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The global scale, distribution and growth of aviation: Implications for climate change

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ABSTRACT

Prior to the COVID-19 crisis, global air transport demand was expected to triple between 2020 and 2050. The pandemic, which reduced global air travel significantly, provides an opportunity to discuss the scale, distribution and growth of aviation until 2018, also with a view to consider the climate change implications of a return to volume growth. Industry statistics, data provided by supranational organizations, and national surveys are evaluated to develop a pre-pandemic understanding of air transport demand at global, regional, national and individual scales. Results suggest that the share of the world's population travelling by air in 2018 was 11%, with at most 4% taking international flights. Data also supports that a minor share of air travelers is responsible for a large share of warming: The percentile of the most frequent fliers – at most 1% of the world population - likely accounts for more than half of the total emissions from passenger air travel. Individual users of private aircraft can contribute to emissions of up to 7,500 t CO_2 per year. Findings are specifically relevant with regard to the insight that a large share of global aviation emissions is not covered by policy agreements.

1. Introduction

Aviation is one of the most energy-intense forms of consumption, and has in the past been characterized by strong growth, with estimates that emissions have increased by a factor 6.8 between 1960 and 2018 (Lee et al., 2020). Industry estimates prior to COVID-19 have suggested a further tripling between 2020 and 2050 (ICAO, 2016). By mid-2020, scheduled flights and revenue passenger kilometers (RPK) had declined significantly (RPK by −50%; ICAO, 2020a). Industry has since then stated to expect a rebound (IATA, 2020a), as witnessed after previous crises including the global financial crisis in 2008 (IATA, 2019). If aviation returns to a volume growth trajectory, the sector will be in a growing conflict with global decarbonization goals (Dubois et al., 2019; Larsson et al., 2019).

Against this background, the COVID-19 pandemic represents an opportunity to critically discuss air transport and aviation climate governance (Dubois et al., 2019; Gössling, 2020; Larsson et al., 2018, 2019), based on patterns of air transport demand. Available data on air transport distributions has remained scattered, but there is evidence of some countries and individuals contributing disproportionally to emissions from air transport. Further analysis of these distributions is warranted because of emerging debates of carbon inequality (Chakravarty et al., 2009; Chancel and Piketty, 2015; Hubacek et al., 2017; Ivanova and Wood, 2020), as well as airlines and air transport advocates' presentation of air travel as an ubiquitous activity, in which a large share of the world population is involved (Gössling et al., 2019). This paper provides new insights on global, regional, national and individual scales of analysis. It also discusses future growth trajectories under business-as-usual recovery scenarios, and their implications for climate change.

2. Background

2.1. Who emits greenhouse gases?

International mitigation agreements including the Kyoto Protocol and the Paris Agreement are founded on 'fairness' principles, recognizing that averaged per capita contributions to greenhouse gas emissions vary widely. Countries with high per capita emissions are expected to make greater contributions to emission reductions (UNFCCC, 2018a,

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2018b). Such ‘common but differentiated’ mitigation principles generally omit the question of production (where?) versus consumption (who?) (Hertwich and Peters, 2009; Peters, 2008), and they do not consider differences in per capita emissions *within* countries (Girod and de Haan, 2009; Munksgaard et al., 2000). Chakravarty et al. (2009: 11884) were among the first to highlight this problem, suggesting that principles for allocating mitigation responsibilities be based on those generated by “individuals, rather than nations”. It is thus of interest to further study the world’s “high-emitters”, i.e. individuals contributing disproportionally more to climate change than the “average world citizen”, (who emitted close to 5 t CO_2 per capita and year in 2014; World Bank, 2020a).

Various national studies have confirmed that high emitters are found mostly among the highly affluent (Büchs and Schnepf, 2013; Gill and Moeller, 2018; Irfany and Klasen, 2016; Ummel, 2014). Chancel and Piketty (2015) calculate that the top 10% emitters in the world account for 45% of global CO_2-eq emissions, while the bottom 50% of emitters contributed 13% (see also Hubacek et al., 2017). In a recent study of consumption in the European Union (EU), Ivanova and Wood (2020) find that the top percentile of emitters is responsible for 27% of emissions, with the top 1% of emitters exceeding annual per capita emissions of 55 t CO_2-eq. While high-emitters live in all countries, Chancel and Piketty (2015) identify the top 1% of wealthiest individuals in five countries as specifically relevant, with per capita emissions exceeding 200 t CO_2-eq per year. These high emitters are at home in the USA, with an estimated 3.16 million people exceed average annual emissions of 318 t CO_2-eq per person; Luxemburg (10,000 individuals emitting 287 t CO_2-eq/year each); Singapore (50,000 individuals, 251 t CO_2-eq/year); Saudi Arabia (290,000 individuals, 247 t CO_2-eq/year); and Canada (350,000 individuals, 204 t CO_2-eq/year). In comparison, low emitters in many parts of Africa emit a mere 0.1 t CO_2 per year (World Bank, 2020a).

While these studies indicate very significant differences in emissions between individuals, it remains unclear how differences come into existence. Frequent movement, and in particular access to private transportation, as well as multiple real estate ownership - often in different continents (Beaverstock and Faulconbridge, 2014) -, appear to be key determinants of carbon-intense consumption. As affirmed by Girod and de Haan (2009: 5655) in a Swiss household survey: “comparison of high and low emitters shows the main difference is that high emitters spend a higher amount on mobility”.

2.2. Emission distributions and air travel

It is generally established that air transport is a highly energy and emission intense activity, but there seem to exist diverse views on the distribution of demand. IATA, 2018 affirms that “the average [world] citizen flew […] once every 22 months”, giving associations of a normal distribution of flight in which the whole world is involved. However, another industry view holds that “less than 20 percent of the world’s population has ever taken a single flight […]” (former Boeing CEO David Muilenburg; CNBC, 2017). The latter would imply that the distribution of air travel is skewed toward a relatively small number of travelers, and that notions of “average world citizens” obscure that many people do not fly at all, while others are very frequent fliers.

National surveys have established that air travelers are disproportionally wealthy (e.g. Banister, 2018; Carlsson-Kanyama and Lindén, 1999), with repercussions for emissions. As Ivanova and Wood (2020: 6) conclude, “air travel is the consumption category with the highest carbon contribution among the top emitters”. Korbetis et al. (2006) found that US-households with incomes of US$75,000 or more emitted 13.74 t CO_2 per year in transport emissions, while households earning less than US$5,000 emitted 5.5 t CO_2. This affects distributions: In the UK, the 20% of the most frequent non-business travelers produced 60% of related emissions, with the contribution by the highest income groups (>£40,000 person/year) being 3.5 times greater than that of the lowest income groups (<£10,000 person/year) (Brand and Boardman, 2008; Brand and Preston, 2010). Studies also established that a share of business travelers may fly on an almost daily basis (Gössling et al., 2009), with some individuals covering vast distances: Former US Secretary of State Hillary Clinton reportedly flew 1,539,712 km, equivalent to more than 38 circumnavigations, in her four years in office (The Atlantic, 2013, referring to the US State Department). Much evidence thus supports notions of highly skewed distributions in air transport demand, with significant implications for climate change governance.

2.3. Climate policy and aviation

Averaged per capita emissions were the basis for the Kyoto Protocol (in 1997) and its consideration of Annex I countries, as well as the Paris Agreement (in 2015), with the expectation that high-emitting countries (on a per capita basis) make “fair and ambitious” contributions to emission reductions (UNFCCC, 2018a, 2018b). The Kyoto Protocol exempted international aviation and shipping from national contributions, due to their transborder and over high seas character, and assigned responsibility for “limiting or reducing” emissions from these sectors to the International Civil Aviation Organization (ICAO) and the World Maritime Organization (WMO) (UNFCCC, 2018a, 2018b). This general distribution of responsibilities has been maintained under the Paris Agreement, i.e. domestic aviation falls under national mitigation targets, while international bunkers are addressed by ICAO (ibid.).

An important omission of Kyoto Protocol and Paris Agreement is their focus on CO_2 and other long-lived greenhouse gases, ignoring aviation’s contribution to radiative forcing from short-lived emissions such as nitrous oxides (NO_x), or in the form of contrails or clouds (H_2O) (Lee et al., 2020). These non-CO_2 emissions are not directly comparable with long-lived GHG, but they do contribute to global warming (Lee and Sausen, 2000). Non-CO_2 warming is expected to remain relevant in the short and medium-term future (Bock and Burkhardt, 2019). To account for non-CO_2 warming, countries such Austria or Germany consider a warming effect of non-CO_2 that is comparable to CO_2 in national assessments of aviation impacts (Environment Agency Austria, 2018; German Environment Agency, 2018). In 2018, aviation has been estimated to account for 2.4% of anthropogenic emissions of CO_2 including land use changes (Lee et al., 2020). There is an additional warming effect related to contrail cirrus and NO_x, which is larger than the warming from CO_2, if calculated as net effective radiative forcing. Lee et al. (2020: 2) conclude that “aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO_2 emissions alone”.

3. Method

Air transport demand is analyzed at global, regional, national and individual scales. Data is presented for the situation prior to the COVID-19 pandemic, including scenarios for future demand that are based on industry projections. COVID-19 challenges all assumptions in principle, though industry expects a return to business-as-usual once the pandemic has passed and the economy stabilizes. For example, IATA (2020b) suggested in April 2020 that 60% of air travelers would “return to travel relatively quickly”. More informative are ICAO’s (2020b) scenarios that show different possible pathways to recovery. The implication for scenarios presented in the paper is that these could be delayed, even by several years, and that growth may be slower than projected if demand adjusts downwards under longer periods. The scenarios remain useful, however, in that they illustrate where aviation growth is headed in the longer run.

Global calculations of transport demand are based on data sources including Airbus (2019), Boeing (2019), IATA (2019), World Bank (2020b), and UN DESA (2020). Data provided by these sources is not always comparable. For example, IATA (2019) provides official passenger statistics for the world and world regions, while the World Bank

(2020b) makes available data for 199 individual countries (based on ICAO data that is not publicly available). Limited information is available on fuel use and emissions by subsector, i.e. commercial passenger versus freight transport, private air travel, and military operations. The share of the global population that is flying is calculated based on IATA (2019), UN DESA (2020) and national surveys (USA: Airlines for America 2018; Germany: IFD Allensbach, 2019; UK: UK Department for Transport, 2014; Taiwan: Tourism Bureau Taiwan, 2019).

Regional flight demand is assessed on the basis of industry data (IATA, 2019) as well as extrapolations of industry growth expectations (Airbus, 2019; Boeing, 2019). Data is presented for seven world regions (Africa, Asia-Pacific, Commonwealth of Independent States, Europe, Latin America, Middle-East, North America, as well as the 'Rest of the World'), and includes RPK as well as emission estimates for 2018 and 2050.

National perspectives on air transport demand and fuel use are derived from IEA (2019a), and UNFCCC (2020, for Annex I countries). Data is used to assess bunker fuel use (domestic/international) in relation to national emissions, and to determine relationships between GDP and transport demand. Nationally averaged transport demand measured in RPK per capita is based on ICCT (2019). Assessments of national transport demand need to consider allocational issues (Larsson et al., 2018). Depending on allocation principle, differences can be significant. For example, in a calculation of distances flown by the Swedish population, defined as the country's residents (national and foreign), Larsson et al. (2018) arrive at an average 5,800 km per person per year in the period 2010–2013. This includes the distances flown by Swedish residents outside Sweden. In comparison, the ICCT database suggests 3,350 RPK (in 2018) per Swedish citizen per year, based on a commercial fuel allocation principle (ICCT, 2019). Significant differences also arise out of inbound to outbound ratios (Sun and Lin, 2019). It is known that some countries are markets, while others are destinations (UNWTO, 2018), and allocation principles thus have significant implications for results. Data in this paper is based on national fuel use (UNFCCC, 2020), with the implication that for countries with outbound to inbound ratios above 1, true fuel use and emissions by these countries' residents is underestimated.

Individual perspectives on transport demand are derived from airport surveys and national travel surveys (UK Department for Transport, 2014; Airlines for America, 2018; Gössling et al., 2009, 2020; GRA Incorporated, 2018), as well as assessments of fuel use and emissions for private flight (Gössling, 2019).

4. Distribution of air transport

4.1. Global emissions from aviation

Aviation fuel use includes commercial aviation (passengers/freight), private air transport, as well as military flight. Estimates of global fuel use vary. Lee et al. (2009) concluded that global emissions from aviation may have been in the order of 733 Mt CO_2 in 2005. More recent estimates presented by IATA (2018) suggest that civil aviation - including international and domestic, passengers and freight - emitted 859 Mt CO_2 in 2017. The International Energy Agency (IEA, 2019a) specifies that the world's total aviation fuel demand was 310.56 Mt in 2017, about 60.4% of this for international aviation, and 39.6% for domestic aviation (Fig. 1). Together, commercial, private and military flight would thus have emitted 978 Mt CO_2 in 2017 (IEA, 2019a), of which, in comparison to IATA (2018) data, 87.8% would fall on commercial aviation (Fig. 1). Lee et al. (2020), also based on IEA data, extrapolate overall aviation emissions to 1,034 Mt CO_2 in 2018.

To differentiate non-commercial, i.e. military and private flight fuel use and emissions is difficult, as there is no global data for military operations. It has been suggested that military aircraft consumed 22% of US jet fuel in 2008 (Spicer et al., 2009), though a lower recent estimate for the US in absolute numbers is 18.35 Mt CO_2 (in 2017; Belcher et al., 2020). In a global estimate for 2002, Eyers et al. (2004) concluded that global military operations required 19.5 Mt of fuel, leading to emissions of 61 Mt CO_2, or 11.1% of global emissions from aviation. More recent data is not available, though given commercial air transport's strong growth over the past 20 years, it can be expected that the share of military operations in total fuel use has declined. For an estimate, the current contribution of military flight to global emissions from aviation is assumed to be 8% (Fig. 1). This estimate is uncertain, but highlights the importance of military flight in aviation emissions.

Data on private aviation is equally limited. The global business aviation market is estimated to have included 22,295 jets, 14,241 turboprops, and 19,291 turbine helicopters in 2016 (AMSTAT Market Analysis, 2018). Assuming an average of 400 h of flight time per year for the global fleet of private jets, with an estimate of a 1200 kg/hour fuel use (Gössling, 2019), jet fuel burn was 10.7 Mt in 2016, corresponding to 33.7 Mt of CO_2. Adding the fuel use of turboprops and helicopters, overall emissions from private transport may be in the order of 40 Mt CO_2. This would suggest that private aviation accounts for about 4% of global emissions from aviation (Fig. 1).

In summary, the estimate for 2018 is that global aviation burned approximately 320 Mt of fuel, and emitted one Gt CO_2, of which 88% fell on commercial aviation, 8% on military operations, and 4% on private flight. For commercial aviation, fuel use can be further divided into passenger transport (81%) and freight (19%) (ICCT, 2019). The overall distribution is shown in Fig. 1.

Fuel use and emissions associated with passenger transport are the focus of this paper. According to IATA (2019), there were 4.378 billion passengers in 2018 (international and domestic). This is not equivalent to trip numbers or individual travelers. Most air trips are symmetrical, i.e. they will involve a departure as well as a return. Apart from an unknown share of asymmetric trips (triangle flights, one-leg air trips), IATA (2019: 4) suggests that close to 4 billion passengers flew origin–destination, while 400 million moved through a hub. Assuming symmetric flight patterns, one trip through a hub will involve at least four individual flights. As ten percent of all flights involve a transfer, 4.378 billion passengers would thus represent a maximum of 1.99 billion trips. Compared to global population of 7.594 billion (UN DESA, 2020), this means that the theoretical maximum share of the world population that

Table 1
Theoretical maximum share of flying population.

	Population 2018 (million)*	Passengers 2018 (million)*	Passengers per capita of the population	Flying population (%)	Maximum flying population (million)
Low income	705	23	0.03	1.63	11
Lower middle	3,023	454	0.15	7.51	227
Upper middle	2,656	1,313	0.49	24.72	657
High income	1,210	2,442	2.02	100.00	1,210
Total	7,594	4,233			2,105

*Source: World Bank (2020b).
The "theoretical maximum" assumes that each individual participates in exactly one trip per year.

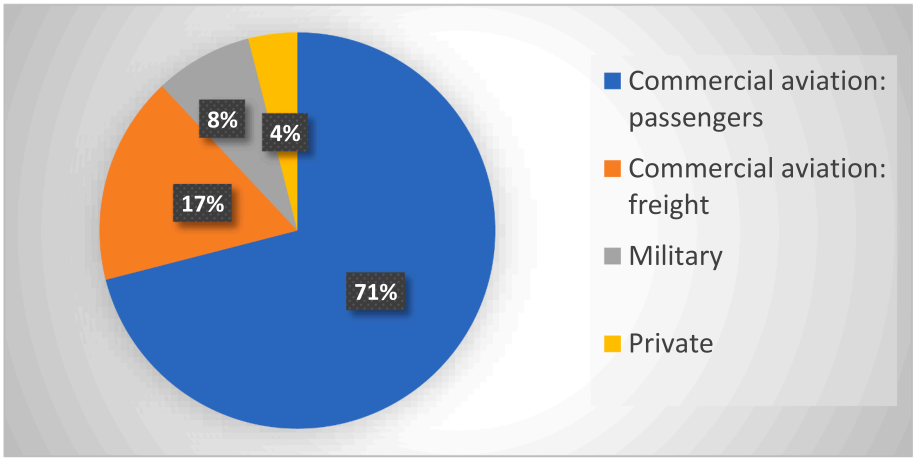

Fig. 1. Global distribution of aviation fuel use. Source: Calculation based on Eyers et al. (2004), IATA (2019), ICCT (2019), IEA (2019a).

could have participated in air travel was 26.2% in 2018 (1.99 billion trips divided by 7.594 billion people, presupposing that each individual participates in exactly one trip).

Demand is not evenly distributed throughout the world, however. Table 1 looks at distributions between countries by income group, on the basis of World Bank (2020b) statistics that consider 4.233 billion passengers in 217 countries. Comparing passenger numbers to population and wealth levels, the number of flights averaged over the population is 0.03 per person and year in low-income countries, 0.15 in lower middle-income countries, 0.49 in upper middle-income countries, and 2.02 in high income countries. The data suggests that the theoretical maximum share of the population that could have participated in air travel is 1.63% in low income countries, 7.51% in lower middle-income countries, 24.72% in upper middle-income countries, and 100% in high income countries. Only the high income countries reach 100%, because it is only in these countries that each individual in the population could have participated in at least one trip.

Distributions in Table 1 do not consider that there is a significant share of the population in every country that does not fly, while some air travelers participate in one, two, or multiple trips. For example, data for the USA suggests that 53% of the adult population do not fly (Airlines for America, 2018). In Germany, 65% of the population do not fly (IFD Allensbach, 2019), while this share is 66% in Taiwan (Tourism Bureau Taiwan, 2019). In the UK, the non-flying share of the population 16 years or older is 59% (DEFRA, 2009). These national surveys indicate that in high income countries, between 53% and 65% of the population will not fly in a given year. The share of non-fliers is likely larger in low-income, lower-middle and upper-middle income countries. For a conservative estimate, and given the lack of data for lower income countries, Table 2 assumes that the share of the population participating in air transport is 40% of the maximum of the flying population on global average (Table 2). The estimate is thus that the share of the world population that flew in 2018 is 11.1% (845 million individual air travelers divided by a world population of 7,594 million; Table 2).

The share of the global population participating in *international* air travel is even smaller, as a significant share of all air travel takes place within countries. Domestic air travel included 2.566 billion passengers in 2018, out of this 590 million in the USA, 515 million in China, and 116 million in India (IATA, 2019). International air travel consequently only comprised 1.811 billion passengers, who are also more likely to move through hubs. On the basis of the conservative assumption that one international trip comprises 2.2 flights (IATA, 2019), some 823 million international trips were made in 2018. As trip numbers do not represent an equal number of individual travelers, it is assumed, conservatively, that with a 60% non-flying population share, 823 million international trips would at most represent 329 million unique air travelers, or 4.3% of the world population. As outlined, this is a conservative estimate. An alternative way of calculating the share of the population participating in international air travel is to divide the number of international trips by an average trip number per traveler. For example, Airlines for America (2018) suggest that the average air traveler makes 5.3 trips per year, with a relatively large share of travelers participating in only one or two trips, and a rather small share accounting for large trip numbers (see also section 4.4). Applying the US average of 5.3 trips as an indication of skewed demand, 823 million international trips involved only 155 million unique air travelers, or 2% of the world population. Even though it is unknown if US data is representative for air transport more generally, it can be estimated that in 2018, only 2% to 4% of the world population participated in international air travel.

4.2. Regional distribution of flight

The uneven distribution of air transport demand on regional scales is illustrated in Table 3 and Fig. 2. Data suggests that a quarter (25.6%) of global air transport takes place in North America, and another 22.7% in Europe (Table 3). The Asia-Pacific region accounts for 32.5%. The remaining four regions, Africa, Commonwealth of Independent States (CIS), Latin America and Middle East, plus all countries not included in the seven regions, together account for 19.2%. Yet, these regions are

Table 2
Share of flying population adjusted for non-flying share of population, 2018.

	Population (million)*	Passengers(million)*	Passengers per capita of the population	Flying population (%)	Flying population (million)
Low income	705	23	0.03	0.7	4.9
Lower middle	3,023	454	0.15	3	90.7
Upper middle	2,656	1,313	0.49	10	265.6
High income	1,210	2,442	2.02	40	484.0
Total	7,594	4,233			845.2

Source: own calculations, based on World Bank (2020b)*. Flying population: The share/number of the population/people in each income group that flies at least once per year.

Table 3
Regional distribution of transport demand and outlook to 2050.

Region	Growth rate per year (%)	RPK 2018 (billion)	RPK share 2018 (%)	RPK 2050 (billion)	RPK share 2050 (%)	RPK per capita 2018	RPK per capita 2050
Africa	5.35	157	1.8	833	2.4	123	335
Asia-Pacific	5.45	2,762	32.5	15,092	44.1	648	3,097
CIS	3.50	213	2.5	641	1.9	894	2,522
Europe	3.45	1,934	22.7	5,727	16.7	2,867	8,616
Latin America	5.10	507	6.0	2,493	7.3	790	3,270
Middle-East	5.35	543	6.4	2,877	8.4	3,181	10,789
North America	3.10	2,174	25.6	5,774	16.9	5,967	13,580
Rest of world	4.28	212	2.5	811	2.4	–	–
Average/ Total	4.45	8,503	100	34,247	100		

Source: own calculations based on Airbus (2019), Boeing (2019), ICCT (2019), UN DESA (2020). RPK development to mid-century is based on industry growth expectations until 2038 (Airbus 2019, Boeing 2019), and extrapolated to 2050. As a result of COVID-19, it is currently unclear whether this growth projection remains a likely scenario.

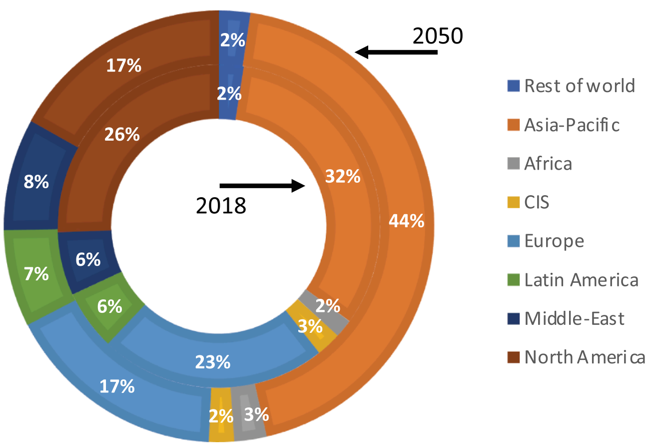

Fig. 2. Distribution of RPK by world region, 2018 and 2050.

home to a large share of humanity. Annual per capita air transport demand illustrates these regional differences, varying between 5,967 RPK in North America, 3,181 RPK in the Middle East and 2,867 RPK in Europe (Table 3). In all other regions, and specifically Africa (123 RPK), air transport demand is significantly smaller.

Table 3 also suggests that differences in individual air transport demand will become even more pronounced in the future. According to industry expectations (Airbus 2019), the Asia-Pacific region would account for 44% of air transport demand by mid-century, followed by North America and Europe (both 17%) (Fig. 2). The share of all other regions would be 22%. Even though the average per capita distance flown in Africa is expected to almost triple to 335 RPK per capita, this is one tenth of the expectation for Asia-Pacific (3,097 RPK) or Latin America (3,270 RPK), and 40 times less than North America (13,580 RPK). Although Africa would account for 25.5% of the world population by 2050 (UN DESA, 2020), it will only represent 2.4% of global air transport demand. In comparison, North America would be the home of 4.4% of the world's population and 16.9% of its air transport demand. Overall, in this post-COVID-19, "resumed growth" recovery scenario, air travel would grow from 8,503 billion RPK in 2018 to 34,247 billion RPK by mid-century, as a result of population and per capita transport demand growth.

Table 4 translates growth in demand into emissions, in a scenario that considers sector-wide efficiency gains of 1% per year, with a specific fuel use of 3.5 l per 100 RPK in 2018 (IEA, 2019b; Peeters et al., 2016). Annual emissions from commercial passenger transport would increase from 0.743 Gt CO_2 in 2018 to 2.169 Gt CO_2 by 2050. The contribution made by world regions varies vastly, however, with averaged per capita

Table 4
Total and per capita emissions from commercial air passenger transport.

Region	CO_2 global (Mt, 2018)	CO_2 global (Mt, 2050)	CO_2 per capita (kg, 2018)	CO_2 per capita (kg, 2050)
Africa	14	53	11	21
Asia-Pacific	241	956	57	196
CIS	19	41	78	160
Europe	169	363	250	546
Latin America	44	158	69	207
Middle-East	47	182	278	683
North America	190	366	521	860
Rest of world	19	51	n.a.	n.a.
Average/ Total	743	2,169		

Source: own calculations based on Airbus (2019), Boeing (2019), ICCT (2019), UN DESA (2020). Emission factors: 0.035 l fuel per RPK burns to 0.087 kg CO_2 per RPK in 2018.

contributions ranging between 21 kg CO_2 per year in Africa to 860 kg CO_2 per year in North America.

4.3. National perspectives on air transport demand

National perspectives on air transport are important because they can illustrate differences between countries, differences in domestic/ international fuel use, developments in emission growth, the relevance of aviation in comparison to overall national emissions, and interrelationships of air transport demand and GDP. UNFCCC (2020) data shows that a significant share of global emissions from air transport is emitted by a few countries, with only 12 of Annex I countries emitting more than 10 Mt of CO_2-eq per year, and 25 countries emitting more than 2 Mt CO_2-eq (Fig. 3). The USA alone emits more CO_2-eq than the following 10 largest consumers of aviation fuel combined. Two thirds of US emissions (67%) fall on domestic air travel (161.5 Mt CO_2-eq, compared to 78.4 Mt CO_2-eq used for international air transport). Other countries, due to their size, have very small domestic emissions (Belgium, Netherlands, or Switzerland). China, as the largest non-Annex I emitter, reported 29.6 Mt CO_2-eq in 2014 (international bunkers; UNFCCC, 2020).

UNFCCC (2020) data also shows that in most countries – though not all – emissions from *international* aviation have grown significantly in the period 1990–2017. Emissions have more than doubled in the United States (104%), the UK (118%), Czechia (105%), Sweden (106%),

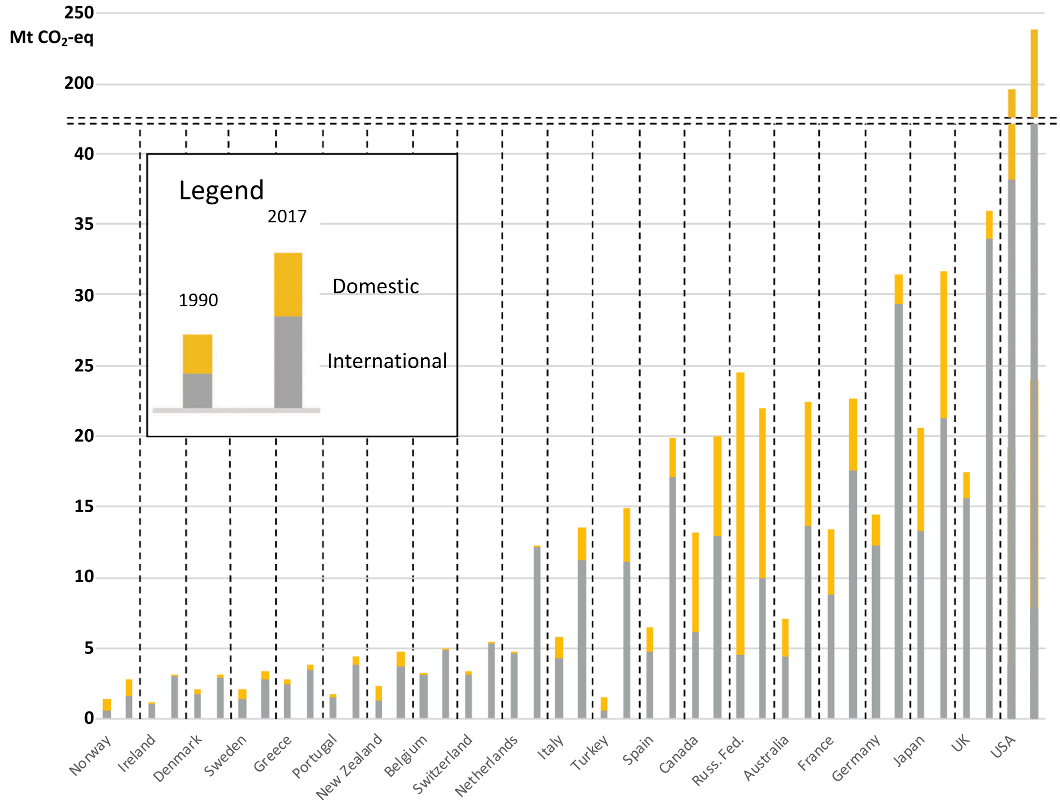

Fig. 3. Aviation bunker fuel emissions in the 21 highest emitting Annex I countries.
Source: UNFCCC (2020).

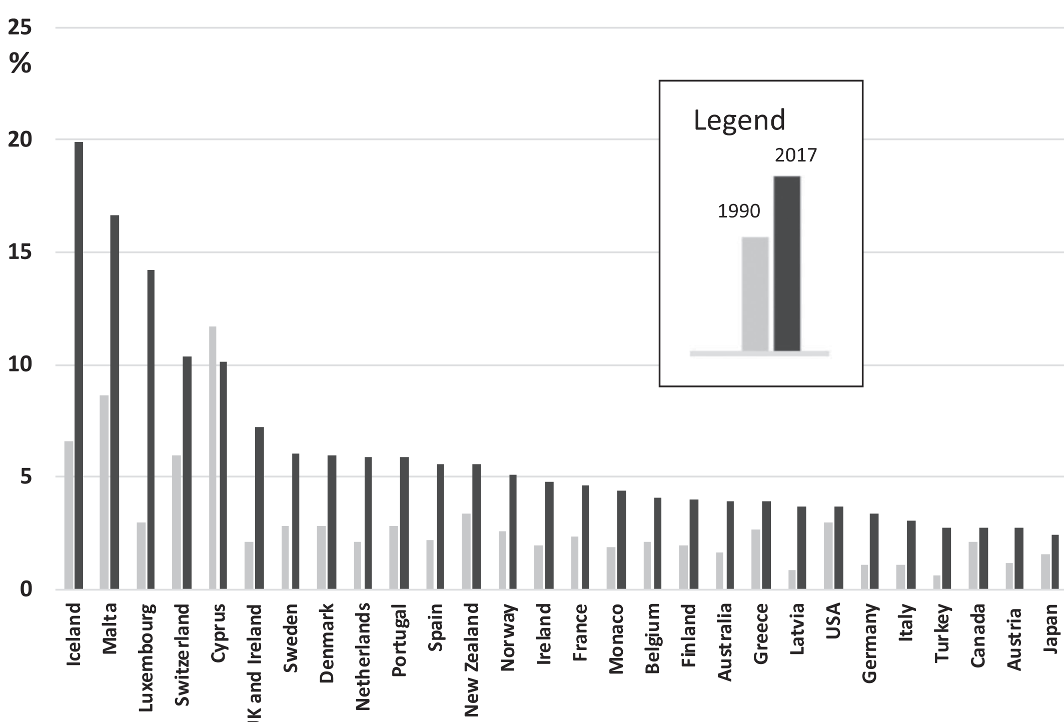

Fig. 4. Domestic & international bunker fuel emissions as share of national total (%). Source: UNFCCC (2020).

Finland (108%), Canada (112%), Germany (141%), Austria (153%), Italy and Norway (160%), Netherlands (161%), New Zealand (178%), or Ireland (184%). They tripled in Australia (210%) and Spain (258%). The most significant growth was seen in Luxembourg (336%), Iceland (423%) and Turkey (1,896%). A decline in emissions was recorded in Belarus, Bulgaria, Kazakhstan, Lithuania, and Ukraine, as well as

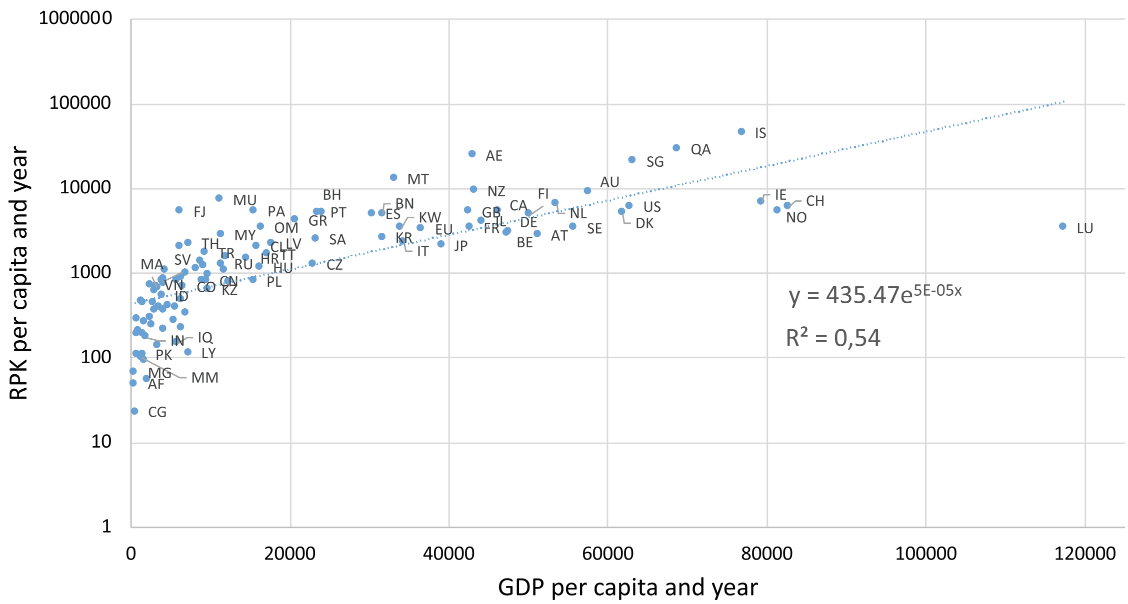

Fig. 5. Interrelationships of RPK and GDP*. *logarithmic scale. Source: ICCT (2019), World Bank (2020b).

Croatia.

Further insights can be derived from the comparison of bunker fuel use (international and domestic) in relation to national greenhouse gas emissions including international bunkers. In 28 of 43 Annex I countries, the share of emissions from air transport exceeded 2% of annual greenhouse gas emissions in 2017 (Fig. 4). For five countries, the share even exceeded 10%, including in Cyprus (10.1%), Switzerland (10.4%), Luxembourg (14.2%), Malta (16.7%), and Iceland (19.9%). As the data represents a ratio, the comparison of 1990 and 2017 also confirms that in virtually all countries, emissions from aviation have grown faster than those from the economy in general. Cyprus is the only country with a lower share of aviation emissions in 2017 than in 1990.

Fig. 5 illustrates national differences in air transport demand on the basis of RPK and GDP per capita relationships, confirming earlier insights that a higher average GDP is linked to air transport demand. Data is based on bunker fuel use by ICCT (2019) for 105 countries, with the lowest transport demand recorded in the Democratic Republic of Congo (23 RPK and a GDP of US$562 per capita per year), and the maximum, more than 45,000 RPK and a GDP of US$76,856 per capita and year in Iceland. It deserves to be mentioned that there are considerable differences in income distribution within countries, and it is likely that a correction of data for income inequality would yield a significantly higher correlation between transport demand and GDP as a proxy of income.

4.4. Individual air transport demand

Previous sections have determined that close to 90% of the world

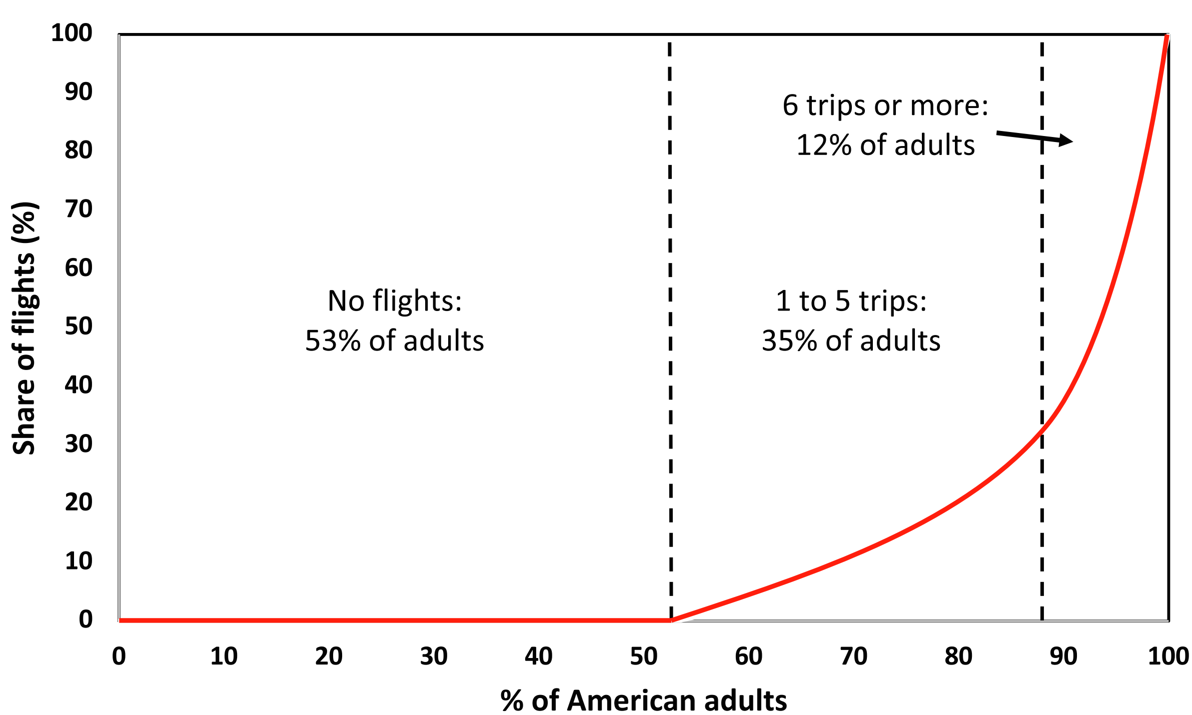

Fig. 6. Air transport demand distribution in the USA. Source: based on ICCT (2019).

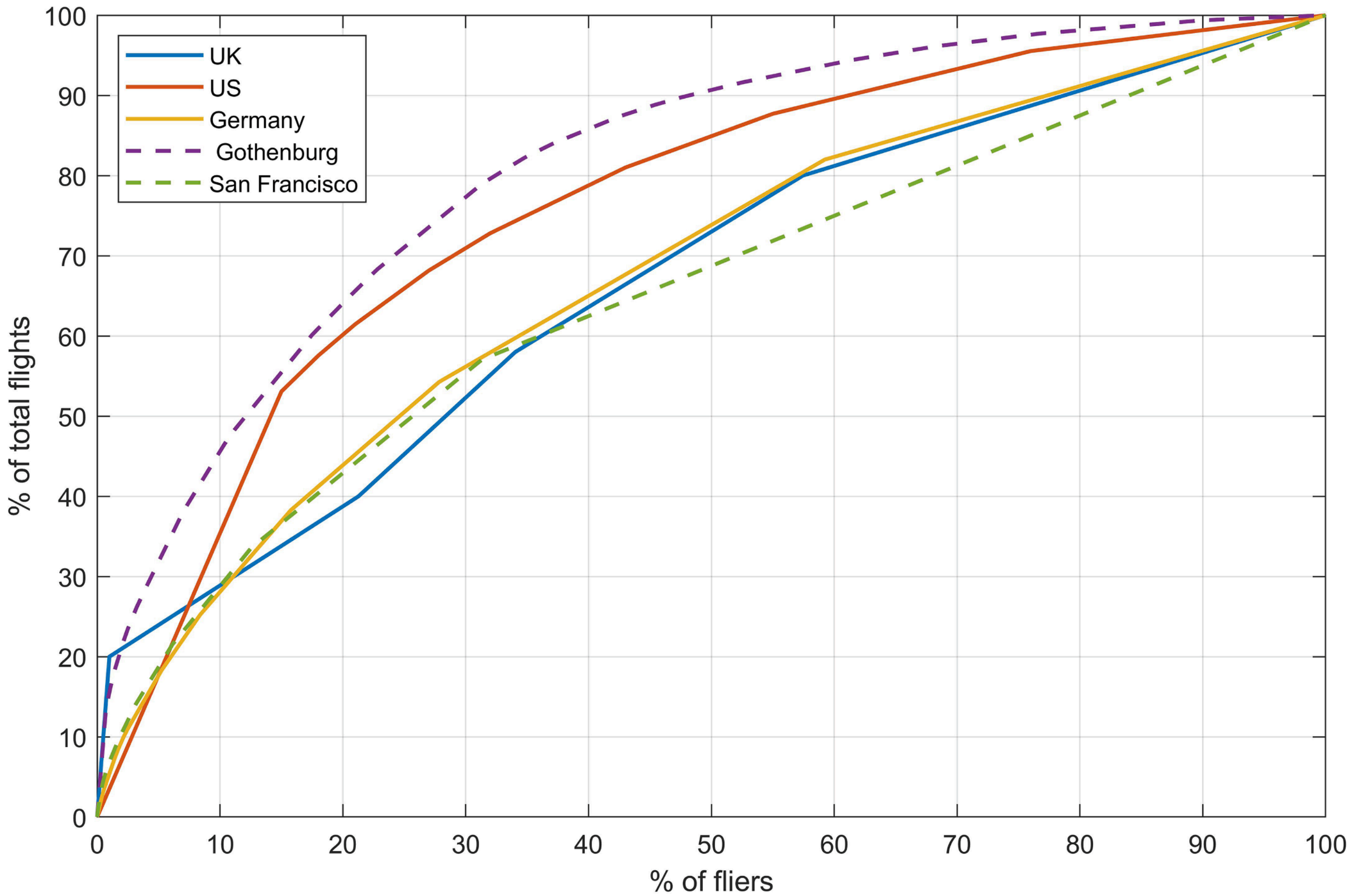

Fig. 7. Air transport demand distribution*. *broken lines: airport surveys. Source: UK Department for Transport (2014); Airlines for America (2018); Gössling et al. (2009); GRA Incorporated (2018).

population does not fly in a given year, and of those flying, shares of in between 11.0% and 26.5% have reported just one trip per year (e.g. Airlines for America, 2018; Gössling et al., 2020). On the other side of the flyer spectrum, very frequent fliers have reported to make 300 trips per year (i.e. some 600 flights), indicating near-daily air travel (Gössling et al., 2009). National transport studies rarely investigate these distributions, as data collection is usually focused on passenger numbers (standardized in the EU, for example, see regulation EC 437/2003; EU, 2003). Available surveys suggest that a minority of very frequent fliers is responsible for many flights. A Swedish airport survey concluded that the 3.7% of the most frequent fliers accounted for 28.3% of all flights taken (Gössling et al., 2009), while in a study representative of adults in Germany, 10.9% of the sample were responsible for 28.8% of all flights (Gössling et al., 2020). Fig. 6 illustrates the overall distribution of air transport for the USA, showing that while more than half of adults did not fly in 2018, the most frequent fliers (6 flights or more), just 12% of adults, accounted for 68% of all flights taken.

Fig. 7 illustrates this relationship for different countries (UK, USA and Germany) as well as two airports (Gothenburg and San Francisco). Surveys suggest that among commercial air travelers, the most frequent 10% of fliers may account for 30–50% of all flights taken. The share of the fuel used by these air travelers is likely higher, as more frequent fliers will more often travel business or first class (Gössling and Nilsson, 2010). For example, The World Bank (2013) estimates that 70% of staff travel is on premium classes, which the World Bank (ibid.) estimates to have a three times (business) and nine times (first class) larger carbon footprint than economy class. The energy demand for people to fly in private First Class Suites, as offered by Singapore Airlines or Ethiad, is even greater, with floor spaces of up to 5.8 m^2 per guest (11.6 m^2 per suite; Mainlymiles, 2018). Larger toilets and additional aisle space make it likely that first class suites require significantly more fuel than first class flights. The ICCT (2014) estimates that the carbon footprint of flying business class, first class, or in a large suite is 5.3, 9.2 or 14.8 times larger than for flying in economy class.

In its A380 cabin layout, Singapore Airlines can transport 471 passengers, with 12 first class suites requiring about the same space as 60 business class seats (Flightglobal 2007). Together, these two classes (72 passengers) require the same space as 399 passengers in economy. This would suggest that premium flight classes require an average 5.5 greater energy demand than economy class seats. Even though aircraft layouts vary, a global 15% share of premium class seats that on average require 5 times more energy than an economy class seat would mean that premium class flights account for 40% of energy use, and economy flights (85% of seats) for 60%. Assuming further, conservatively, that the 10% of the most frequent fliers take 40% of all flights, including all those available in premium classes, the estimate is that the most frequent flier percentile accounts for 55% of energy use and emissions from commercial passenger transport. Given that at most 11% of the world population participate in air travel, this also means that 1% of the world population is responsible for 50% of emissions from all air travel.

Finally, private air travel is the most energy-intense form of flight. Emissions can be determined on the basis of hours of flight and fuel use per hour (Gössling, 2019). While private jet membership programs report average annual operation times of up to 1,090 h per aircraft (Private Jet Card Comparisons, 2020), privately owned aircraft may be used at lower levels of between 200 and 350 h/year, with an average fuel use of about 1200 kg/hour (Gössling, 2019). Importantly, private aircraft may also be made available to friends, relatives or business partners, which will add hours of operation. It has been documented that private air travel can exceed fuel use of 500 t (or about 1500 t CO_2) per capita per year (ibid.). Again, this can be seen in the context of 75% of private jets worldwide being registered in the USA (Forbes, 2017). Where larger aircraft are involved, such as the US president's Air Force Ones (two Boeing 747-200B; Whitehouse, 2020) or the Boeing 767 reportedly owned by Russian oligarch Roman Abramovich (Aircraftcompare, 2020), fuel consumption will increase significantly. As an example, to cover a distance of about 8,200 km, a B744 (with a seat capacity similar to the Boeing 747–200), requires in excess of 97 t of fuel (Park and Kelly, 2014). To cover a distance of 200,000 km per year (cf. Gössling, 2019) will entail fuel use in the order of 2,365 t, and result in emissions of 7,450 t CO_2. Note that actual fuel use will be influenced by flight distances, as shorter flights (high energy use for take-off) and longer flights (additional weight of fuel carried) are characterized by higher specific fuel burn.

5. Discussion

Two major insights emerge from the analysis of global, regional, national and individual patterns of air transport demand. First, a large share of emissions is unaccounted for in global mitigation plans for aviation, which under Kyoto Protocol and Paris Agreement focus on commercial international bunker fuels, and CO_2 alone. Domestic commercial and private fuel use is a responsibility of nation states, but several key emitting countries have shown limited ambition to curb these emissions, or even formally rejected responsibility (UNFCCC, 2017). Military flight remains unaddressed, as well as a large share of private flight with smaller aircraft.

This highlights that aviation's contribution to global warming is only partially covered by climate policies, which currently address international bunkers from commercial aviation (505 Mt CO_2) and domestic emissions in countries joining the Paris Agreement (182 Mt CO_2). Not covered are domestic emissions in the USA (161 Mt CO_2), military flight (80 Mt CO_2), private aviation (40 Mt CO_2) as well as non-CO_2 radiative forcing from all aviation.

In all countries that remain signatories to the UNFCCC Paris Agreement, domestic aviation falls under these States' NDCs. International bunkers fall under the remit of the ICAO. As a caveat, national aviation CO_2 emissions are theoretically covered by climate policies, but this does not necessarily mean they will be addressed in mitigation schemes. Military flight as well as private international flight would fall, at least partially, under Nationally Determined Contributions (NDCs) under the Paris Agreement. However, in practice countries do not report fuel use for these sectors. A large share of military aviation and private flight take place in the USA, a country that also stands for more commercial air transport emissions than the next ten major Annex I contributors combined (Fig. 3), yet has rejected any formal responsibility for emissions. Including domestic, military and private air travel, the overall emission gap from aviation is considerably larger than currently anticipated (Healy, 2017). It will continue to grow if the aviation sector rebounds and resumes its pre-COVID growth trajectory, raising urgent questions regarding climate governance for aviation.

With regard to the second major insight of this research, a major share of aviation emissions is generated by a very small share of very high emitters who are geographically located in a few countries. These frequent air travelers are very wealthy individuals, and the effect of market-based measures on reducing their emissions is debatable, specifically in regard to industry plans for mitigation. The international aviation industry's Carbon Offsetting Scheme for International Aviation (CORSIA) is designed to offset emissions from international commercial aviation at a low cost, and hence unlikely to slow down fuel consumption and emission growth (Warnecke et al., 2019). This is also true for the EU ETS for aviation (Efthymiou and Papatheodorou, 2019). None of the schemes addresses private flight. Given the future cost of climate change (Tol, 2018; DeFries et al., 2019), the absence of markets for aviation's negative environmental externalities represents a major subsidy to the most affluent. As half of aviation's (non-CO_2) warming remains unaddressed, together with close to one Gt CO_2 per year under CORSIA's carbon neutral growth proposition, the value of this subsidy to global aviation is, at a minimum carbon cost of US$50 per ton (cf. Rockström et al., 2017), in the order of US$100 billion per year (at US $50 per ton of CO_2 multiplied by one Gt CO_2 and weighted by a factor two as a conservative approximation of non-CO_2 effects).

This highlights the need to scrutinize the sector, and in particular the super emitters, i.e. the 10% of the most frequent fliers emitting more than half of global CO_2 emissions from commercial air travel, as well as the users of private aircraft who cause emissions of up to 7,500 t CO_2 per year. Adding air transport's non-CO_2 warming effects, super emitters may contribute to global warming at a rate 225,000 times higher than the global poor (0.1 t CO_2 per person per year). This calculation is based on emissions of 7,500 CO_2 per year and an approximation of a warming effect three times the rate of CO_2, i.e. more aligned to recent research (Lee et al., 2020). It does not include the importance of multiple housing, the energy required by other transport modes such as superyachts and helicopters (Harding, 2019; Superyachts, 2020), or the energy to produce and the infrastructure to operate these. Notably, a future intensification of energy-use among the very affluent may be triggered by emerging opportunities for space tourism (Spector et al., 2020).

Chancel and Piketty (2015) highlighted the carbon importance of the lifestyles of the most affluent individuals in the USA, with an average annual income purchasing power parity of €542,000 in 2013. These 3.16 million individuals - or 0.04% of the world population – were calculated to contribute to emissions exceeding 1 Gt CO_2 (3.6% of the global total). As this research shows, a significant share of these emissions is likely represented by transportation. A key question is thus how continued growth in GDP and concentration of wealth will affect emission growth. Notably, this is a distributional issue that is relevant for the wider population of air travelers: As Banister (2018) highlights, the opportunity to fly does not change the share of the population flying, rather than the intensity of flight activity among those already flying.

In the current policy domain, economic instruments have aimed for market efficiency, i.e. least cost solutions delivered through the EU ETS (Maertens et al., 2019) or CORSIA (Scheelhaase et al., 2018; Warnecke et al., 2019). These are inappropriate for a sector in which the distribution of air transport demand and associated emissions is more highly skewed than in other areas of consumption. From a market-based viewpoint, a modest increase in the cost of air travel will not affect business travelers (Falk and Hagsten, 2019), who are causing disproportionally high emissions. Yet, as the data presented in this paper suggests, halving the flight activity of the percentile of the most frequent fliers would reduce emissions from commercial passenger transport by more than 25%. These insights confirm the need to develop more complex transition policies for aviation (Lyle, 2018; Larsson et al., 2019).

Industry projections (Airbus, 2019; Boeing, 2019) as well as scenarios of GDP growth (World Bank, 2020b) and the low cost of fuel (Bloomberg, 2020) support an expectation of continued growth in global air transport, much of this in domestic markets (IATA, 2019). The COVID-19 pandemic currently delays growth trajectories. To help global aviation to recover, IATA (2020a) has asked for "immediate relief measures" including direct financial aid, loans, and tax relief; in a situation in which an estimated US$100 billion in State aid have already been allocated to airlines (Gössling, 2020), adding to the carbon subsidy of US$100 billion per year calculated in this paper. At the same time, IATA has called on ICAO to postpone CORSIA (Euractiv, 2020). These findings should raise a wide range of questions regarding the economic foundations of air transport, the distribution of aviation's cost and benefits, and the efficiency of climate policies to resolve the sector's interference with the climate system (Gössling, 2020).

6. Conclusions

This paper systematically reviewed air transport demand on global, regional, national and individual scales. Results support two insights of key relevance for climate change, i.e. the large share of overall emissions from aviation not covered by climate policies - notably in light of evidence that existing climate policies for aviation are inadequate -; as well as the significant concentration of air transport demand among a small share of affluent frequent fliers. Both highlight the lack of and need for aviation climate governance – possibly at national and regional scales – to tackle emissions from aviation. The ongoing COVID-19 pandemic represents an opportunity to rethink aviation in terms of demand distributions, air transport wants and needs (private aircraft, first class suites), as well as aviation's growth trajectory under recovery scenarios and the sector's growing interference with mitigation goals.

Results also underscore the need for further research to better understand a wide range of interrelationships, such as the distribution of air transport demand under different allocational principles, and on the basis of revenue passenger kilometers rather than trip numbers; general interrelationships of GDP growth and wealth concentration with the energy intensity of air transport demand; or the quantification of subsidies forwarded to air travelers in current policy regimes. There is also a limited understanding of military aviation's interference with climate goals. These will provide important further input for air transport governance, i.e. the design of transition policies that align the sector with low-carbon economy goals.

7. Author statement

Stefan Gössling: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Andreas Humpe:** Data curation, Formal analysis, Validation, Visualization, Writing – review & editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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