THE REGIONAL DISTRIBUTION OF AIR TRAFFIC EMISSIONS IN THE PAST, PRESENT AND FUTURE

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ABSTRACT

The expected growth of air traffic in the future poses significant challenges regarding aviation's environmental impact. Gaseous emissions from aircraft engines influence local air quality and climate. Ambitious goals regarding improvements in terms of fuel efficiency and specific emissions have been put into place in order to reach sustainable growth of the air traffic system. The current paper presents a forecast for fuel consumption, CO_2 and NO_x emissions of global air traffic. Simulation models of future aircraft and engine types are used in combination with assumptions about traffic growth, development of the aircraft fleet and operational aspects. Methodology and results of the model will be discussed, with a focus on the regional distribution of emissions in the present and in the future.

The applied model consists of an automated chain of software modules covering engine and aircraft simulation, flight mission analysis, air traffic emissions and emissions forecasting. Aircraft models from the EUROCONTROL BADA database are used by the flight mission module, supplemented by additional models representing aircraft of the near future. The air traffic module, which is based on historical flight schedules, determines fuel burn and emissions in a "bottom-up" approach, i.e. by simulating each individual flight. Inefficiencies due to Air Traffic Management (ATM) are accounted for. A forecast module predicts future emissions based on flight movements for a base year, regional traffic growth and simulation models of future aircraft types. The forecast model includes a fleet rollover simulation, which accounts for the retirement of old aircraft and the introduction of new aircraft into the fleet. Three-dimensional inventories of emissions have been created by linking the model to specialized software available at DLR.

Results can be used to assess the environmental footprint of aviation and its potential impact on climate. The results presented in this paper cover fuel burn and emissions of scheduled air traffic for the years 2000 until 2010 and a forecast of emissions until the year 2030. In addition, evaluations by world region are performed, showing e.g. the impact of the above-average traffic growth in Asia compared to lower growth rates for Europe and the US. Results are validated against reference data including simulation results from ICAO and international research projects.

1. ABBREVIATIONS

AAGR	Average Annual Growth Rate
ACFT	Aircraft
AEDT	Aviation Environment Design Tool
ASK	Available Seat-Kilometres
ATM	Air Traffic Management
BADA	Base of Aircraft Data (by EUROCONTROL)
BPR	Bypass Ratio
CANSO	Civil Air Navigation Services Organisation
CO_2	Carbon Dioxide
DLR	German Aerospace Center
FAA	Federal Aviation Administration
FOI	Swedish Defence Research Agency
FTKT	Freight Tonne-Kilometres Transported
GDP	Gross Domestic Product
GMF	Global Market Forecast (by Airbus)
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ISA	International Standard Atmosphere
NO_x	Nitric Oxides
OAG	Official Airline Guide
OPR	Overall Pressure Ratio
RPK	Revenue Passenger-Kilometres
RTK	Revenue Tonne-Kilometres (including passengers and/or freight)
RQL	Rich-Burn / Quick-Mix / Lean-Burn Technology
SC	Successor
SQL	Structured Query Language
TAPS	Twin Annular Premixing Swirler
TKO	Tonne Kilometres Offered
TFS	Traffic by Flight Stage
4D RACE	4-Dimensional Distribution of Aircraft Emissions

2. INTRODUCTION

As air traffic is increasing, gaseous and particulate emissions of aircraft engines are increasingly in the focus of governments and the public. Local air quality around airports and particularly the influence of aircraft emissions on global warming are topics of general interest.

Jet and turboprop engines of large transport aircraft burn hydrocarbon fuel with air, resulting in the production of carbon dioxide (CO_2) and water vapour (H_2O). Additional products of non-ideal combustion include nitric oxides (NO_x) and soot (see Figure 1). While CO_2 and H_2O are greenhouse gases and contribute directly to global warming, aircraft NO_x emissions were found to indirectly affect climate by their influence on atmospheric ozone and methane concentrations [24], [25]. Additional contributions to global warming result from aircraft-produced contrails and the influence of emitted particles on the formation of cirrus clouds [24], [25], [34].

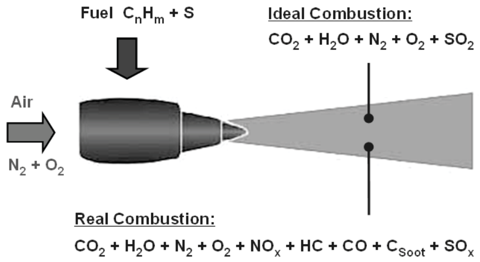

FIG 1: Emissions of an aircraft engine [24]

Commercial air traffic has increased by 5% per year in the last decades [21] and similar growth rates are expected for the next 20 years, according to forecasts by Airbus [2] and Boeing [6]. It is difficult to compensate such growth rates by technological improvements. Ambitious goals regarding future aviation emissions have been set by the airline industry and international policy makers. The International Air Transport Association (IATA) targets an annual improvement of fuel efficiency of 1.5% until 2020, carbon-neutral growth from 2020 onwards and a reduction of aviation's greenhouse gas emissions in 2050 to half the levels of 2005 [16]. Similarly, the "FlightPath 2050" published by the European Commission aims at a 75% reduction of aircraft CO_2 emissions and a 90% reduction of NO_x emissions per passenger-kilometre in 2050, compared to technology of the year 2000 [13].

Potential to improve fuel efficiency and specific emissions by means of technology exists: Since the early days of commercial jet aircraft in the 1960s, fuel efficiency of transport aircraft has improved by 50-70%, depending on metrics and reference [24], [28]. However, as technology has matured, further "step changes" become more difficult to achieve. Improved aerodynamics (e.g. by laminar flow control), more advanced engines with higher bypass and pressure ratios and the introduction of improved and lighter materials are expected to deliver further efficiency increase in the near-term and medium-term future [17]. New combustor technologies like TAPS or improved RQL enable a further reduction of NO_x emissions.

While it is difficult to forecast the availability of new technologies and their influence on emissions on aircraft level, effects on fleet level are even more challenging to assess, as these are influenced by a large number of parameters: Future traffic growth, the age structure of the fleet and the average retirement age influence the demand for new aircraft and hence the introduction of up-to-date technology into the worldwide fleet. In the current paper, a consistent forecast of air traffic, fleet composition and emissions until the year 2030 is presented. The simulation model applied for this purpose and the main assumptions are described in chapter 3. Model results will be presented in chapter 4.

3. MODEL DESCRIPTION

3.1. Overview

The simulation model consists of software modules and databases for aircraft and engine simulation, flight mission simulation, emissions of worldwide traffic and the emissions forecast. The model, which has been developed at the DLR Institute of Propulsion Technology, is described in detail in [32]. Fuel consumption and NO_x emissions of air traffic are calculated in a bottom-up approach, i.e. calculations are performed for each flight in a flight movements database (and emissions can be summed up for further analysis). For the forecast, traffic growth and fleet rollover are simulated in a year-by-year process based on information from the Airbus Global Market Forecast (GMF) [2]. Simulation models for aircraft and engine types of the present and the near future are applied in order to simulate the forecasted traffic and calculate its emissions. Further assumptions are made regarding load factor changes and improvement of Air Traffic Management (ATM). A summary of methodology and assumptions are presented in the following sections.

3.2. Air Traffic Emissions Module

The Air Traffic Emissions Module aims at estimating fuel consumption and emissions of historical air traffic. Information is stored in a flight movements and emissions database, which is based on monthly flight schedules from the Official Airline Guide (OAG) [27]. These flight plans, which contain all scheduled flight movements worldwide, include most passenger flights supplemented by a number of (scheduled) cargo flights. OAG schedules covering the years 2000 until 2010 are used for this study. Airport-pairs, departure and arrival times, aircraft types and aircraft capacities are given by OAG, while load factor information for each flight are supplemented from various ICAO statistics [23], providing seat load factor and weight load factor by flight stage, airline or world region. The ICAO Traffic-by-Flightstage (TFS) data is used as the preferred data source for load factors, while more aggregated information (by airline or world region) is used if TFS information is not available for a particular connection.

While OAG includes the aircraft type and aircraft version of each flight, engine types are required for emissions calculation and are assigned stochastically to each flight, based on aircraft- and airline-specific statistics from the ASCEND fleets database [3]. Fuel consumption is calculated by DLR's aircraft performance software VarMission [32]. The software uses models from the EUROCONTROL BADA database [12] in order to calculate fuel burn along a trajectory between departure and arrival airports. For simplicity, great-circle routes, ISA atmospheric conditions with no wind, aircraft-specific cruise altitudes and typical reserve fuel policies are assumed for flight mission simulation. Emissions of NO_x are calculated by the DLR fuel flow correlation method [10], based on reference emissions from the ICAO engine emissions databank for jet engines [18] and the FOI database for turboprop engines [37]. In a post-processing step, inefficiencies due to ATM and the additional fuel and emissions resulting from these inefficiencies are estimated. Details regarding the treatment of ATM efficiency are provided later in section 3.3.5.

The three-dimensional distribution of emissions around the globe (with an additional time coordinate) is stored in a MySQL database using software named 4D RACE, which has been developed at the DLR Institute of Air Transport and Airport Research. The figures which visualize the regional distribution of emissions presented in section 4.4 are based on information from this database.

3.3. Air Traffic Emissions Forecast Module

In a year-by-year simulation, the Air Traffic Emissions Forecast Module converts the flight movements and emissions database of a base year to an equivalent database for a forecast year. Flight movements of 2010 are used as the base year data for this study. Traffic growth and load factor changes are simulated in a first step of the forecast, while fleet rollover is simulated in the following step. Emissions for each flight are estimated by the VarMission software, based on simulation models for selected aircraft and engine types of the near future.

3.3.1. Simulation of Traffic Growth

The Airbus Global Market Forecast (GMF) 2011-2030 [2], [7] provides average annual traffic growth rates for the forecast model, specified separately for different time periods and world regions (see Table 1). These growth rates apply to the transport performance measured in revenue passenger-kilometres (RPK). As cargo traffic is not covered by the GMF 2011-2030, regional growth rates for freight tonne-kilometres transported (FTKT) are obtained from the previous edition of the GMF [1].

From	To	Dom / Int*	2011-2015	2016-2020	2021-2030
Western Europe	Western Europe	D	2.7%	2.9%	2.7%
Western Europe	Western Europe	I	3.8%	3.4%	2.8%
Western Europe	Central Europe		7.3%	6.2%	4.7%
Western Europe	Russia		5.8%	5.0%	4.4%
Western Europe	China		7.4%	6.5%	5.4%
Western Europe	Japan		2.0%	3.5%	2.8%
Western Europe	Indian Sub		7.9%	5.8%	5.7%
Western Europe	Asia		5.3%	4.5%	3.8%
**** Marker for domestic (D) or international (I) traffic***					

TAB 1: Excerpt of annual growth rates for RPK [2], [7]

Growth rates for passenger traffic are applied as a factor onto the monthly frequencies of passenger flights. Region and country codes for departure and arrival airports provided in the OAG schedules are used to identify the most appropriate growth rate for each flight. A slightly modified approach is taken for cargo flights: Growth rates for FTKT are typically similar or slightly larger than for RPK, and refer to freight transported on passenger flights as well as on flights by cargo aircraft. Consequently, traffic growth for passenger flights (including belly cargo) is simulated first, while cargo-only flights are considered in a second step. For each region-pair, a frequency correction factor is calculated for cargo flights such that the forecasted growth in terms of total FTKT is met.

3.3.2. Assumptions on Load Factors

Given an increasing trend for load factors in the past, a moderate improvement of load factors is assumed until the year 2030. For 2010, the average seat load factor obtained from ICAO statistics [23] is 78% and the average weight load factor (including passenger and freight) amounts to 65%. Until 2030, these average load factors are assumed to increase linearly to 81% and 68% respectively. After simulating traffic growth by increasing flight frequencies, another frequency correction is applied to each flight in order to reflect a load factor change over time: The load factor and hence the payload of each flight is increased annually while, at the same time, the flight's monthly frequency is decreased such that the transport performance in RPK (or FTKT for cargo flights) remains unchanged. The moderate increase of load factors assumed until 2030 is consistent with the 80% average seat load factor predicted for the year 2025 in the ICAO Outlook for Air Transport [19].

3.3.3. Simulation of Fleet Rollover

The fleet rollover includes the retirement of old aircraft and the introduction of new aircraft and is simulated year by year until 2030. The basic assumption used here is the proportionality between the number of active aircraft of a certain type and the type's transport performance in the flight schedules measured in tonne-kilometres offered (TKO). This implies constant (or similar) aircraft utilization over time. For the base year 2010, the number of active aircraft by build year are obtained from the ASCEND fleets database [3] while the corresponding TKO are obtained from the flight movements database. The age distribution of the fleet can be linked to the flight schedule by stochastically assigning an aircraft build year to each flight, using airline- and aircraft type-specific fleet statistics and considering the aforementioned proportionality. Given this information and typical lifetime assumptions for aircraft, retirements in each forecast year can be modeled.

Retirement curves describe the lifetime of an aircraft or, more exactly, the "survival" percentage as function of aircraft age. Such curves have been developed for three aircraft categories, based on historical statistics from ASCEND [3]. These retirement curves are shown in Figure 2 and are applied for the majority of aircraft types in the model. Deviations from these curves are made for some older aircraft types, if fleet statistics for a particular type show a different trend than obtained from the (averaged) retirement curve. A further simplification is made for cargo aircraft: A constant lifetime of 30 years is assumed for widebody freighters and 25 years for narrowbody freighters, based on evaluations of ASCEND statistics [3].

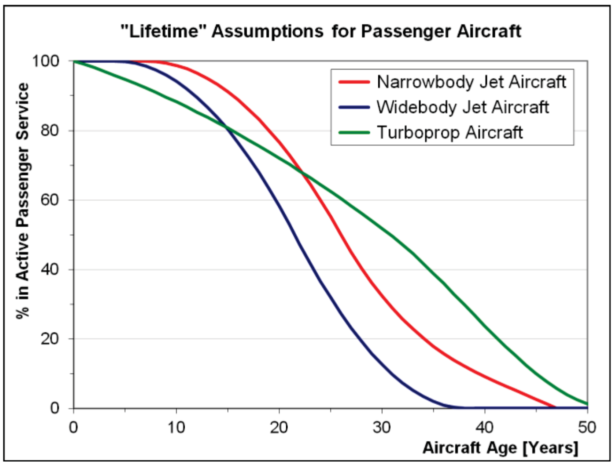

FIG 2: Retirement curves for the fleet forecast

Given the retirement number by aircraft type, the number of aircraft that are still active in the following year and hence the TKO that can be covered by the base year aircraft fleet is known. The remaining transport performance that is predicted needs to be covered by newly delivered aircraft, assuming that no constraints limit the manufacturers' production capacities.

In an iterative process, flights which need to have a new aircraft assigned are selected and have their aircraft type replaced. The new aircraft type is chosen amongst all types that are in production in the year of the forecast. The aircraft assignment algorithm aims at selecting replacement aircraft of similar size and range as the base year type, but considers a target size distribution of newly delivered aircraft, which is specified as input to the model. For the forecast presented here, the relative number of deliveries by size category is based on a combination of market forecasts by Airbus (for large transport aircraft) [2] and Embraer [11] (for regional aircraft) that is shown in Figure 3. A correction of the monthly flight frequencies is performed if the original aircraft is replaced by an aircraft with a different capacity. The correction factor is chosen such that the product of the number of available seats (or the freight capacity for cargo flights) and the flight frequency remains unchanged for the affected connection.

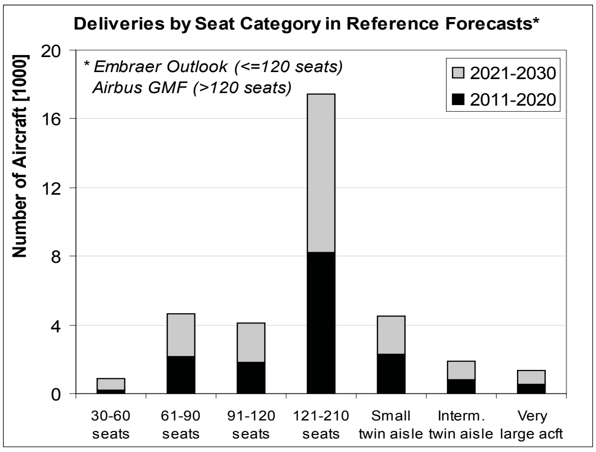

FIG 3: Deliveries by seat category in reference forecasts

All major transport aircraft types that are introduced in the near future are considered in the forecast, including e.g. the Airbus A350XWB, the Boeing 787 and a major upgrade of the Boeing 777 family assumed to be delivered around the year 2020. The Airbus A320 NEO and Boeing 737 MAX families as well as the Bombardier C-Series and the Mitsubishi MRJ are the most important new aircraft in the narrowbody and regional aircraft segments. Entry into service and production periods of all aircraft types correspond to current plans by the manufacturers, supplemented by assumptions for aircraft of the more distant future. Similarly, market shares between competing aircraft types reflect current order backlogs or are assumed to be equally split between major manufacturers.

3.3.4. Aircraft and Engine Simulation

More than 100 aircraft models from the BADA database v3.9 [12] are used in combination with DLR's VarMission flight simulation module [32] in order to calculate fuel consumption and emissions of historical air traffic. For the forecast, influential aircraft types of the near future were selected and modeled at DLR. These models are based on publicly available information regarding characteristic weights (e.g. empty weight and MTOW) and aerodynamics (drag polars) in combination with thermodynamic engine models developed at DLR [29]. Parameters for which no information was found in literature were estimated by use of aircraft predesign methods [31]. DLR's VarCycle engine simulation is applied for engine performance modeling. This way, total energy models of the Boeing 787-8 and 747-8, Airbus A350XWB-900, A320 NEO family and a generic regional jet similar to the MRJ90ER have been developed.

Engine emissions of NO_x are modeled by use of the DLR fuel flow correlation method [10], except for the GEnx engine with TAPS combustor technology, for which a modified p_3T_3 approach was chosen. The GEnx engine model is one of two engine options simulated for the 787-8 and is also used for the 747-8. Plausibility checks regarding the new models' fuel consumption and emissions have been performed by comparison of results on flight mission level with reference data or statements by the aircraft manufacturers. More information on the aircraft models and corresponding mission-level results are provided in a detailed model description [32].

The limited number of simulation models for future aircraft types requires simplifications when forecasting fleet-wide emissions. Similar to the approach for historical air traffic, each individual flight of the forecasted traffic is simulated, using the aforementioned aircraft models as representative aircraft. Simplifying assumptions shown in Table 2 are used for aircraft types, for which no detailed performance model was available.

Aircraft type (seats)	Representative model	Assumptions for aircraft representation
737 MAX 7/8/9	A319/320/321 NEO*	equal CO_2 and NO_x per kg payload
787-9	787-8	equal CO_2 and NO_x per kg payload
A350-800/1000	A350-900	equal CO_2 and NO_x per kg payload (PL)
777-200/300 Successor (SC)	A350-900	equal CO_2 per PL, -30% NO_x per PL**
E-Jet SC (98)	Generic RJ (~ MRJ-90ER)	equal CO_2 per PL, -30% NO_x per PL**
CRJ SC (90)		
CRJ & E-Jet Successor (70)	E170 (BADA)	-20% CO_2 and NO_x per PL
ERJ SC (50)	E145 (BADA)	-25% CO_2 and NO_x per PL
Future TP (90)	ATR 72 (BADA)	-25% CO_2 and NO_x per PL
ATR & DHC Successor (70)	ATR 42 / 72 (BADA)	-20% CO_2 and NO_x per PL

** LeapX engine option ** Assuming TAPS technology*

TAB 2: Assumptions for selected new aircraft types

Based on the simulation of the GEnx engine with TAPS combustor, a 30% improvement of NO_x emissions on flight mission level was estimated for this technology compared to RQL combustors of the same technology level. These results are reflected in the assumptions shown in Table 2. Modern engines with RQL combustor are assumed to be equipped with improved low-NO_x technology from 2020 onwards. New engine revisions are assumed to be introduced on newly delivered aircraft, as is shown in Table 3.

Engine	Aircraft	EIS improved combustor	Assumed effect of improved combustor
Trent 1000	B787	2020	NO_x as for GEnx
Trent XWB	A350	2022	-30% NO_x
Trent 900	A380	2024	-30% NO_x
GP 7200	A380	2026	-30% NO_x

TAB 3: Assumptions for new engine revisions

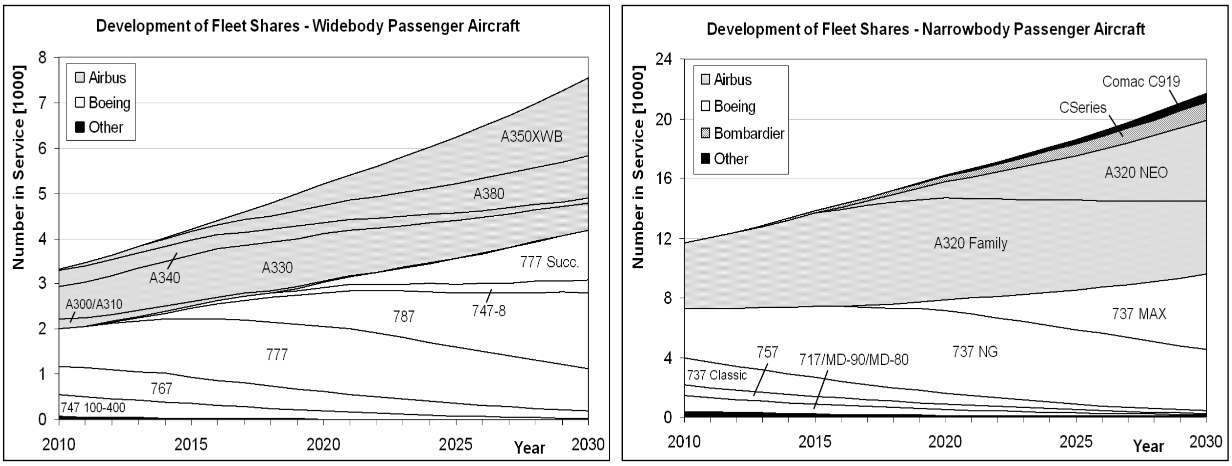

FIG 4: Results of fleet forecast for widebody aircraft (left) and single-aisle aircraft (right) by aircraft family

3.3.5. Assumptions on ATM Efficiency

The efficiency of the Air Traffic Management (ATM) system is considered in a simplified approach suggested by CANSO [9]. By definition, 100% ATM efficiency assumes ideal trajectories and cruise altitudes, as requested by the airlines, while efficiency below 100% implies additional fuel burn compared to ideal conditions due to ATM measures. A system-wide ATM efficiency of 93% was estimated as global average for the year 2010 [9], implying an inefficiency of 7% and an equal percentage of additional fuel burn. In accordance with current goals by CANSO [9], ATM efficiency is assumed to increase to 95% by the year 2030.

4. FORECAST RESULTS

4.1. Overview on results

Section 4 provides an overview on the emissions forecast by discussing results for global air traffic and the regional distribution of traffic and emissions. Global results are summarized in Table 4. The table shows the number of flights, revenue passenger kilometres (RPK) and revenue tonne-kilometres (RTK) as well as fuel consumption and NO_x emissions from the year 2000 until 2030. RTK include both passenger transport and freight transport. For hydrocarbon fuels like JET A-1, emissions of CO_2 are proportional to fuel consumption with a constant emission index of 3156 gram CO_2 per kg fuel [30].

Tabulated values for 2000-2010 are based on flights contained in the OAG schedules [27]. The coverage of traffic in terms of RPK and RTK for the year 2010 is within 3-6% of comparable ICAO statistics [21]. However, an incomplete coverage of cargo-only flights must be expected in both the OAG and the statistics by ICAO [32].

Year	Flights $[10^6]$	RPK $[10^{12}$ Pkm$]$	RTK $[10^9$ tkm$]$	Fuel $[10^9$ kg$]$	NO_x $[10^9$ kg$]$
2000	27.6	3.25	412	155	1.95
2005	28.4	3.92	495	168	2.14
2010	30.5	4.95	603	188	2.47
2015	38.1	6.59	801	241	3.20
2020	46.2	8.38	1032	293	3.89
2025	54.2	10.33	1301	344	4.43
2030	64.1	12.74	1640	405	4.96

TAB 4: Scheduled air traffic from 2000 until 2030

The traffic growth from 2010 until 2030 reflects the input assumptions to the model: Traffic growth rates from the Airbus GMF [1], [2] are used for the forecast, as described in section 3.3.1. As can be seen from Table 4, fuel consumption and NO_x emissions grow significantly slower than RPK and RTK, mainly due to the introduction of more modern aircraft into the fleet.

4.2. Fleet Composition

Newly delivered aircraft are assumed to replace old aircraft that are retired and additionally cover traffic growth. Fleet composition and its development over time are shown in Figure 4. The left diagram focuses on widebody aircraft while the right diagram shows the development of the narrowbody fleet. Regional jets and turboprops are also considered by the model, but have a much smaller influence on global emissions than larger aircraft with more range. As a consequence, these fleet segments will not be discussed in detail.

The widebody fleet in the year 2010 is dominated by the Boeing 767 and 777 families as well as the Airbus A330 and A340. New aircraft families introduced in the first decade of the forecast include the Boeing 787 and the Airbus A350XWB, while the 777 family retains a considerable fleet share until 2030. In 2020, a major update of the 777 family is assumed to be introduced, which will cover a considerable fraction of total traffic by 2030. Similarly, the number of very large aircraft like the A380 is increasing. In the narrowbody segment, A320 NEO and Boeing 737 MAX families are introduced in the second half of the current decade. Bombardier CSeries and Comac C919 are assumed to take over smaller shares of the narrowbody market while older aircraft types are gradually phased out.

As was described in section 3.3.3, the distribution of newly delivered aircraft amongst the seat categories follows the Airbus GMF [2] for aircraft above 120 seats and the Embraer Market Outlook [11] for smaller aircraft: The relative delivery numbers by seat category from these reference forecasts are input parameters to the model, while the absolute number of deliveries is a result of the forecast, as it depends on the demand for air traffic and the yearly number of retired aircraft. It is worth noting that the total number of deliveries calculated for the period 2011-2030 is within 3% of the number of new aircraft predicted in the reference forecasts (see Figure 3).

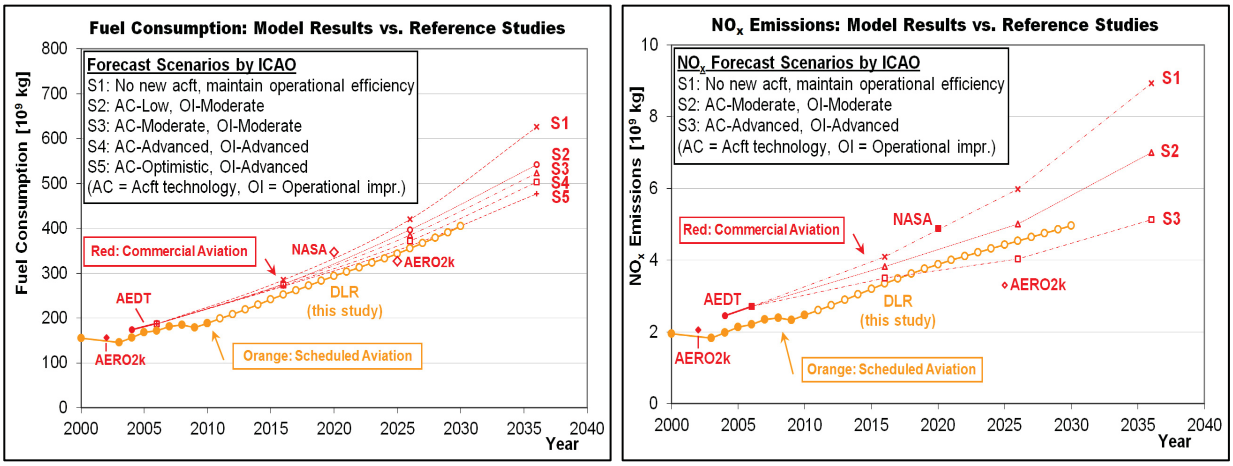

FIG 5: Development of fuel consumption and NO_x emissions until the year 2030

4.3. Global Fuel Burn and Emissions

Figure 5 shows the development of fuel consumption and NO_x emissions from 2000 until 2030[1]. Results from reference studies are included in the diagrams. As can be seen in the left chart, the fuel consumption calculated for historical air traffic until 2010 is slightly lower than results from AEDT [38] and the Aero2k [14] project. The effects of the economic crises after 2001 and 2008 are visible in the diagrams. The delta between the AEDT calculations and fuel burn from the current study amounts to approximately 9% and can be attributed to the more complete coverage of commercial aviation in the AEDT: The current study is restricted to scheduled air traffic, while Aero2k and AEDT use ATC radar data for the US and Europe, supplemented by flight schedules for other continents [38], [14]. The forecast until 2030 is between older predictions by NASA [36] for 2020 and Aero2k [14] for 2025. Different assumptions on traffic growth and technology development explain these deviations. The increase in fuel consumption predicted here resembles the ICAO S1 or S2 scenarios [22] in early years of the forecast, whereas from 2020 onwards the development is more similar to the S3 scenario [22]. The average improvement of fuel efficiency measured in fuel consumption per RTK amounts to 1.18% p.a. for the period 2011-2030, with slightly lower values in the first decade and a higher improvement from 2020 onwards. The fleet rollover delivers the largest contribution to the efficiency improvement (around 0.76% p.a.), while the remaining contributors are increasing load factors (0.16% p.a.), improvement of ATM efficiency (0.1% p.a.), a trend towards longer flight distances and the above-average growth of the cargo segment (0.15% p.a.).

The right diagram of Figure 5 shows results for global NO_x emissions. The comparably large delta between the current calculations compared to AEDT results [38] for 2004-2006 are due to the different coverage of air traffic mentioned above in combination with different calculation methods for NO_x: The current study (and Aero2k) use the DLR fuel flow correlation [10] for NO_x calculation, while the Boeing fuel flow correlation [5] is used in the AEDT, ICAO and NASA studies. The Boeing method was found to deliver higher NO_x emissions on average than the DLR method [32]. Lower traffic growth and more optimistic technology assumptions lead to significantly lower NO_x emissions in the Aero2k forecast for 2025 [14]. The NO_x forecast from this study resembles the ICAO scenario S1 [20] in the first decade of the forecast, whereas in the second decade the predicted increase is more similar to the S2 scenario [20]. The lower increase of NO_x emissions from 2020 until 2030 is mainly due to the wide-scale introduction of low-NO_x combustors assumed for this forecast, as described earlier in section 3.3.4.

4.4. The Regional Distribution of Emissions

Air traffic and its growth rates are closely linked to the development of the GDP and differ by world region. According to the Airbus GMF [2], which provides annual traffic growth rates for the simulation, the highest relative growth is expected for Asia and the Middle East. Figure 6 evaluates the transport performance in passenger-kilometres by world region. As can be seen from the figure, traffic in Asia and the Middle East will more than triple between 2010 and 2030. North American traffic, on the other hand, is forecasted to grow by a factor of 1.9 only, the lowest traffic growth amongst the world regions considered here.

Worldwide traffic flows are visualized in Figure 7, showing the distribution of RPKs between and within the world regions. Only those relations with a transport performance of more than 0.05% of the total RPKs in the year 2000 are shown in the figure. The above-average growth of traffic in Asia and the Middle East is clearly visible.

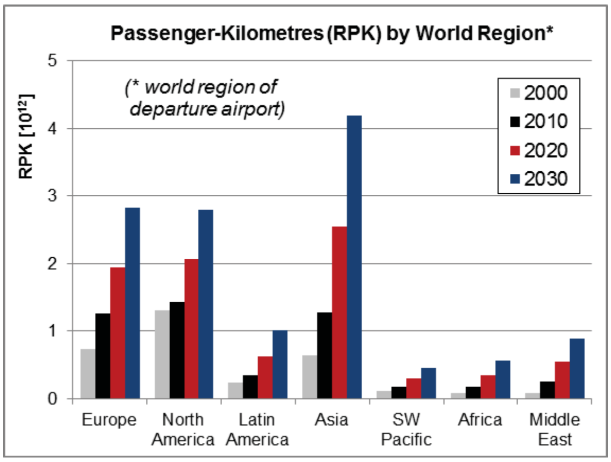

FIG 6: Development of RPKs by region

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[1] No calculations are available for 2001-2002, as OAG flight schedules for these years were not available for this study.

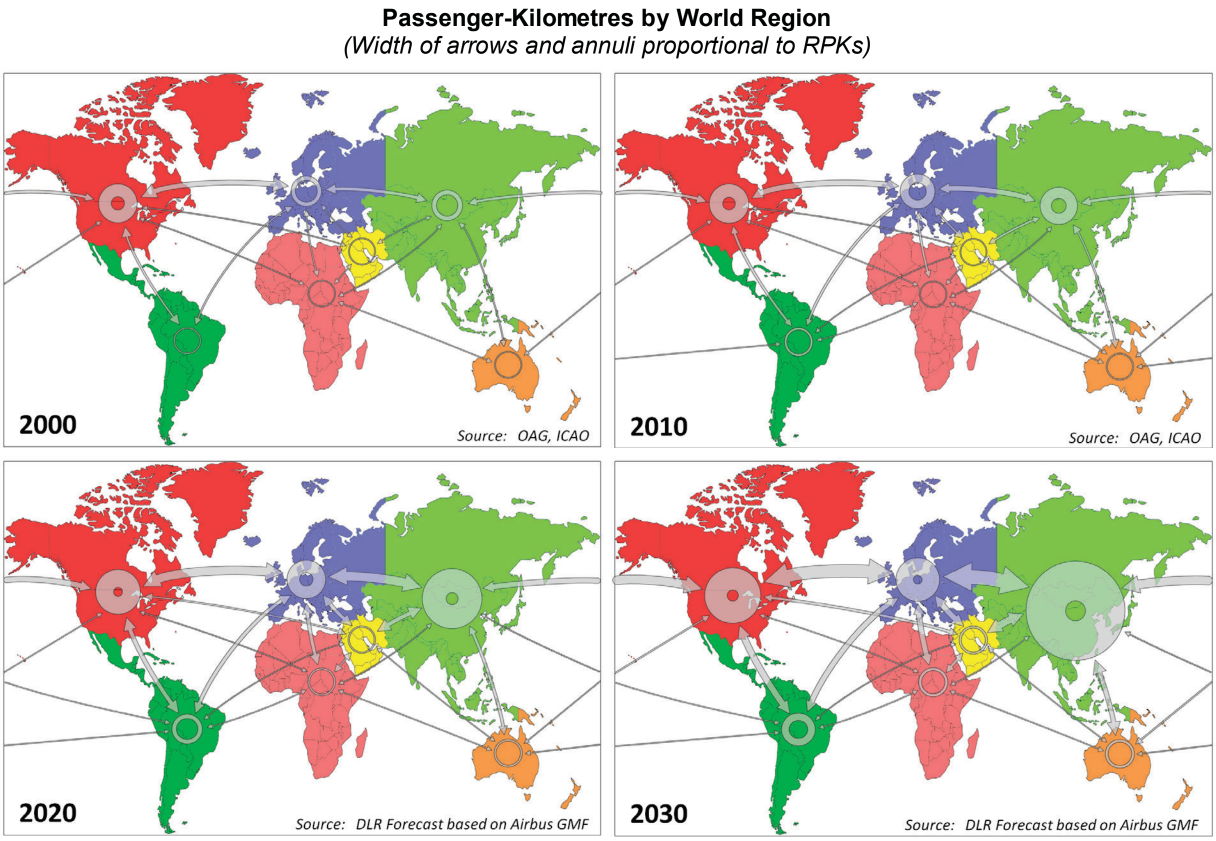

FIG 7: Undirectional passenger traffic within and between world regions from 2000 until 2030

Intra-regional growth rates are higher for Asia than the growth rates for traffic from and to this continent: Intra-Asian traffic is forecasted to grow by a factor of more than 3.5 between 2010 and 2030, compared to 2.8 for traffic from Asia to other world regions. The impressive traffic growth for the Middle East, on the other hand, results predominantly from traffic to and from this region.

Fuel consumption, which is proportional to CO_2 emissions, grows slower than RPKs, due to the modernization of the aircraft fleet. Figure 8 presents the model results for fuel consumption and NO_x emissions by departure region. Both charts show a continuous increase of fuel burn and emissions for all regions, with one notable exception: Between 2000 and 2010, a decrease of fuel consumption by 15% (and a decrease of NO_x by 12%) was calculated for flights departing from North America. This is attributable to a very modest growth of RPKs (+9.5%, see Figure 5), which is overcompensated by the improvement of fuel efficiency. This decrease in fuel burn is confirmed by data of the US Bureau of Transportation Statistics (BTS), which identifies a 14% reduction of fuel consumption for scheduled flights from and to the United States [8]. US traffic is responsible for more than 90% of North American traffic according to OAG [27], and showed only minor growth in terms of passengers, flights and RPKs between 2000 and 2010 [8].

Until approximately 2018, the forecasted growth of NO_x emissions is slightly higher than the growth of fuel consumption, i.e. the average emission index for NO_x measured in gram NO_x per kg fuel is increasing.

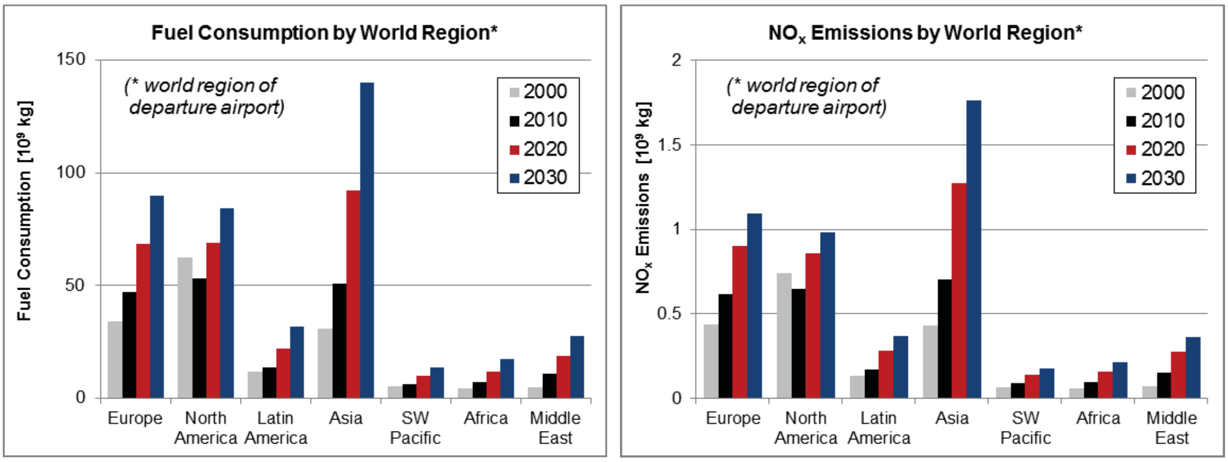

FIG 8: Development of fuel consumption and NO_x emissions by region

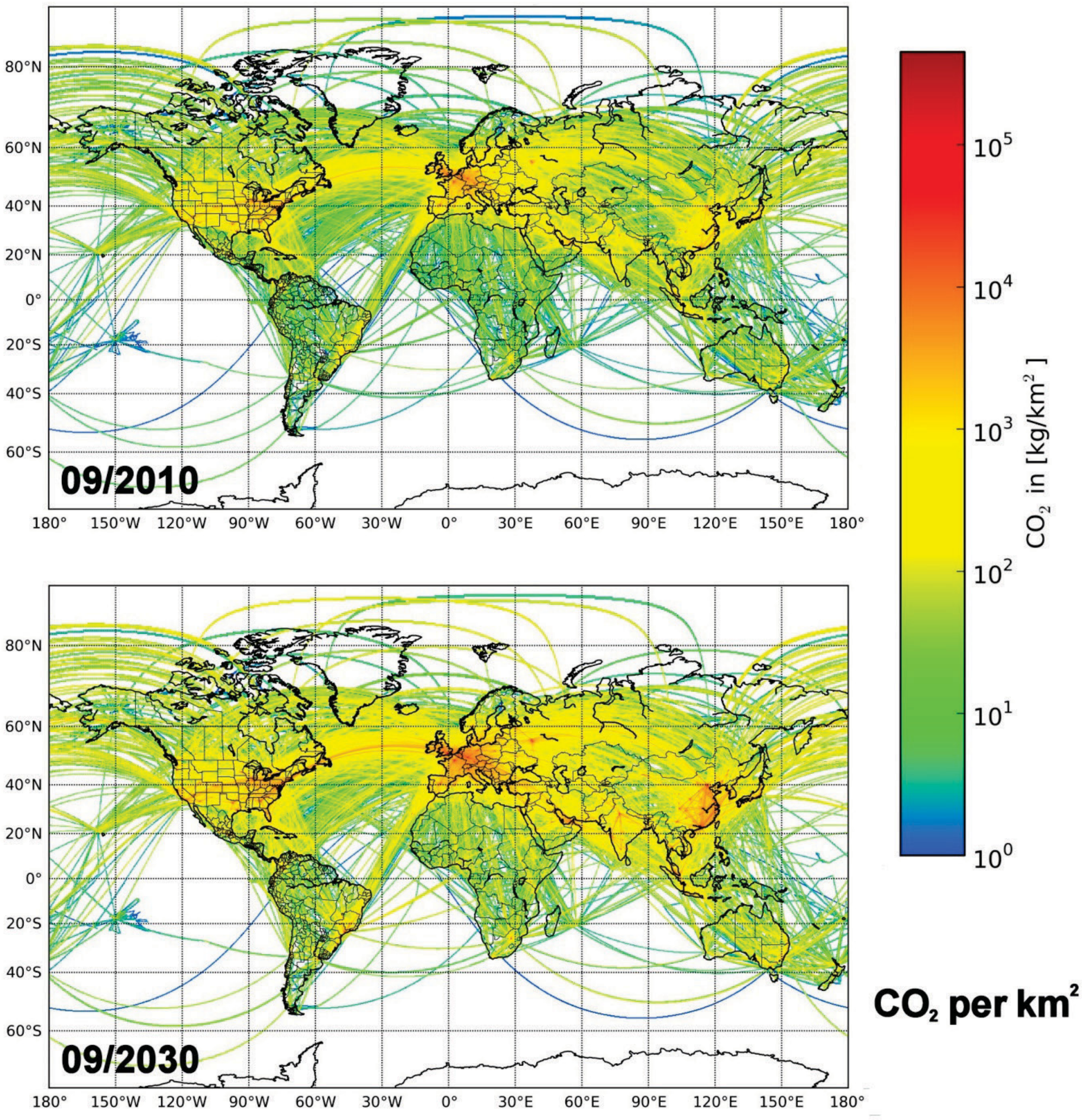

FIG 9: Distribution of scheduled aviation’s CO_2 emissions in 2010 and 2030

This can be explained by higher combustion pressures and temperatures of current-generation aircraft engines compared to their predecessors. In general, a trade-off exists between an engine’s fuel consumption and its NO_x emissions: Increasing pressures and temperatures in the combustor improve an engine’s thermal efficiency and reduce fuel consumption, but typically lead to rising NO_x output [24]. New combustor technology, e.g. lean-burn combustion, is required to enable a reduction of NO_x emissions without compromising fuel efficiency. Lean burn combustors have been introduced recently in the TAPS combustor of the GEnx engine, which is one of two engine options in service on Boeing 787 aircraft. As mentioned before, the wide-scale introduction of low-NO_x combustors assumed in the forecast from 2020 onwards leads to a slower growth of NO_x emissions (compared to RPKs or fuel consumption) between 2020 and 2030.

The regional distribution of CO_2 emissions per km² is shown in Figure 9, which presents emission inventories for September 2010 and September 2030. Due to the exponential scale used for the charts, the differences between emissions in 2010 and those of 2030 appear less obvious in Figure 9 than e.g. in Figure 8. The above-average growth of traffic in Asia, however, is clearly visible. The corresponding distribution of NO_x emissions, which (qualitatively) looks similar to the CO_2 distribution, is shown in Figure 10 on the following page.

The forecast of CO_2 and NO_x emissions presented here should be seen as an estimate of future air traffic emissions on global and regional levels. Simplifications have been made for the analysis: Most importantly, no constraints regarding airport capacities were taken into account. In addition, no new city pair connections were established during the forecast. Consequently, results from this model are not suited for analyses on city-pair or airport levels. Instead, the modeling focus was put on the fleet forecast and on consistent assumptions for emissions quantification.

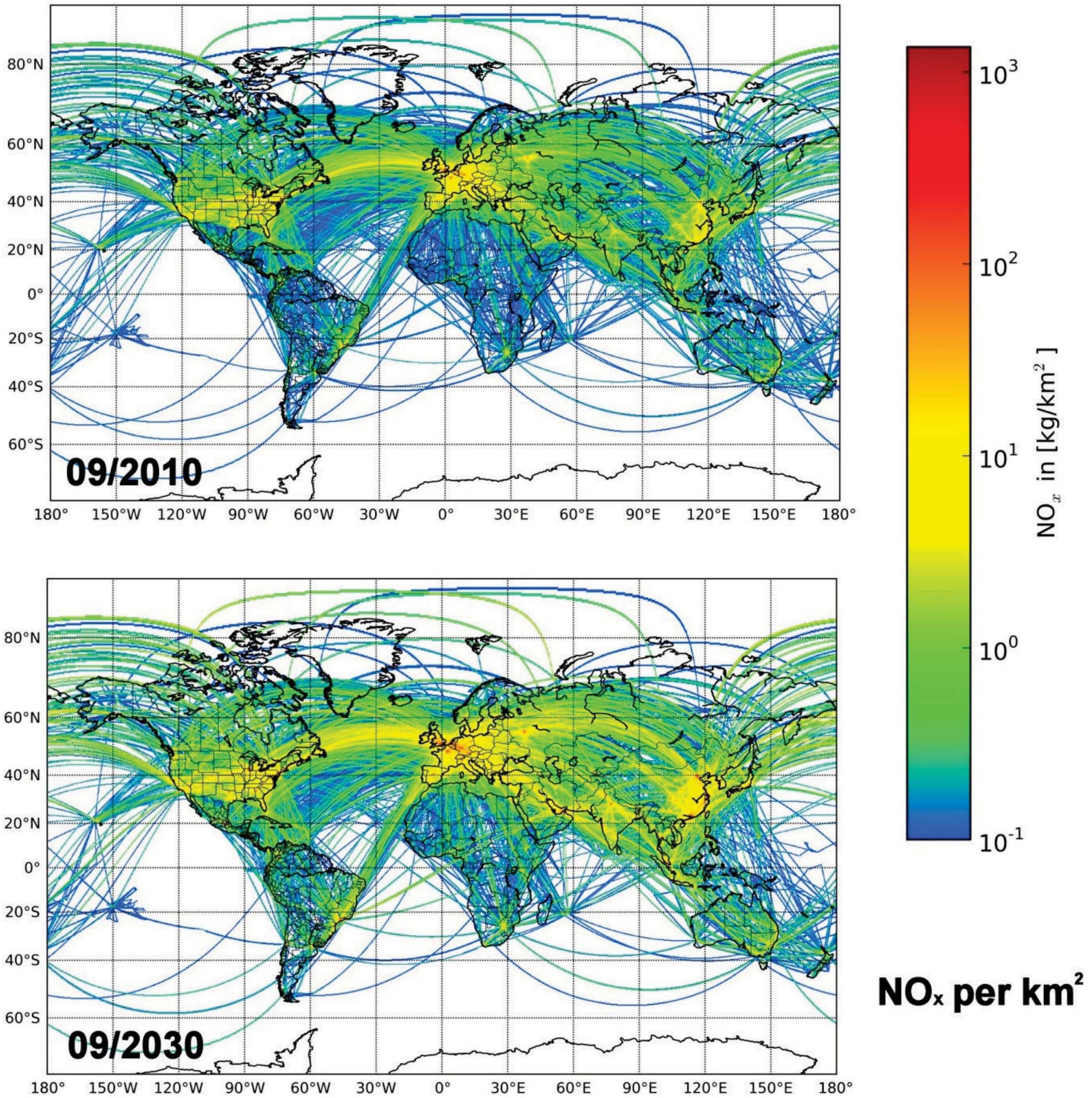

FIG 10: Distribution of scheduled aviation's NO_X emissions in 2010 and 2030

5. COMPARISON OF RESULTS TO ENVIRONMENTAL TARGETS

The growth of air traffic in the order of 5% per year makes it difficult to reduce air traffic emissions. While progress is made on the aircraft and engine sides, it cannot compensate for the high growth of RPKs predicted for the next 20 years. Ambitious goals have been set by the airline industry in order to reduce aviation's environmental footprint. Short-term and medium-term targets of the International Air Transport Association (IATA) include a 1.5% improvement of fuel efficiency per year until 2020 and carbon-neutral growth from 2020 onwards [16].

The improvement of fuel efficiency according to the forecast amounts to 1.2% p.a. on average between 2010 and 2030. The improvement is 1.0% p.a. on average in the first decade, but reaches 1.4% p.a. from 2020 until 2030. As a consequence, IATA's short-term goal of 1.5% p.a. appears ambitious, but not out of reach. The accelerated introduction of fuel-saving aircraft technology or higher load factors than assumed in the forecast may be feasible ways to achieve this target.

Carbon-neutral growth from 2020 onwards appears more challenging. Drop-in biofuels are in the focus of the airline industry, as they reduce aviation's dependency on fossil resources and enable reductions of greenhouse gas emissions from a life-cycle perspective: While CO_2 emissions from the combustion of biofuels are of similar magnitude as those of fossil fuel, CO_2 is absorbed while the feedstock required for fuel production is grown. Depending on feedstock and production process, the potential for a 40-90% reduction of equivalent life-cycle CO_2 emissions compared to fossil fuel has been identified [35]. Considering the demand for JET fuel predicted here for the year 2030, a 30-40% market share of biofuels would be required in order to limit aviation's equivalent CO_2 emissions to levels of the year 2020. The required market share is based on the (rather optimistic) assumption of biofuels with an 80% average reduction of life-cycle CO_2 emissions per energy compared to fossil JET A-1. Given the challenges for a quick ramp-up of biofuel production regarding cost-competitiveness, feedstock availability and production capacities [26], a 30% market share in 2030 appears unlikely today. If carbon-neutral growth is to be achieved at a continuous traffic growth of 5% per year, further innovation in the fields of aircraft and engine technology as well as alternative fuels are required, but need to be supplemented by economic measures. This includes options like emissions trading with other industry sectors and carbon-offset mechanisms.

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