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Domestic and international aviation emission inventories for the UNFCCC parties

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Abstract

Global aviation emissions have been growing despite international efforts to limit climate change. Quantifying the status quo of domestic and international aviation emissions is necessary for establishing an understanding of current emissions and their mitigation. Yet, a majority of the United Nations framework convention on climate change (UNFCCC)-ratifying parties have infrequently disclosed aviation emissions within the international framework, if at all. Here, we present a set of national aviation emission and fuel burn inventories for these 197 individual parties, as calculated by the high-resolution aviation transport emissions assessment model (AviTeam) model. In addition to CO_2 emissions, the AviTeam model calculates pollutant emissions, including NO*x*, SO*x*, unburnt hydrocarbons, black carbon, and organic carbon. Emission inventories are created in aggregated and gridded format and rely on Automatic Dependent Surveillance–Broadcast combined with schedule data. The cumulative global fuel burn is estimated at 291 Tg for the year 2019. This corresponds to CO_2 emissions of 920 Tg, with 306 Tg originating from domestic aviation. We present emissions from 151 countries that have yet to report their emissions for 2019, which sum to 417 $TgCO_2$. The improved availability of national emissions data facilitated by this inventory could support mitigation efforts in developed and developing countries and shows that such tools could bolster sector reporting to the UNFCCC.

1. Introduction

With climate change affecting societies worldwide, global efforts to curb anthropogenic emissions are being taken (Shukla *et al* 2022, SPM, p 14, Lee *et al* 2023, p 5). The United Nations framework convention on climate change (UNFCCC) established an international treaty in 1992 as the first of a series of international agreements by the United Nations targeting climate change (United Nations 1992). The UNFCCC reporting requirements contain principles on inventory creation, and a distinction between industrialised countries (Annex I countries), which are required to submit inventories on greenhouse gases annually, and developing countries (non-Annex I countries), which have fewer reporting obligations (United Nations 1992). As of today, the UNFCCC has 198 signing parties, whereof one is the European Union and 197 parties that are called countries in the context of this paper (UNFCCC 2023b). Within the UNFCCC reporting, aviation CO_2 emissions are regularly reported by Annex I countries and voluntary by non-Annex I countries and separated into domestic and international emissions. The subsequent Kyoto Protocol from 1997 is an international agreement that sets binding emission reduction targets based on values reported under the UNFCCC (UNFCCC 1997). Following up, the 2015 Paris Agreement aims goal to limit global warming to below 2 °C with a 1.5 °C warming compared to preindustrial temperatures as the target (UNFCCC 2015). The primary means to achieving this target are emission reduction pledges compared to 1990 by participating nations called National determined contributions (NDCs). In these agreements, emissions are allocated to the country of emission (territory-based allocation).

Despite national pledges and international agreements, CO_2 emissions from aviation have been increasing, and aviation is estimated to have contributed 2.4% to global anthropogenic CO_2 emissions in recent years (Lee *et al* 2021). Non-CO_2 emissions from aviation fuel combustion comprise nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), non-volatile particulate matter (nvPM), and organic carbon (OC). These emissions also affect the climate, increasing aviation's contribution to human-induced global warming to date to about 4% (Klöwer *et al* 2021). Non-CO_2 emissions can also affect air pollution and human health (Eastham and Barrett 2016, World Health Organization 2021), the environment (Sand *et al* 2016), and contribute to condensation trail formation (Lee *et al* 2021).

The international nature of aviation poses challenges to legislators and mitigation efforts in addition to being widely recognised as a 'hard-to-abate' sector for technological reasons (Jaramillo *et al* 2022, Mayer and Ding 2022). One challenge is that territory-based allocation is not straightforward to apply where international flights cross borders and overfly third countries. A second challenge is that air travel demand has a distribution highly skewed towards affluent countries and individuals in the top 1%-percentile of emitters, causing as much as 50% of global aviation emissions (Gössling and Humpe 2020). Hence, demand and territory-based allocation may give largely different results. Both challenges may have motivated the exclusion of international aviation and shipping from the Kyoto Protocol (Lyle 2018), which affects an estimated 70% (the share of international flights' fuel burn) of all aviation emissions (Teoh *et al* 2023).

The International Civil Aviation organization (ICAO) serves as a United Nations entity responsible for international coordination in the sector. However, its existing climate strategy has drawn critique for perceived insufficiency in ambition and means to meet the Paris Agreement's goal (Lee 2018, Lyle 2018, Pathak *et al* 2022, Fuglestvedt *et al* 2023, p 99). Hence, national efforts formulated in the NDCs could play an important role in mitigating aviation emissions. Yet, we note that many parties' NDCs currently do not explicitly encompass either domestic or international aviation (https://unfccc.int/NDCREG), while other parties, such as the European Union, the United Kingdom, Switzerland and New Zealand, include both domestic and international aviation emissions in their general mitigation planning (Mayer and Ding 2022). Countries committed to quantifiable mitigation targets for aviation emissions have an incentive to maintain regular aviation emission inventories (similar to the UNFCCC Annex I countries) to track their progress.

Aviation emission modelling building on individual flight trajectories in combination with flight physics-based fuel burn models is an established practice to create emission inventories (IPCC 2006, Wilkerson *et al* 2010, Wasiuk *et al* 2016). The introduction of Automatic Dependent Surveillance–Broadcast (ADS-B) technology has opened a new, high-resolution data source in this field. ADS-B technology is a surveillance technology that entails that aircraft periodically broadcast their position and other flight parameters. The usability of ADS-B data for emission inventory creation has been demonstrated in several studies (Klenner *et al* 2022, Quadros *et al* 2022, Zhang *et al* 2022, Teoh *et al* 2023), some using only the origin-destination information in the ADS-B data (Quadros *et al* 2022). Some recent studies provide global emission inventories (Quadros *et al* 2022, Teoh *et al* 2023), while a few national inventories exist (van Pham *et al* 2010, Klenner *et al* 2022, Zeydan and Şekertekin 2022, Zhang *et al* 2022, Puliafito 2023). However, there is no recent inventory that uses ADS-B locations for emission locations and provides a consistent set of national inventories for all countries compatible with UNFCCC standards.

In this work, we address the need to establish robust quantifications of aviation's contribution to individual countries' emissions, as this could promote a further inclusion of aviation into NDCs. We introduce a set of national emission inventories with global coverage that concurrently functions as a set of national inventories aligned with UNFCCC standards (Tier 3B methodology from IPCC 2006). In section 2, we describe how we use the aviation transport emissions assessment model (AviTeam) established in Klenner *et al* (2022) to create inventories of domestic and international aviation emissions for all 197 UNFCCC-ratifying countries. We describe a fuel burn and emissions inventory based on ADS-B telemetry data and how we extract aggregated emissions inventories for economically developing (non-Annex I) and Annex I countries. In section 3, we inspect the generated UNFCCC-compliant data that uncover the contribution of each country's domestic and international aviation emissions (allocated to the airport of departure). We conduct a benchmarking exercise with other aviation emission inventories, demonstrating how both overall emission levels and allocation of emissions to nations agree with existing inventories. Section 4 discusses the role of the study in informing decision-makers engaged in reducing national emissions.

2. Methods

We calculate aviation fuel burn and emissions with the (AviTeam). In the following sections 2.1–2.4, we describe the AviTeam model, the global flight data, the process of flight trajectory creation, and, eventually, the conversion from flight trajectories to emission inventories.

2.1. The AviTeam model

The model was introduced by Klenner *et al* (2022), and posterior improvements are described in Klenner *et al* (2023). Here, we provide a short summary and updates for the global version. The AviTeam computes fuel burn for individual flights for the entire flight envelope based on a given or simulated geospatial trajectory, usually provided by ADS-B data, using the base of aircraft data 3 version 15 (BADA 3) model (Nuic *et al* 2010). The BADA 3 model uses simplified flight physics in combination with a parametrisation of more than 250 aircraft types. Each aircraft type is assigned the representative engine used in BADA 3. Combining fuel burn, atmospheric conditions assuming the standard atmosphere, and engine information allows estimating emissions of the species CO_2, H_2O, SO_x, OC (all linear to fuel burn), NO_x, HC, CO, and nvPM (all non-linear to fuel burn). NO_x, HC, and CO emissions are calculated using the boeing fuel flow method 2 (Dubois and Paynter 2006). In the context of aviation emission modelling, non-volatile particulate matter (nvPM) mass and BC mass are often understood as synonyms (Abrahamson *et al* 2016, Quadros *et al* 2022). nvPM mass and number emission indices (EI $nvPM_m$, EI $nvPM_n$) are estimated using the latest available nvPM method (T4/T2 method), described by Teoh *et al* (2023). If relevant nvPM measurements are not given for a specific engine, EI $nvPM_m$ values are calculated with a method that correlates nvPM emissions with the smoke number reported in the ICAO engine emission database (Peck *et al* 2013, Federal Aviation Administration 2021, ICAO 2023a). If neither approach is applicable, an EI $nvPM_m$ of 30 mg kg-fuel^{-1} is used (Federal Aviation Administration 2021, Quadros *et al* 2022). For EI $nvPM_n$, if the T4/T2 is not applicable, a default value of 1.0×10^{15} particles kg-fuel^{-1} is used (Teoh *et al* 2023).

Compared to the previous AviTeam model version in Klenner *et al* (2022), a new algorithm to estimate aircraft masses is implemented. Take-off-mass (m_{tow}) is now explicitly estimated based on operating empty weight (m_{OEW}), payload (m_{payload}) and mission fuel (m_{fuel}):

$$m_{\text{tow}} = m_{\text{OEW}} + m_{\text{payload}} + m_{\text{fuel}}. \qquad (1)$$

In addition, the aircraft mass is updated iteratively in each timestep by subtracting the previous fuel burn. Further information on the model update is presented in the supplementary material of Klenner *et al* (2023).

2.2. Global flight data

Global flight movement data are sourced from ADSBexchange (adsbexchange.com). The global ADS-B telemetry data set for 2019 contains trajectory information, aircraft identifiers, and callsigns. As the spatial coverage of ADS-B data varies (Teoh *et al* 2023, SI, p 4), we complement ADS-B data with schedule data from cirium aviation analytics (www.cirium.com/), which is described below. The final data set contains 36.2 million individual flights for 2019. Flights contain information on departure and arrival airports, scheduled departure time, estimated arrival time, aircraft type, aircraft (hex code), airline and trajectory. Flights with several stops are divided into individual legs.

To align the airport information with the UNFCCC countries, we identify the departure airports' countries with the help of the airport database of ourairports.com. The European Union is represented by the individual member states. Disputed areas like Western Sahara are included in international departing traffic, but no national datasets are extracted, and neither are flights allocated to other countries. We define flights and their emissions as domestic if the departure and arrival airports are in the same country. This sometimes entails domestic aviation emissions occurring above foreign territory (compare Klenner *et al* 2022). Information on seat configurations per aircraft type is provided in the supplementary section C.10.

2.3. Flight trajectory creation

The combination of ADS-B and scheduled flight information follows these steps:

1. ADS-B raw data processing with division into individual flights
2. Matching of ADS-B trajectories and scheduled flight data
3. Completion of matched ADS-B trajectories with fuel burn calculation
4. Filtering of flights with the removal of conflicting flights
5. Repeat matching of processed ADS-B trajectories and scheduled flight data

In Step 1, raw ADS-B data available in a 60 s resolution are grouped by aircraft identifier, and separated into individual flight legs using a combination of callsign information and altitude and speed profiles. Further, missing data points along the trajectory are added along the shortest great-circle distance. In Step 2, ADS-B trajectory data are combined with schedule information. Missing ADS-B trajectories are simulated using a surrogate flight that was operated on the same route and by the same aircraft, if possible. If no surrogate flights are found, flights are simulated using idealised flight trajectories. These flight trajectories are simulated using idealised climb and descent profiles contained in BADA 3 and cruise flights at a cruise altitude uniformly distributed around the cruise altitude suggested by BADA 3. In Step 4, flights that present irregular fuel consumption or emission indices are eliminated from the dataset. This filtering

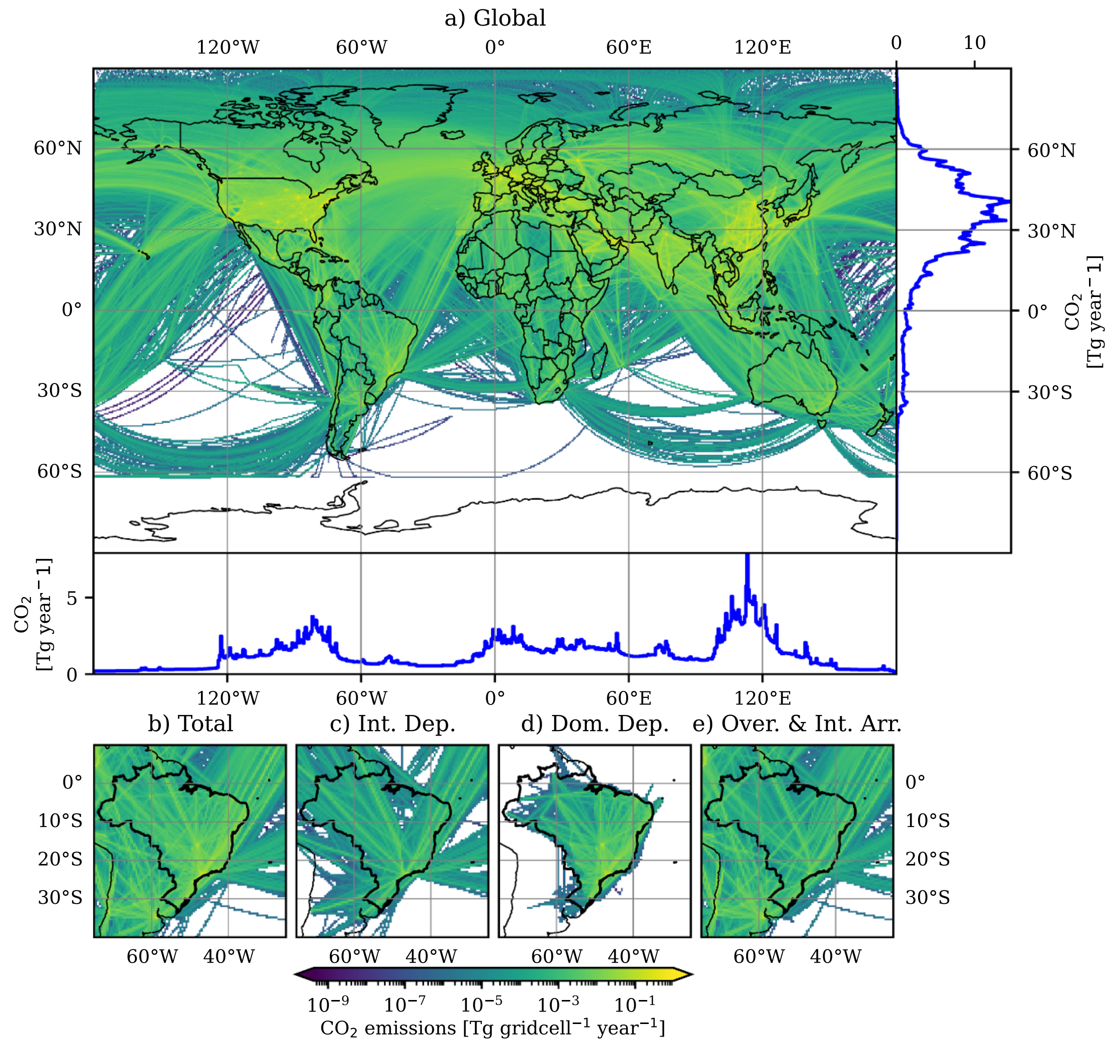

Figure 1. CO_2 emissions from aviation in 2019. (a) Global aviation emissions with longitudinal and latitudinal sum distributions. Lower panel: (b) total emission sum over Brazil, (c) emissions from Brazilian international departures, (d) emissions from Brazilian domestic departures, (e) emissions from overflights and international arrivals. Colours encode the intensity of CO_2 emissions in Tg gridcell^{-1} y^{-1}. Blank pixels represent the absence of relevant emissions.

warrants 'Step 5: Repeat matching of processed ADS-B trajectories and scheduled flight data' to replace the eliminated flights. We refrain from computationally expensive weather matching, as excluding wind data is expected to introduce only a small error at a global scale of approximately 1% (Quadros *et al* 2022).

2.4. From flight trajectories to global aviation inventories

When applying the AviTeam to the global flight trajectory data, gridded emission inventories are created. Figure 1(a), shows the resulting global annual aggregated CO_2 emissions. Given that flights' departure airports are contained in the global flight data, we can further disaggregate global emissions into different emission layers, as exemplified for the emissions in the area of Brazil and its surroundings (figures 1(b)–(e)). Total global emissions (figure 1(b)) are divided into emissions from international departures (figure 1(c)), domestic departures (figure 1(d)), and emissions caused by overflights and international arrivals (figure 1(e)). This approach is applied to all flights and all countries, providing 394 distinct emission layers (one domestic and one international departure layer for 197 countries) for each emission species.

The gridded data have a longitudinal and latitudinal resolution of 0.5°, fifteen altitude levels, and are provided in annual aggregates. Higher resolutions can be made available as the inputted ADS-B data are available at a much higher resolution. A view of the global distribution of aviation CO_2 emissions shows dense traffic in certain areas and flight corridors (figure 1). The latitudinal distribution reveals a hemispheric skewness in the distribution of emissions. Aviation activity and emissions are to a large share located in the Northern Hemisphere (92%) and in the areas of the United States, Europe, and Southeast Asia (details in supplementary section C.2).

We calculate emissions for 36.2 million flights in 2019. The global sum of CO_2 emissions amounts to 920 Tg, with jet, turboprop, and piston aircraft flights accounting for 99.4%, 0.6%, and less than 0.01%, respectively. With a total distance flown of 5.7×10^{10} km, we observe average emissions of 82 gCO_2 seat-km^{-1} or 102 gCO_2 passenger-km^{-1}, assuming a cabin load factor of 0.8. International flights caused 614 TgCO_2 (67%) and domestic flights 306 TgCO_2 (33%). The lower domestic share in CO_2 emissions than flight numbers (compare supplementary material section C.1) is expected, given the longer average distance of international flights. We provide a short analysis of figures 1(b)–(e) as a case study on Brazilian aviation emissions in the supplementary section C.3.

3. Results

In this section, we first present the resulting national aviation emission inventories. Then, we compare our inventories to currently reported emissions in the UNFCCC database and other national reports. We further benchmark the results at a global scale with other geospatial emissions inventories, showing that results largely align.

3.1. 197 national aviation emission inventories

Allocating flights and their emissions to the country of departure allows us to provide aviation emission inventories for all 197 UNFCCC-ratifying countries. Figure 2 shows total (domestic + international) aviation emissions reported under the UNFCCC (a) and calculated by the AviTeam (b). Figure 3 shows corresponding domestic aviation emissions, and supplementary material figure C4 shows international aviation emissions. Whilst under the UNFCCC, a total of 604 TgCO_2 are reported for 2019, we calculate a total of 911 TgCO_2 emitted by UNFCCC parties in the same year. Another 9 TgCO_2 are allocated to non-UNFCCC parties Taiwan, Kosovo, South Sudan, and West Sahara. The difference is caused by a total of 197 countries being quantified in our dataset in contrast to 45 emission reports under the UNFCCC, 43 of them by Annex I countries.

We find emissions of 417 TgCO_2 by non-Annex I countries and 494 TgCO_2 by Annex I countries. Normalising with population numbers (UN 2023), this gives average emissions of around 364 kgCO_2 per capita for Annex I countries and 64 kgCO_2 per capita for non-Annex I countries. The complete set of national data, including the year of last reported international aviation emissions under the UNFCCC (UNFCCC 2023a), is presented in the supplementary material tables C4–C7 and for non-CO_2 emissions in supplementary material data 1.

Importantly, for many non-Annex I countries, e.g. Bangladesh, Djibouti, etc these may be the first aviation emission inventories beyond CO_2 inventories aligned with the UNFCCC 3B methodology. For other countries, e.g. Brazil, these may be the first national inventories of this kind since 2016 (figure 2). In the case of 45 countries that have never reported complete national aviation emissions (domestic + international) under the UNFCCC, we provide estimates of their national aviation emissions in 2019 that sum to 110 TgCO_2 (12% of total CO_2 for 2019). CO_2 emissions from international departures in these 45 countries sum to 93 Tg (84%) and domestic departures to 17 Tg (16%). These shares compare to an international share of 64% and a domestic share of 36% in Annex I countries, confirming our initial assumption that domestic aviation is of subordinate importance in many of these 45 countries.

Ninety-five countries last reported values under the UNFCCC before 2016. Their total emissions in 2019, calculated with AviTeam, sum to 236 TgCO_2, and international departures contribute 139 TgCO_2. The sum of the last international aviation emissions reported to the UNFCCC in these countries is 73 TgCO_2, thus showing growing aviation emissions.

In the 2019 set, the five countries with the highest CO_2 emissions from departing flights (global percentage share in total CO_2 aviation emissions in parentheses) are the USA (22.2%), China (14.4%), Great Britain (3.8%), Japan (3.5%), and the United Arab Emirates (3.3%) (figure 2). The top five non-Annex I countries (all without 2019 values reported to the UNFCCC) are China (14.4%), the United Arab Emirates (3.3%), India (2.9%), Thailand (1.8%), and Brazil (1.6%). We observe zero aviation emissions for Andorra, Liechtenstein, Monaco, Vatican, and San Marino, as these countries do not possess any commercial airports, given the caveat that helicopter flights are fully and general aviation flights partially excluded from this inventory (figure 2).

The countries with the highest absolute domestic aviation CO_2 emissions (global percentage share in total CO_2 aviation emissions in parentheses) are the USA (13.4%), China (8.9%), India (1.5%), Russia (1.2%), and Japan (1.1%) (figure 3). Domestic CO_2 emissions in kg per capita per year are largest in the USA (366), Australia (252) and Norway (162) (supplementary figure C7).

If international aviation emissions were included in national budgets and NDCs based on the departure country, they would imply limited changes ($<$8%) for many of the largest economies (figure 4). However, aviation emissions could substantially change ($\geqslant$8%) the emission records of other countries, e.g. Ethiopia, Portugal, and Niue. Many of these countries have in common that they are popular destinations for international tourism or host

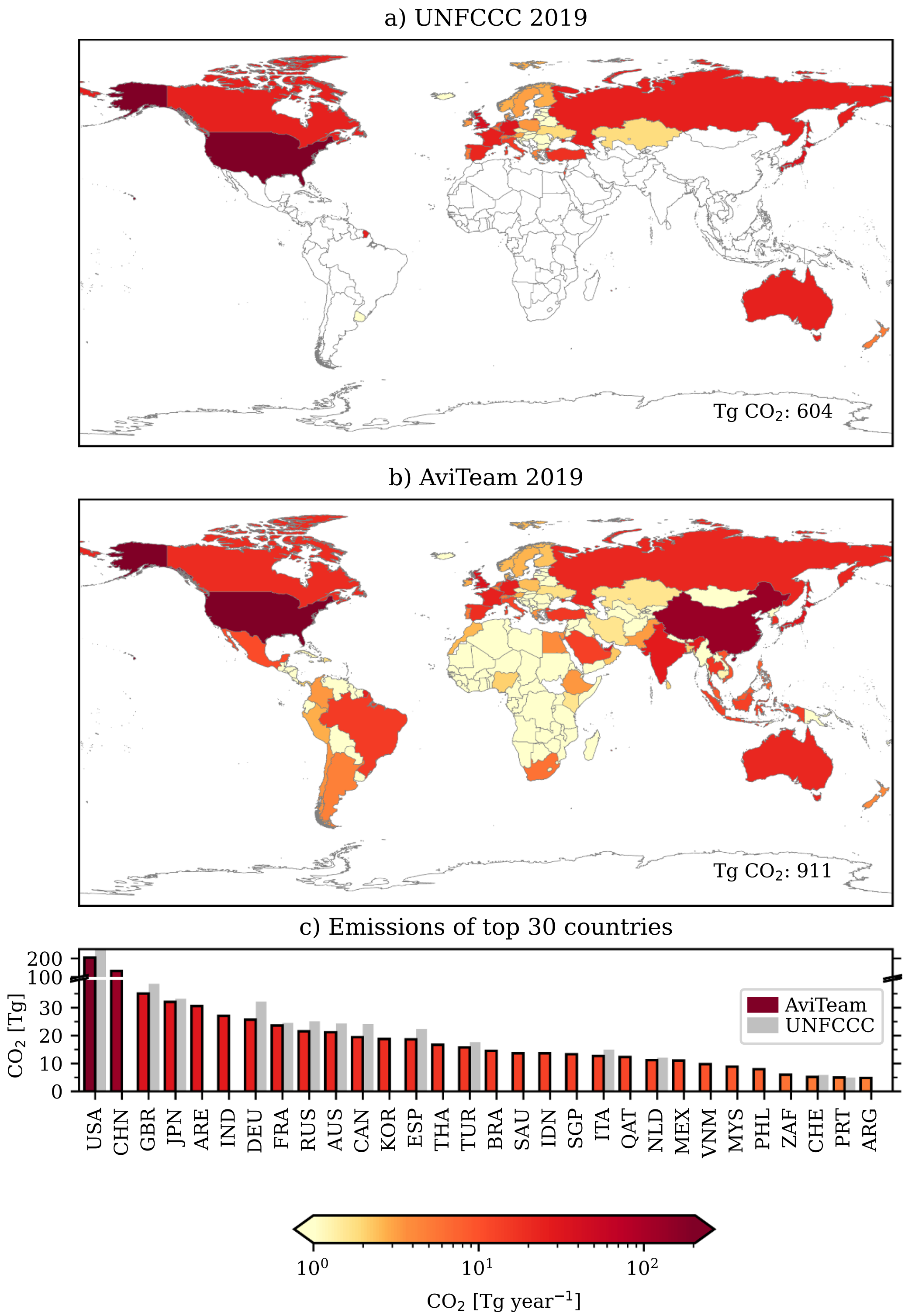

Figure 2. Total aviation emissions by country in 2019. (a) National aviation emissions reported under the UNFCCC by 45 countries for 2019, and (b) national aviation emission inventories established in this work with the AviTeam model for 2019. The colour-coding represents the total annual sum of national CO_2 emissions in Tg. (c) AviTeam and UNFCCC data on CO_2 emissions in Tg from aviation for 2019 with countries by ISO3 country code. White indicates no data. The numerical data are provided in supplementary material table C4. ISO3 country codes in supplementary data 2.

important airports for connecting flights, revealing a limitation to purely departure country-based allocation.

Further, we group emissions by continent (supplementary table C8), and compute emissions that would have been covered by ICAO's CORSIA scheme (international flights that departed and arrived in a country participating in the scheme, status 2023). 8.1 Million flights emitting 336 $TgCO_2$ convert to a CORSIA coverage of 37% of global aviation CO_2 emissions based on 2019 values (supplementary table C8).

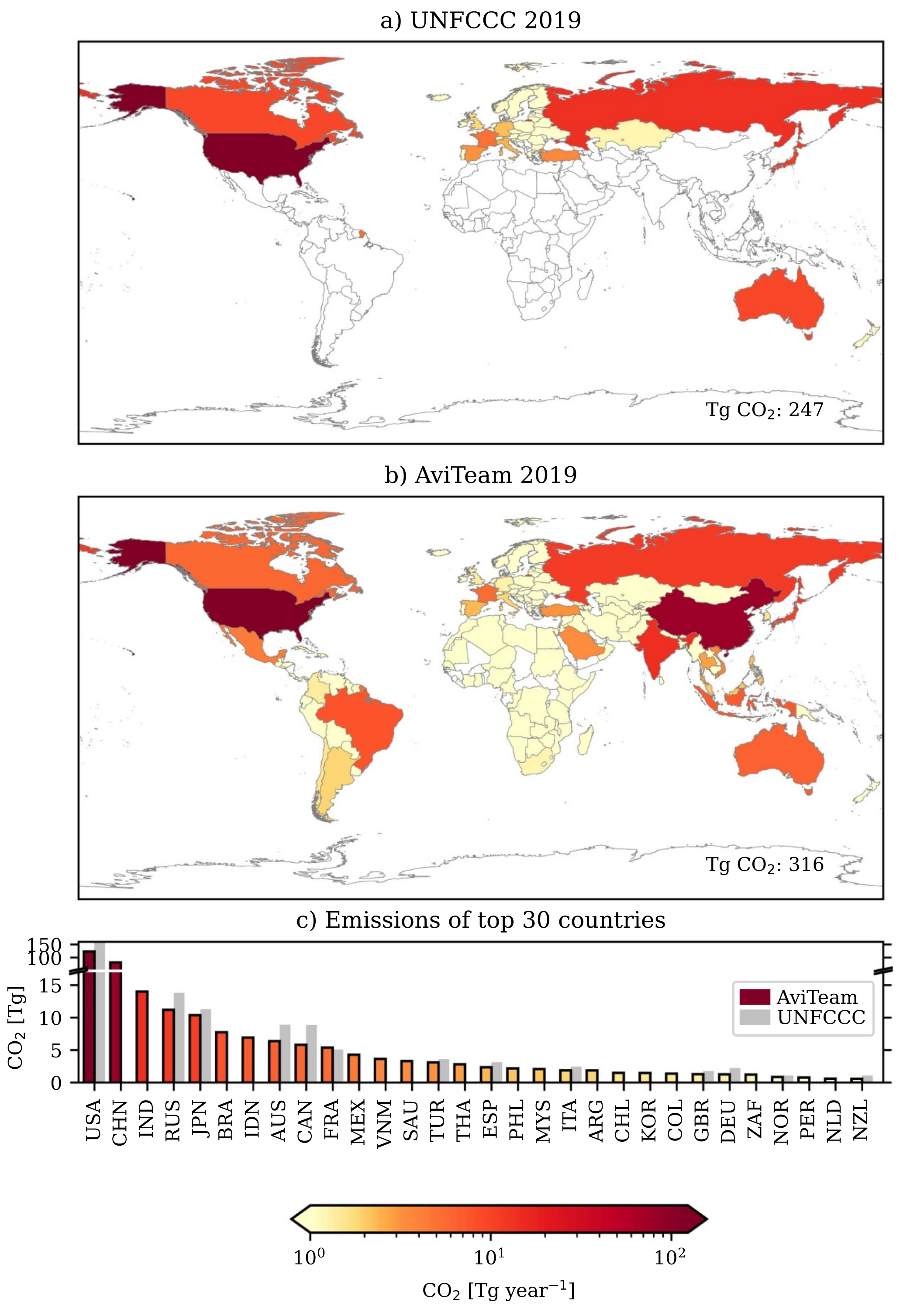

Figure 3. Domestic aviation emissions by country in 2019. (a) National domestic aviation emissions reported under the UNFCCC by 43 countries for 2019, and (b) national domestic aviation emission inventories established in this work with the AviTeam model for 2019. (c) AviTeam and UNFCCC data on CO_2 emissions in Tg from domestic aviation for 2019 with countries by ISO3 country code. White indicates no data. The numerical data are provided in supplementary material tables C4–C7. ISO3 country codes in supplementary data 2.

Aviation emissions per country are compared to other macroeconomic variables (figures and regression analysis in supplementary section C.4). Total aviation emissions show the strongest correlation with the GDP and economy-wide CO_2 emissions, domestic aviation emissions also correlate with the territory area. Differences between Annex I and non-Annex I countries' aviation emissions exhibit largely similar behaviours relative to those variables. Linear regression finds (sign of coefficient in parenthesis) GDP (+), GDP per capita (+), Population (+), log(Population) (−), Gini coefficient (+), territory

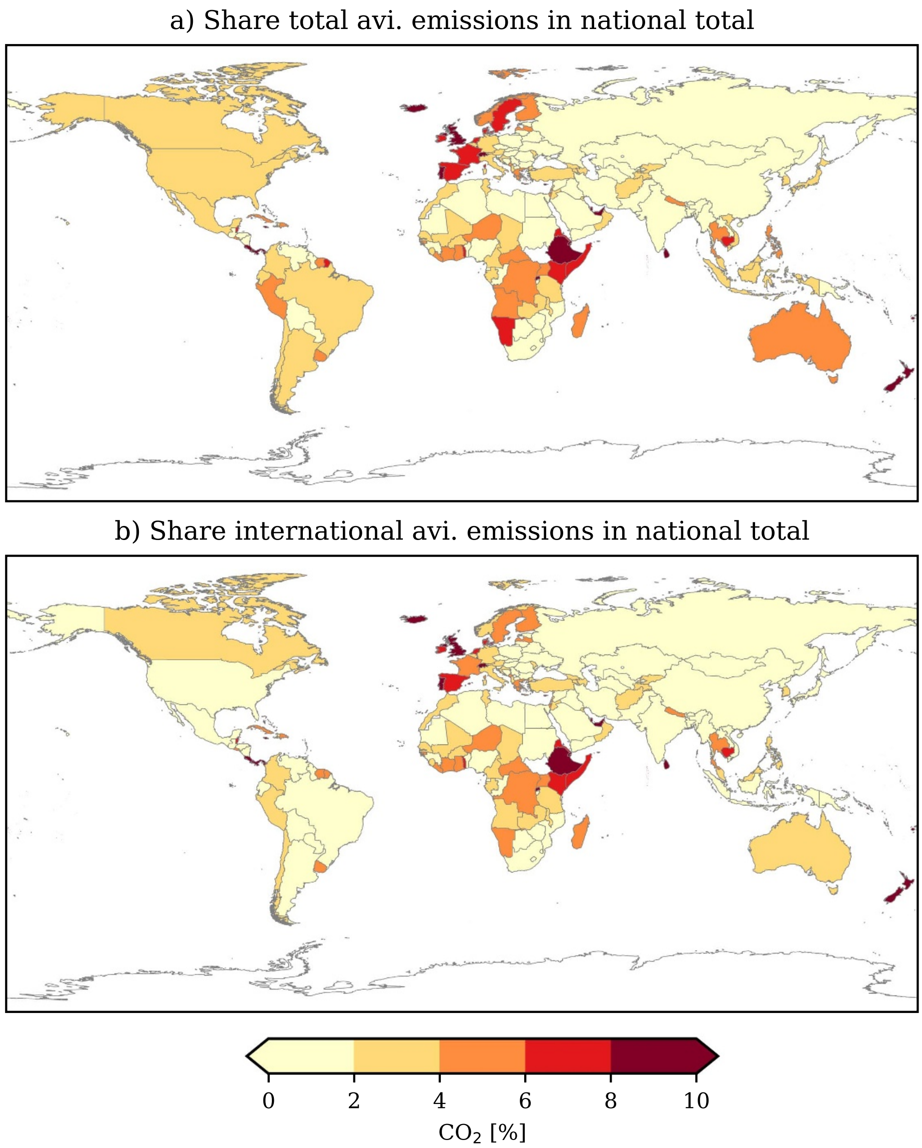

Figure 4. Shares of aviation emissions if they were included in national UNFCCC inventories. Total anthropogenic CO_2 emissions (2019) from Friedlingstein *et al* (2023), which are based on UNFCCC reports where available and international aviation emissions from the AviTeam inventories. (a) Share of total (international and domestic) aviation emissions, and (b) share of international aviation emissions estimated by AviTeam in the national total.

area (+), Asia (+), and railway passengers (−, which can be interpreted as an indicator of the competition of rail and aviation for domestic travel) as good explanatory variables for total aviation emissions.

3.2. Comparison to national and global aviation emission inventories

CO_2 emissions from international and domestic departures are compared against UNFCCC inventories (UNFCCC 2023a) and a study by the International council on clean transportation (ICCT) on aviation emissions for 2019 for validation purposes (Graver *et al* 2020) (figure 5). Our results cover 197 countries, the ICCT reports 106 countries, and the UNFCCC data 45 countries for international and 43 for domestic emissions. The comparison shows a high agreement with UNFCCC values for international aviation (figure 5(a)) with an R^2 of 0.99 (ICCT: 0.87), with many of the national inventories showing a difference between our and UNFCCC values of less than 20%. On average, UNFCCC values are 18% larger than emissions quantified with the AviTeam. A likely cause for the deviations is the partial coverage of private and general aviation and the exclusion of helicopter traffic from this work. This becomes relevant for countries with very few or no commercial domestic flights, such as Slovenia (figure 5(b)). The larger share of commercial aviation flights also explains a larger agreement between the AviTeam and the UNFCCC reports in the international segment. Compared to the ICCT, the estimates by the AviTeam are generally larger, reflecting a lower total emissions estimate by the ICCT compared to other studies. For domestic aviation emissions, an R^2 of 0.90 (ICCT: 0.99) and a trend of stronger agreement with higher total emissions are observed.

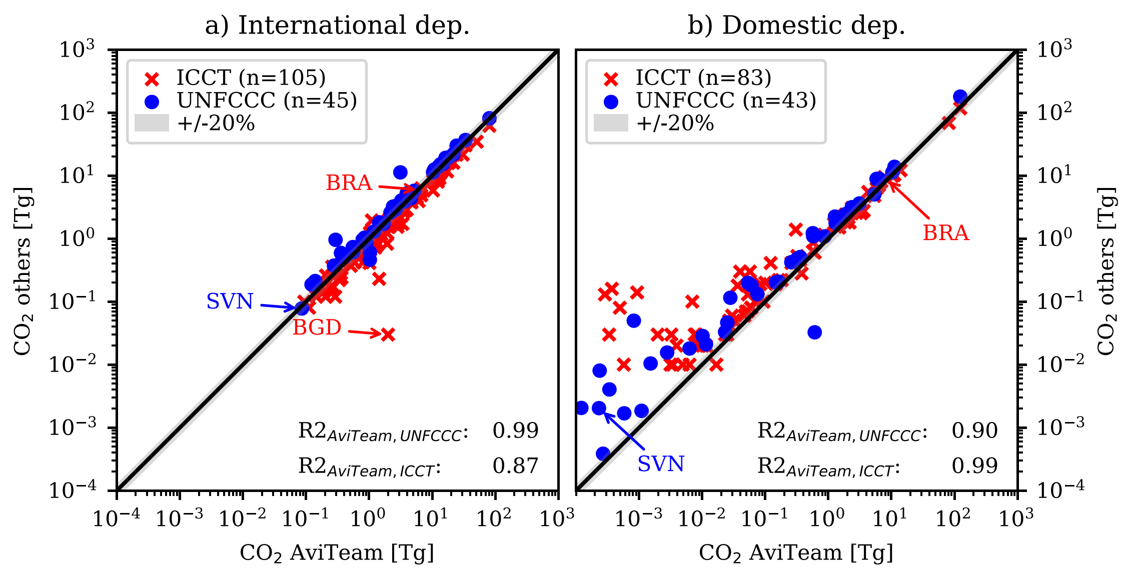

Figure 5. Comparison of national inventories. (a) International, and (b) domestic departures. CO_2 emissions from the AviTeam model in this study are on the *x*-axis, and CO_2 from the UNFCCC (blue circles) and ICCT (red crosses) are on the *y*-axis, logarithmic scales. The black diagonal shows perfect correlation. The grey-shaded area around the diagonal shows a $\pm$20% deviation. CO_2 emissions in Tg. Countries with missing data are excluded from a pairwise comparison. BRA: Brazil, BGD: Bangladesh, SVN: Slovenia.

Table 1. Comparison of global aviation emission inventories. $\sim$ shows approximate numbers.

		AviTeam	Quadros *et al* (2022)	Teoh *et al* (2023)	Lee *et al* (2021)	ICCT	ICAO
Reference			Quadros *et al* (2022) (FR24)	Teoh *et al* (2023)	Lee *et al* (2021)	Graver *et al* (2020)	ICAO (2023b)
Year of emissions		2019	2019	2019	2019	2019	2019
Source		ADS-B and schedule	Enriched ADS-B	ADS-B and schedule	Various	Schedule	Reports
Seat-km	$\times 10^{13}$ km	1.07			$\sim$1		1.09
RPK[a]	$\times 10^{13}$ km	0.84			$\sim$0.8	0.87	0.86
Flights	Million	36.2		36.5		38.8	38
Fuel	Tg	291	297	283	327		
CO_2	Tg	920	937	893	1033	785	
SO_x[b]	Gg	174	178	170[d]			
H_2O	Tg	358	367	348			
NO_x[c]	Tg	5.51	4.62	4.49			
CO	Gg	604	814	400			
HC	Gg	36.3	42.6	33.9			
$nvPM_m$	Gg	20.8	9.7	21.4			
$nvPM_n$[e]	$\times 10^{26}$	3.76	3.47	2.83			
EI NO_x	g kg^{-1}	18.9	15.6	15.9	15.1		
EI CO	g kg^{-1}	2.08	2.74	1.42			
EI HC	g kg^{-1}	0.125	0.143	0.120			
EI $nvPM_m$	g kg^{-1}	0.071	0.033	0.068	0.030		
EI $nvPM_n^{(v)}$	$\times 10^{15}$ kg^{-1}	1.29	1.17	1.00	0.20		

[a] RPK: Revenue passenger kilometres.
[b] in S mass.
[c] in NO_2 mass.
[d] Calculated from emission indices in Teoh *et al* (2023), table 1.
[e] $nvPM_n$ is the number of non-volatile particulate matter particles.

At a global level, values are compared to other global aviation emission inventories and statistics (table 1). A general agreement of this work with other ADS-B-based inventories is evident (Quadros *et al* 2022, Teoh *et al* 2023). The number of flights and fuel burn is close to those by Teoh *et al* (2023), although different scheduled flight information and ADS-B data were used. The larger fuel burn in Quadros *et al* (2022) is related to considerably larger emissions in the landing-and-take-off phase (supplementary material figure C9). All ADS-B-based inventories also find a similar spatial distribution (supplementary material figures C10 and C11), yet the use of stylised flight trajectories explains larger local concentrations in Quadros *et al* (2022). This work presents slightly higher emission indices for NO_x mass, nvPM mass, and nvPM numbers than other bottom-up inventories. Differences in the emission indices can be caused by different atmospheric humidity, distribution of thrust settings, and in the case of nvPM indices, methods. The aircraft-engine matching may be another source of differences, particularly concerning HC and nvPM emissions, as differences between engines for the same aircraft type reach factors of 100 and 20, respectively (compare Quadros *et al* 2022, section S8).

4. Discussion

Using the AviTeam model, which leverages ADS-B telemetry data, allows us to compile gridded and aggregated inventories for all 197 UNFCCC-ratifying countries. The compiled set of inventories is aligned with the UNFCCC Tier 3B methodology outline on inventory creation and thus allows comparing newly calculated annual emissions with reported values. Our current inventories focus on the main aviation pollutants. To fully comply with UNFCCC reporting, additional assumptions for CH_4 and NO_2 emissions and alignment with IPCC quality assurance and verification protocols, as presented in IPCC (2006), are needed. Nonetheless, this set of inventories can be useful in cases where no recent national aviation emission inventory exists and supports previous reports under the UNFCCC.

Taking a share of aviation in total anthropogenic CO_2 emissions of 2.4%, our analysis indicates that about 1% of anthropogenic CO_2 emissions attributable to non-Annex I countries' aviation were not reported under the UNFCCC for 2019. In light of the expected growth of aviation overall, this supports efforts to extend the emission reporting in non-Annex I countries. A caveat is that while the list of non-Annex I countries includes some large emitters, such as China (values compared against values from Zhang *et al* (2022) and official records from the CAAC (2020)) and India, it comprises mostly countries where aviation emissions are of smaller absolute values (cf, supplementary material figure C8). The benchmarking further highlights a larger divergence between inventories for smaller countries, potentially motivated by different approaches to handling general aviation and a varying coverage of ADS-B in particular in some developing countries (Teoh *et al* 2023, SI, p 4 and Quadros *et al* 2022, S14). Thus, there is value in complementing ADS-B information with country-specific flight records from national agencies that provide even higher completeness than achievable with global commercial flight data (e.g. Klenner *et al* 2022).

Agreement on international aviation emissions is larger, and these emissions can significantly impact national budgets. For instance, in many island nations or countries of large international airlines aviation emissions, including international aviation, could alter the national total by more than 8%, potentially giving rise to questions regarding the justness of an allocation of emissions to the flights' departure country. Yet, including international aviation emissions into national accounts could reduce the ambiguity in responsibilities (Jaramillo *et al* 2022).

Our results indicate the largest explanatory value of GDP in predicting the total national aviation emissions but also an explanatory value of other variables, e.g. rail passengers and the Gini coefficient measuring economic inequality. Expecting further GDP growth and continued efficiency increases in the aviation sector, the activity and, hence, emissions from the sector are likely to grow without further mitigation.

The comparison with previous global aviation inventories indicates a general agreement with regard to other emission species and fuel burn, but all are subject to various uncertainties. The largest deviation between the inventories exists in the case of nvPM mass and numbers. This may be caused by the intrinsic difficulty of modelling those emissions in the presence of significant variability of emission indices across engines, engine thrust settings for the same engine, and varying engine data availability (Quadros *et al* 2022, Teoh *et al* 2023). Our inventory shows 15% higher NO_x emissions, which may be caused by a slightly lower average cruise altitude and more data points close to maximum thrust settings than in other inventories or a different fleet composition. Future inventories may potentially present larger NO_x emissions, as Quadros *et al* (2022), observe a general trend of increasing NO_x emissions per kg-fuel over the last decades. Further uncertainty in regard to NO_x, HC, CO, and nvPM emission modelling is introduced by relying on emission indices of likely new engines reported to the engine databases, while engine emission indices vary with the engine's operational age (Zaporozhets and Synylo 2017).

Beyond the aggregated data, we generate gridded data consistent with the UNFCCC methodology that may facilitate climate and air pollution simulations that emphasise national or domestic aviation or regional studies. We hope that the inventories may improve the modelling of local aviation effects, strengthen the credibility of existing inventories, emphasise the need for ambitious mitigation targets for domestic aviation, and further the explicit inclusion of aviation into more NDCs. Stronger mitigation efforts in domestic aviation potentially spill over to international aviation, eventually aiding in curbing the climatic effects of the entire aviation sector.

Data availability statement

The data that support the findings of this study are available in the supplementary material and additional data are available upon reasonable request from the authors.

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CRediT role(s)

J K: Conceptualization, Methodology, Software, Formal analysis, Writing—original draft; H M: Conceptualization, Analysis, Resources, Writing—review & editing; A H S: Conceptualization, Supervision, Writing—review & editing.

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