic has peaks in early morning and mid evening, while most freight moves at night. This schedule is different in Europe and North America, where there is little passenger movement at night (many airports close), than in Asia, with much more flights in those hours.

In the previously mentioned 2006 worldwide emissions analysis (Wilkerson et al. 2010) the yearly distribution of emissions corresponds to the North Hemisphere traffic fluctuations, with initial growth in April up to a maximum in July-August and going down to a minimum in January-February. The hourly distribution depends on the adjustments to the local time, with a maximum around 15:00 UTC for North America and Europe traffic and 02:00-04:00 UTC in Asia.

Same relation between traffic and local air quality emissions appears in Copenhagen airport (Winther et al. 2000) and in South Korean 4 largest airports (Song et al. 2012). This is quite evident in China (Bo et al. 2019), where the historical emissions series has two sharp decrease moments, the first in 2002-2003, corresponding to the SARS (Severe Acute Respiratory Syndrome) epidemy, and the second to the global financial crisis in 2008-2009.

Once emitted, the pollutants may evolve in different ways, depending on the atmospheric conditions of the emission zone, The Artic region has a particular situation because more than 70% of aviation fuel emissions are in the stratosphere (Jacobson et al. 2012) that is very stable. Then, transport times of pollutants to the surface are very high and different along the year. For example, an inert pollutant emitted at 11,000 m needs 70 days in January and 40 days in July for half of it reaches the Artic surface, considering that wet removal does not happen until the particles get into the troposphere.

In the North Atlantic, data gathered in the POLINAT project (Schumann et al. 2000) show some seasonal variation in the NOx concentration and in the creation of ozone. It is relevant to note that the probability of persistent contrail creation increases in September-October due to large air masses with high degree of ice supersaturation.

The future evolution of air transport emissions has received a lot of attention with respect to CO2 but there are very few studies covering in detail the rest of contaminants, where there is still a relatively high level of scientific incertitude. In the majority of the cases, the effect of all non-CO2 pollutants on climate change is grouped in a coefficient to multiply the CO2 effect.

A relatively short-term projection of China situation (Zhou, W., Wang, T., Yu, Y., Chen, D. and Zhu, B.: Scenario analysis of CO2 emissions from China's civil aviation industry through 2030. Applied Energy, vol. 175 pp. 100-108 (2016)) was relatively pessimistic with respect to CO2 emissions. In 2015 China proposed to reduce CO2 per PKT by 60-65% with respect to 2005 level and reach a peak of emissions in 2030. The analysis showed an increase of 37% of CO2 emissions in 2030. Proposed solutions were based in an intensive introduction of SAF, lowering their prices, and a number of political planning measures like fuel tax or High Speed Train increased services.

There are very few analyses of the expected evolution of air transport emissions into the future. CO2 emissions are supposed to be adjusted to the international policies of decarbonization, what requires a zero-carbon emissions situation by 2050. A good example of this type of work is the already mentioned Liu H. et al. (2019) paper, projecting all emissions of the China domestic traffic up to the year 2050 under three scenarios: BAU (Business as Usual), SC (Strengthen Control) and MFTR (Maximum Feasible Technological Reduction). Figure 7.17 provides an idea of the differences of the three projections.

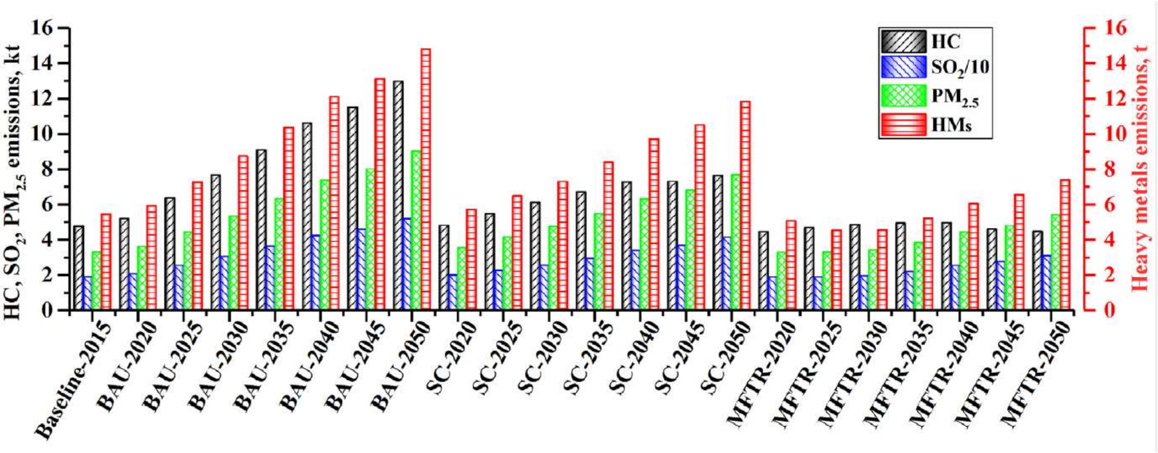


Figure 7.17 Evolution of some pollutants for the China domestic air transport market until 2050 (Source: Liu, H. et al., like Figure 7.15)

The conclusion points to that the emission reduction from the improvement of new technology (even in the MFTR scenario) between 2015 and 2050 would be largely offset by the rise in multi-pollutants emissions from air traffic growth.

2.3. DEVIATIONS AND CORRECTIVE ACTIONS

2.3.1. DESCRIPTION OF THE DEVIATION

No deviations to be reported with respect to the original project plan.

2.3.2. CORRECTIVE MEASURES IMPLEMENTED

N. A.

3. CONCLUSIONS AND NEXT STEPS

The information contained in this report provides the first input to characterize the scientific description of the impact of aviation emissions to climate change, which is the objective of the first WP of MWP7. The results of the tasks corresponding to the state-of-the-art review on aviation environment impact and the spatial and temporal distribution characteristics of aviation emissions are reported.

These results, together with the investigations on the remaining task of WP7.1, related to the Aviation emissions impact on the environment, will provide the necessary inputs to continue the work in this MWP7 and begin the next WP7.2 Development of an evaluation methodology for environmental impact, which is the work planned for the next 12 months.

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