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Measuring greenhouse gas emissions from international air travel of a country's residents methodological development and application for Sweden

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ABSTRACT

Global civil aviation accounts for 4–5% of total greenhouse gas emissions and these emissions are increasing. In the absence of sufficiently effective global climate instruments, national instruments might be considered as a complement, in which case some way of allocating emissions from international air travel between countries is needed. The purpose of this paper is to develop an accounting method that reflects one country's greenhouse gas emissions from international air travel, and to apply this methodology to Sweden. The new methodology consists of three parts: the number of international air trips made by the country's residents; the average distance of these trips; and the greenhouse gas emissions per passenger km. For Sweden, data for 1990 to 2014 show an increase in the number of trips by Sweden's population of 3.6% per year, resulting in, on average, one international journey (round trip 5800 km) per capita in 2014. The average distance to the final destination has increased only marginally due to simultaneous growth in both long and short trips. However, global average greenhouse gas emissions per passenger km have decreased by 1.9% per year between 1990 and 2014. Because the increase in the number of their trips has outweighed the decrease in emissions per km, the total emissions from Swedish residents' international air travel have increased by 61% between 1990 and 2014. The total emissions from Swedish residents' air travel, including both CO_2 and non-CO_2-effects, were 11 Mt CO_2 equivalents in 2014, which is the same level as the emissions from Swedish car traffic. This type of reliable data is important when designing policies and for getting public support for new policies.

1. Introduction

Global civil aviation emitted 815 Mt of CO_2 in 2016 (IEA, 2017), which constituted 2.5% of global energy-related CO_2 emissions (IATA, 2017). In addition to this, there are non-CO_2-effects from civil aviation; principally emissions of nitrogen oxides, contrails and aviation-induced cirrus clouds, and these effects are estimated to be almost as significant as the CO_2 emissions themselves in terms of their global warming potential (GWP) 100-year perspective (Azar and Johansson, 2012; David S Lee et al., 2009). If the non-CO_2-effect are also taken into account, this would mean that 4–5% of total energy-related greenhouse gas emissions are due to civil aviation, which is in line with Lee et al. (2010). The climate impact from air travel increased by 40% between 1990 and 2010 (IPCC, 2014a) and will most likely continue to grow (Owen et al., 2010). It has been projected that the aviation industry's share of global emission may rise to 22% by 2050 if no new radical technologies or policies are introduced (Cames et al., 2015).

According to the Intergovernmental Panel on Climate Change (IPCC), total global greenhouse gas (GHG) emissions must decrease by around 60% by 2050 for a credible chance of meeting the 2-degree climate target (IPCC, 2014b, RCP 2.6). The target set by the air transport industry (to reduce total CO_2 emissions by 50% by 2050 compared to 2005) is roughly in line with the IPCC estimates (IATA, 2009). Globally, the number of air travel passengers is predicted to rise by 4% per year in the next 20 years (IATA, 2015a), which can be seen in relation to the anticipated reductions in emissions intensity of around 1–2% per year depending on policy strategies (Macintosh and Wallace, 2009; Owen et al., 2010; Schäfer et al., 2016). Technological efficiency potentials are limited and unlikely to meet the predicted increases in demand (Bows-Larkin, 2015; Peeters et al., 2016).

In 2016, the International Civil Aviation Organization (ICAO), a specialized agency of the UN, reached an agreement to implement a global Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) system. CORSIA stipulates that airlines are obliged to offset their increases in emissions after 2020 by purchasing credits from projects that reduce emissions outside the aviation sector (ICAO, 2016b). Even if CORSIA were to work perfectly, it would still only partly offset the anticipated rise in GHG emissions (since non-CO_2

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Table 1
Nine options for the allocation of GHG emissions from international aviation. Options 1–8 were presented by the SBSTA (UNFCCC, 1996) (boldface, our emphasis). We also add a ninth option of consumption-based allocation.

1) No allocation.
2) Allocation of global bunker sales and associated emissions to parties in proportion to their national emissions (from all sectors).
3) Allocation according to the country where the bunker fuel is sold.
4) Allocation according to the nationality of the transporting company, or to the country where an aircraft of ship is registered, or to the country of the operator.
5) Allocation according to the country of (a) departure or (b) destination of an aircraft or vessel; alternatively, emissions related to the journey of an aircraft or vessel (c) shared by the country of departure and the country of arrival.
6) Allocation according to the country of departure or destination of passengers or cargo: alternatively, emissions related to the journey of passengers or cargo shared by the country of departure and the country of arrival.
7) Allocation according to the country of origin of passengers or owner of cargo.
8) Allocation to a party of all emissions generated in its national space.
9) Allocation according to the country of residency of the final consumer (consumption-based accounting).

effects and domestic aviation are not included). The additionality of the offsetting projects are also often questioned (Anderson and Bernauer, 2016; Becken and Mackey, 2017). In addition, there are some national and regional policy instruments, such as the European Union Emission Trading System (EU ETS) which covers CO_2 emissions, but not non-CO_2 emissions, from intra-EU flights[1] (European Commission, 2017). Hence, global GHG emissions from aviation are likely to continue to grow, even after the implementation of these policy instruments. Since CORSIA will not be fully implemented until 2027, there is little hope that more radical international policy instruments will be implemented in the next decade. Therefore, national aviation climate policies are worth considering.

Essential to well-grounded national policy decisions is the availability of data on trends and absolute levels of GHG emissions from aviation (Gössling et al., 2016). Emissions from domestic flights are included in the national greenhouse gas inventories reported to the United Nations Framework Convention on Climate Change (UNFCCC), but the emissions from international aviation (and shipping) are not accounted for by any country. According to the Kyoto protocol the emissions from international aviation (and shipping) can instead be reported separately to UNFCCC (IPCC, 2006; Wood et al., 2010). As such, emissions from international aviation are not included in the national totals, and neither UNFCCC nor ICAO communicate this clearly. Considering that aviation emissions are predominately from international travel, a large share of aviation emissions are essentially made “invisible”. The lack of visibility of these emissions can be a contributing factor to the fact that there are no policies on the horizon that will decrease the absolute emission levels. For global climate policies, there is no need for emissions allocations to specific countries. Awaiting sufficiently effective global climate instruments, national instruments might be considered as a complement, in which case some way of allocating emissions from international air travel between countries is needed.

The purpose of this paper is twofold: (1) to develop an accounting method that reflects a country's GHG emissions from international air travel; and (2) to assess the GHG emissions from international air travel for Sweden between 1990 and 2014. Our calculations are made available in a Microsoft Excel file via this paper's supplementary information, with the aim of facilitating similar assessments for other countries as well as for the purpose of making improvements to the methodology.

2. Methodological development and data

This section describes different options for the allocation of GHG emissions to different countries along with the method developed (2.1) and the application and data sources used for the case of Sweden (2.2).

2.1. Allocation options for GHG emissions from international air travel

Previous research has pointed out the difficulties in identifying coherent system boundaries and collecting data for assessing national emissions from aviation and tourism (Gössling, 2013; Perch-Nielsen et al., 2010). While some studies cover the whole tourism sector, including air and land-based travel, accommodation, etc., this paper focus on air-travel alone. How allocation of emissions from international aviation should be allocated to different individual countries is far from obvious. This issue has been discussed since the 1990s and there are many potential options, e.g. based on where the jet fuel is sold, in which territory the emissions occur or where the final consumer lives. In this paper, the emissions are allocated to the country where the passengers are residing. Our choice is based on an analysis of nine options in relation to a set of five criteria.

The options that are considered are the eight options presented by the UNFCCC Subsidiary Body of Scientific and Technological Advice (SBSTA) (see Table 1). In addition to these original eight options we have added the option of allocation to the country of residency of the *final consumer*, i.e. a consumption-based allocation. Allocations based on the residency of the passenger (Option 7) or of the final consumer (Option 9) are identical regarding air travel for private purposes (vacations, etc.) since the passenger is also the final consumer. For business travel, however, these options differ. For the consumption-based option, emissions from business trips would be allocated to the country of residency of the final consumer of the product that the company produces. For example, if an employee at Volvo in Sweden makes a business trip abroad, then the emissions from this trip would be allocated to the various countries in which the buyers of Volvo cars live.

The five criteria for choosing an allocation option used in this study were sensitivity, additivity, non-leakage, validity, and reliability (inspired by Kander et al., 2015; Wood et al., 2010). Our assessment concludes that Option 7 (allocation based on residency of the passenger) is the one that is the most suitable. Below is a summary of our analysis of the different options in relation to the criteria.

Sensitivity implies that an emissions accounting system should be responsive to factors that countries can influence. Options 1 and 2 are ruled out based on this criterion. An assessment of the other options would depend on which specific policy instruments are considered, all the other options can however be said to satisfy this criterion.

Additivity implies that the sum of all national emissions should be equal to global emissions. Provided accurate measurements are available, this criterion would be fulfilled by all allocation options except Options 1 and 8 (since a lot of aviation occurs over international waters).

Non-leakage implies that countries should not be able to reduce their emissions in a way that increases global emissions. As an example, fuel tax in one country might lead to extra fuel being carried, resulting in additional emissions. Carbon leakage could be a problem for several of the options, but we see no such risks for Options 7 and 9.

Validity refers to that the allocation should accurately reflect a country's GHG emissions from international air travel. Option 3 – allocation based on in which country the fuel is sold – is one way in which the countries can calculate the emissions that they report to UNFCCC (IPCC, 2006). The validity with this option is problematic since it allocates large emissions to countries with large transit airports, and low emissions to countries without transit airports even if its residents are frequent air travellers.

Reliability - Option 7 (allocation based on the residency of the passenger) and Option 9 (allocation based on residency of the final

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[1] EU ETS covers countries within the European Economic Area (EEA), which consists of all EU-members as well as Iceland, Liechtenstein and Norway. Since the abbreviation EEA is less well-known EU is used instead in this paper.

consumer) both satisfy the first four criteria well. However, regarding the fifth criterion reliability, we found the passenger-based option (7) to be significantly better than option 9. For allocation to the final consumer (9), the predominant method is input-output analyses, where emissions from production are reallocated to consumption (see for example Davis and Caldeira, 2010). This method is often used for comparing GHG emissions from the total consumption of the average resident in different countries (see for example Hertwich and Peters, 2009), but when total consumption is broken down into specific consumption categories, such as airline tickets, the data become much less reliable.

Option 7 (residency of the passenger) has previously been disregarded in assessments due to a lack of reliable data (Faber et al., 2006; Lee et al., 2005; Wit et al., 2005), and previously GDP has been used as a very rough proxy for passenger residency (Velzen and Wit, 2000). Indeed, precise data down to actual tickets sold to all residents is not available, but analyses that are mainly based on travel surveys have been performed either to the first landing airport or to the final destination. In this paper, we have developed the reliability significantly and applied the method for Swedish residents for 1990–2014.

Measuring GHG emissions from long distance travel and tourism is complex. Gössling (2013) clarifies the various system boundaries for measuring GHG emissions that are used in different studies, where one important boundary is which sectors that are included. Our approach covers only air travel and no other transport modes, accommodation, etc. Other relevant system boundaries are whether a resident or a territorial approach is applied, which parts of the air travels that are covered (domestic, to transit airport, after transit airport) and which greenhouse gases that are included. Table 2 illustrates the scope of our residential perspective compared to the established territorial perspective.

The columns in Table 2 illustrates whether the passenger is a Swedish or a foreign resident, often called outgoing or incoming tourists respectively. The rows in the Table 2 illustrate both which parts of air travel that are included and simultaneously which GHG emissions that are included. The territorial perspective covers the CO_2 emissions that occur from the bunker fuel sold at national airports, which is what is reported to UNFCCC although only emissions from bunker sales for domestic aviation are included in the national totals (IPCC, 2006). Finally, our scope includes emissions after transit airport abroad, as well as the non-CO_2 effects (see section 2.2.3).

Previous studies using a resident perspective use travel surveys as data source, e.g. Aamaas and Peters (2017) and Åkerman (2012). We argue that the reliability is improved in our methodology since we use total statistics of departing passengers as the core data. Travel surveys are only used to estimate the average distance to the final destination and to exclude the trips conducted by foreign residents (foreign citizens residing in Sweden are however included). Details on which Swedish and international data sources that are used is described in the next section.

2.2. Data for Sweden 1990–2014

Besides developing a methodology, this study also aimed to apply the methodology to Swedish from 1990 to 2014. The method consists of three parts: the number of international trips made by a country's residents [passengers], multiplied by the average distance per trip [km], multiplied by the global average emissions per passenger-km [kg CO_2 equivalents/PKM] for each year. For details regarding the calculations, see the Microsoft Excel file that is available as Supplementary information in the online version of this paper. It is important to note that the approach in this paper does not cover domestic air travel, freight/airmail or military aviation.

Table 2
Scope of the territorial perspective (T) and the resident perspective (R) on GHG emissions from air travel.

	Swedish residents	Foreign residents
Domestic in Sweden, CO_2	R, T	T
To first airport abroad, CO_2	R, T	T
After transit airport abroad, CO_2	R	
Non-CO_2 effects	R	

2.2.1. Number of trips made by Swedish residents

To calculate the number of trips made by a country's residents one needs passenger statistics from all airports in the country. These statistics do however cover the country's residents as well as foreign residents. To account only for the trips made by the country's passengers, the passenger statistics need to be adjusted so that only passengers who are residents are included. Additionally, if it is likely that residents also use airports in other countries as outbound international airports, the same statistics are needed from these airports.

For the Sweden case, total statistics of arriving and departing international passengers to and from Swedish airports were used (Agency, 2016; Transport Analysis Sweden, 2015). The proportion of passengers who are Swedish residents is based on passenger surveys conducted by the state-owned enterprise Swedavia, which operates the major airports in Sweden (Widmark, 2016). Many Swedish residents live close to Kastrup airport (Denmark) or Gardermoen airport (Norway) and often use these airports as their primary international airport. To account for these trips, data on international air travel made by Swedish residents was collected from Kastrup (Danaei, 2016) and Gardermoen (Tvetene, 2016).

2.2.2. Average trip distance for trips made by Swedish residents

After assessing the number of trips, the next step is to calculate the average trip distance for international trips. To do this, you need to know both where the international trip starts and what the final destination is (not only the first destination abroad). So, for example, for a multi-transit international trip Kiruna (Sweden) – Stockholm (Sweden) – London (UK) – New York (USA), Kiruna is referred to as the *starting point*, Stockholm as the *departure airport for an international flight*, London as a *transit airport* and New York as the *final destination*.

In applying the methodology developed to the Sweden case, data from travel surveys conducted for *Turistdatabasen* (TBD) in 1990, 1991, 2010, 2012 and 2013 were used (Resurs, 2014). TBD is based on 20,000 telephone interviews per year where interviewees report the trips they have made in the past 30 days. For the five years mentioned above, 9207 international air trips were reported. The data were then weighted to represent the Swedish population before analysis. The dataset provides the departure airport for international flights and the final destination. Since domestic trips are already accounted for in national reporting, domestic flights prior to an international flight were excluded.

The Google Maps API, via the Google Sheets add-on *Geocode*[2], was used to find the coordinates for each departure airport for international flights and final destinations. The distance between each pair was then calculated via the Great Circle Distance (GCD)[3], which is the shortest distance between the two points. This calculation is in accordance with the ICAO's instructions for reporting of passenger kilometres performed by Member States (ICAO, 2009). Extra distances due to transit stops are not accounted for, which results in an underestimation.

An average distance for a round trip was calculated for each year where data was available on which a linear fit was calculated for each year.

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[2] See https://chrome.google.com/webstore/detail/geocode-by-awesome-table/cnhboknahecjdnlkjnlodacdjelippfg?hl=en.

[3] The great circle distance (GCD) is defined as the shortest distance between two points, with coordinates (lat1, lon1) and (lat2, lon2), on the surface of a sphere. It is given by: $GCD = R\cos^{-1}[\sin(lat1)\ \sin(lat2) + \cos(lat1)\cos(lat2)\cos(lon1\text{-}lon2)]$, where R is the mean radius of the earth. $R = 6371.01$ km.

2.2.3. Global specific emissions per passenger kilometre

The final step in the methodology is to calculate the emissions per passenger kilometre (PKM). To calculate the average emissions per PKM, you need statistics on global aviation fuel consumption as well as the number of PKM. Statistics on freight-tonnes are also needed to allocate emissions between freight and passengers.

Time series of global aviation fuel consumption were collected from the International Energy Agency (IEA, 2016). Aviation fuel data from the IEA includes commercial as well as general (non-commercial business flights or pleasure flights) and military aviation fuel burn, which likely makes it a higher estimate for fuel burn compared to other estimates (Olsen et al., 2013). The military share of global fuel burn was excluded based on data from 1976, 1984, 1992 and 2015 used by the IPCC (1999). Data was interpolated for each year with an exponential fit. The fuel mass was subsequently translated into CO_2 emissions by a factor of 3.15 kg CO_2/kg jet fuel.[4]

There are also non-CO_2 effects from aviation on the climate including nitrogen oxides, contrails and aviation-induced cirrus clouds (Azar and Johansson, 2012; Boucher et al., 2013; ICAO, 2013; David S Lee et al., 2010). There are significant uncertainties about how large these effects are. Our choice to include them is mainly based on that they are accounted for in the last scientific review carried out by the IPCC (Boucher et al., 2013). We apply this by using the most cited scientific estimate (David S Lee et al., 2010). The inclusion of non-CO_2 effects is done by multiplying CO_2 emissions by an *Emission Weighting Factor* (EWF). The EWF is highly dependent on the time perspective considered: the shorter the time perspective, the higher the EWF will be. In this paper, we used Global Warming Potential (GWP) with a 100-year perspective, for which the EWF is 1.9 (Lee et al., 2010).

To allocate emissions between freight and passengers, a suitable metric need to be used. Since weight is an essential factor for the generation of emissions in aviation, it was chosen as the metric in these calculations. To create a single metric, passengers were translated into an average weight of 100 kg including luggage (IATA, 2015c; ICAO, 2014). But passengers also need seats, restrooms, etc. Therefore, we assume an extra 60 kg in accordance with R. C. Wit et al. (2002) and the ICAO (2014),[5] resulting in a total of 160 kg per passenger. Global PKM statistics were thus translated into passenger-tonne-km performed, and global emissions were subsequently allocated based on share of passenger-tonne-km performed compared to freight-tonne-km. Finally, the emissions allocated to passengers were divided by global PKM to get emissions per PKM.

Data for 1998–2014 was collected from the ICAO, which publishes statistics for global passenger-km, freight-tonnes and mail-tonnes performed in scheduled traffic, as well as estimates of international non-scheduled PKM (ICAO, 2008, 2015). IATA also publishes data for PKM and tonne-km for freight, which was used for 1990 and 1995 (IATA, 2015c).

3. Results: international air travel 1990–2014 by Swedish residents

3.1. Number of trips

From 1990 to 2014, the number of arriving and departing international passengers (Swedish and foreign residents) at Swedish airports has increased from 9 million to 26 million (Agency, 2016; Transport Analysis Sweden, 2015). During this period, however, the proportion of Swedish passengers has fallen. At Stockholm Arlanda Airport for example, (through which about 2/3 of international passengers in Sweden pass) the proportion of Swedish residents has decreased from an average of 66% in 2001–2005 to an average of 56% in 2011–2014. Fig. 1 shows the number of round trips that Swedish residents made by air travel per year. The number of international round trips increased by 130% in 1990–2014, which gives an average annual increase of 3.6%.

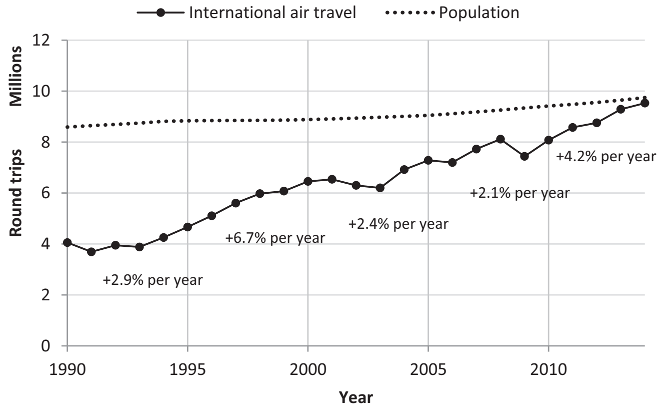

Fig. 1. Number of round trips made by Swedish residents compared to population. Percentages illustrate the average annual increase over several years, i.e. 1990–1995, 1995–2000, 2000–2005, 2005–2010 and 2010–2014.

Three distinct temporary declines are visible in Fig. 1. The first one was in the early 1990s, when Sweden underwent an economic recession that could very well explain stagnation in the frequency of air travel. The second, more pronounced, decline in the early 2000s may be due to the 9/11 terrorist attacks in 2001. The effect of 9/11 on global air travel is well documented (Ito and Lee, 2005). The third decline in 2009–2010 was during the global financial crisis. Furthermore, 1993–2000 shows a steep and steady increase that is likely linked to the deregulation of the aviation industry and the creation of a single market within the EU (Scharpenseel, 2001).

If per capita numbers are used, the number of international trips per year was on average 0.5 in 1990, and by 2014 it had increased to 1.0 round trip per person. This means an annual increase of 3.1% per capita. If the same method is applied to domestic air travel, where the number of trips has been more or less stable over this 24-year period, Swedish residents also made 0.4 domestic round trips per person in 2014.

3.2. Average trip distance

The average distance for a round trip has not changed markedly between 1990 and 2014. In 1990–1991, the average distance for a round trip from the departure airport for international flights to the final destination was 5400 km, which increased to 5800 km on average in 2010–2013, meaning a change of only a few percent over the period. Since Swedish residents on average carried out 1.0 international round trips in 2014, the average annual international air travel was 5800 km. For comparison, 5800 km is the approximate distance of a round trip from Stockholm to Portugal, while a round trip from Stockholm to New York is about 13,000 km.

3.3. Specific emissions per PKM

From 1990 to 2014, global fuel burn has increased considerably, from 160 million tonnes of jet kerosene in 1990 to 260 million tonnes in 2013 (including military and general aviation) (IEA, 2016). However,

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[4] Based on net calorific value and effective CO_2 emissions factor for jet kerosene from 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy, table 1.2 and table 1.4 respectively (IPCC, 2006). Hence, emissions from the production of jet fuel are not included.

[5] ICAO calculates the total weight of passengers, luggage, seats, lavatories, etc., as 100kg · number of passengers (pass) + 50 kg · number of seats (seats). With a load factor $\frac{\text{pass}}{\text{seats}} = 80\%$, the weight per passenger is $\frac{100\text{kg} \cdot \text{pass} + 50\text{kg} \cdot \text{seats}}{\text{pass}} = 100\text{kg} + 50\text{kg} \cdot \frac{1}{\text{load factor}} = 162\,\text{kg}$, which is very similar to Wit et al. (2002).

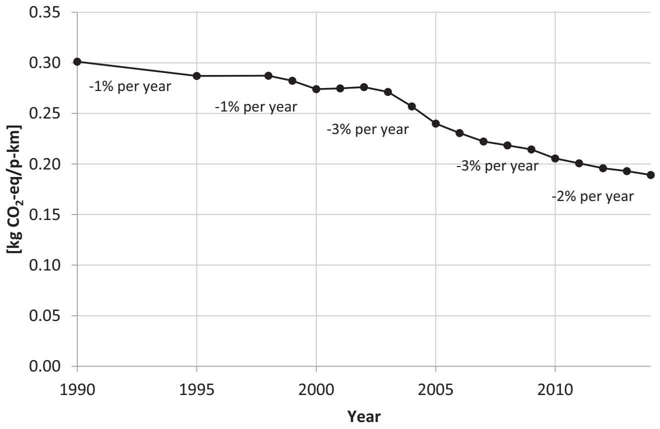

Fig. 2. Global average CO_2 equivalent emissions per PKM 1990–2013. Percentages illustrate the average annual decrease over different periods, i.e. 1990–1995, 1995–2000, 2000–2005, 2005–2010 and 2010–2014.

the military's share of global fuel burn has decreased from 36% in 1976 to 26% in 1984, 18% in 1992 and was projected to be only 7% in 2015 (IPCC, 1999). Civil aviation fuel burn has thus increased by 86%, meaning an average annual increase of 2.6%.

Furthermore, scheduled PKM have increased from 1900 billion PKM in 1990 to 6100 billion PKM in 2014, an increase of 220% and an average annual increase of 4.5% (IATA, 2015c; ICAO, 2015). However, estimates for non-scheduled traffic illustrate that it has not increased during this period (ICAO, 2008, 2015). Aviation consist of passenger transport as well as freight and mail transport and during the period 1990–2014, passengers have been responsible for about the same share (80–84%) of total transportation (measured in tonne-km) (IATA, 2015c; ICAO, 2015).

The resulting emissions of CO_2 equivalents per PKM can be seen in Fig. 2.

Specific emissions decreased from approximately 300 g CO_2 equivalents per PKM in 1990 to 190 g CO_2 equivalents per PKM in 2014. The figures for CO_2 alone decreased from 158 g CO_2 per PKM in 1990 to 100 g in 2014. Between 1990 and 2014, emissions per PKM decreased by 37%. This means an average annual decrease of 1.9%, which is similar to a previous estimate of 1.8% within Europe for the period 1996–2011 (European Environment Agency, 2012). These reductions are due to technological development, load factor improvements, and changes in air traffic management. Load factors have increased drastically, from 66% in 1991 to 80% in 2014 (ICAO, 2015, 2016a), which means an annual increase of 0.84%. Hence, assuming that emissions per PKM scales with the load factor, there has been an average annual efficiency improvement of 1.1% between 1998 and 2014 due to technological development and air traffic management.

3.4. Emissions from Swedish residents' international air travel

The GHG emissions from Swedish residents' air travel are shown in Fig. 3. Emissions, including non- CO_2 effects, increased from 6.6 Mt CO_2 equivalents in 1990 to 11 Mt CO_2 equivalents in 2014, which is an increase of 61% with an average annual increase of 2.0%. The figures for CO_2 alone increased from 3.5 Mt CO_2 in 1990 to 5.6 in 2014. Emissions increased drastically in 1993–2000, from 5.8 Mt CO_2 equivalents to 9.9 Mt. Between 2000 and 2009, emissions have fluctuated, but since 2009 there have been five consecutive years with increased emissions.

For emissions per capita the result is an increase from 0.76 t CO_2 equivalents per person in 1990 to 1.1 t CO_2 equivalents in 2014, which is a 42% increase or on average 1.5% per year.

Emissions from domestic air travel in Sweden were 0.5 Mt CO_2 in 2014 (Swedish Environmental Protection Agency, 2016). The non-CO_2 effects from domestic flights are low since they rarely reach altitudes above about 8000 m, which is where these effects occur. Hence, about 95% of GHG emissions from Swedish residents' air travel is caused by international air travel. If we add the emissions from domestic to international flights emissions, the total is 1.15 t CO_2 equivalents per resident in Sweden in 2014. Using the same fuel data from IEA, globally emissions were 0.17 t CO_2 equivalents per capita in 2014. Consequently, the emissions resulting from air travel for the average Swedish resident are seven times higher than the global average.

Fig. 4 shows the trends in emissions per PKM, load factor, number of trips and total emissions of all Swedish residents, with base year 1990 = 100. From 1990 to 2003, total emissions followed the increase in the number of trips closely.

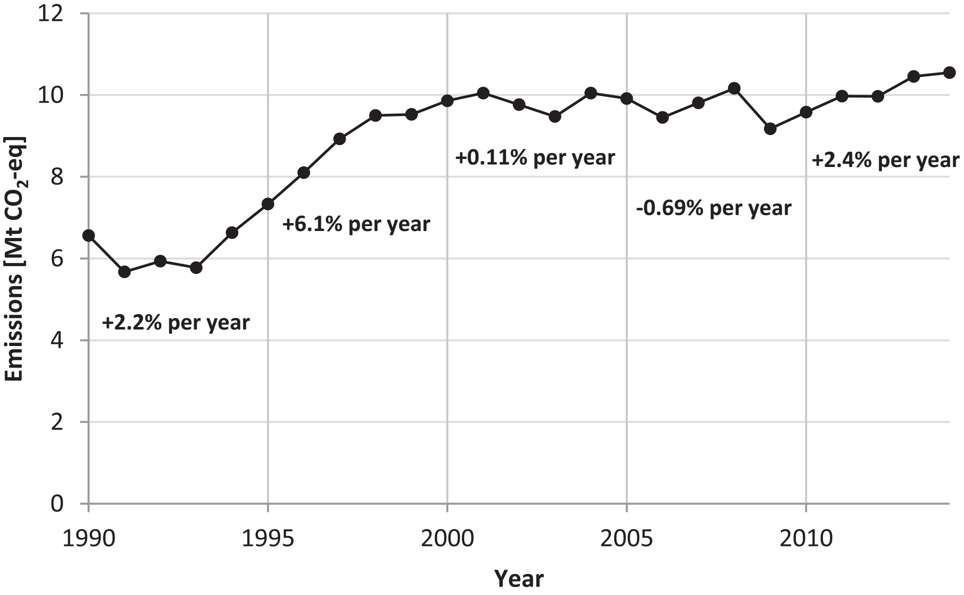

Fig. 3. GHG emissions from Swedish residents' international air travel 1990–2014. Percentages illustrate the average annual increase during each 5-year period, i.e. 1990–1995, 1995–2000, 2000–2005, 2005–2010 and 2010–2014.

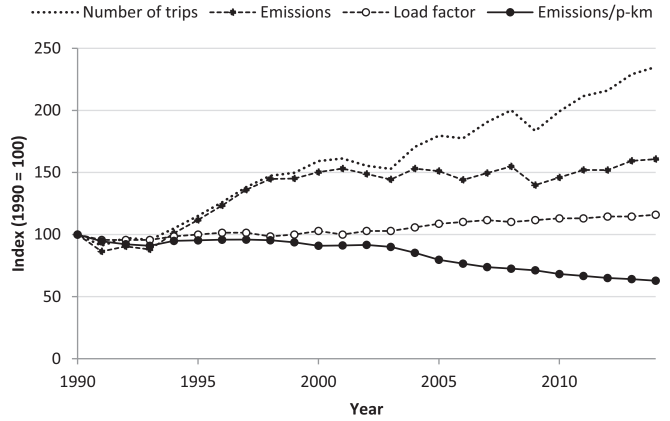

Fig. 4. Trends in total emissions from Swedish residents' international air travel, emissions per PKM, number of trips and average trip distance. Base year 1990 = 100.

3.5. *Uncertainty and sensitivity analysis*

Since the calculations are not only based on total statistics, but also on surveys which have inherent uncertainties, it is important to evaluate the reliability. If we take a look at the different components in the calculations, there are some that pose larger uncertainties than others.

The estimate of the share of trips made by Swedish residents is based on several different data sources. The basis is the official total passenger statistics from the Swedish public authority Trafikanalys. To adjust it to the number of trips made by the Swedish residents we used Swedavia's travel survey conducted at the airports, which to some extent poses an uncertainty. In an effort to identify the reliability of this data we examined the percentage of Swedish residents at Arlanda airport which account for 2/3 of all international passengers. The data shows that the share of Swedish residents has decreased steadily from 68% in 2004 to 55% in 2014. There are no strong outliers over the years, which indicates that the figures are robust.

Since the data used for estimating the average trip distance is based on a telephone survey, there is some uncertainty in the results. The data in Turistdatabasen has however been statistically evaluated previously with an estimated 95% confidence interval for the number of trips of around ± 5% (Johansson et al., 2005). Under the assumption that the surveys do not contain any systematic errors, we hence conclude that the reliability in the dataset is satisfactory. It should however be noted that the extra distance that is the result from changing flights, compared to flights directly to the final destination, are not accounted for in this calculation due to the lack of data on this matter, resulting in a systematic underestimation of the actual distances to the final destination.

Looking at the specific emissions per PKM, this number is based on official global statistics for PKM and fuel consumption. Our result, looking solely at CO_2 emissions, was 100 g CO_2 per PKM for 2014, while the European Union authorities made the estimations of 99 g CO_2 per PKM for flights within the EU (Eurocontrol, 2016). Hence our methodology for calculating this global average is in line with previous estimates which indicates robustness. Although emissions vary between different flights, due to the type of aircraft and load factor, a global emission average should give a good estimate of the emissions from a country's population, here in the case of Sweden, since residents fly all over the world and particularly in Europe.

On the other hand, the emission weighing factor used for non-CO_2 emissions has a significant scientific uncertainty. To the best scientific knowledge, the total effect of aviation emissions should be multiplied by 1.9 (Lee et al., 2010), but it has also been suggested that it is closer to 1.7 (Azar and Johansson, 2012). Should the effects be 1.7 instead, the final results regarding total emissions would drop by about 10%. Even with this level of uncertainty, it is important to point out that the relative development throughout the period would not be affected.

Our results are about 20% higher than the most similar previous study (Åkerman, 2012). The study by Åkerman was mainly based on telephone interviews, and individuals who are travelling frequently are more difficult to reach by telephone. It is also likely that some trips are simply forgotten by the respondents. These factors have likely resulted in an under estimation of the number of trips. In the study described in this paper, we avoid this by using official total statistics for the number of trips.

Whether the achieved level of reliability is adequate or not depends on the purpose of the accounting system. For an accounting system with the purpose of giving national decision-makers information on the levels and trends of emissions from international aviation, we would argue that the reliability is “good enough”, at least with the data that is available for Sweden.

4. Discussion and conclusion

An adequate accounting system for emissions from air travel is important for decision-makers assessing the need for new instruments. Such a system exists for domestic flights but is lacking for international flights. There are several different options for how emissions from international air travel might be allocated between different countries. We find that the option ‘residency of the passenger’ is the one that best meets the established criteria. With this option, countries with major transit hubs are not attributed unreasonably large shares of emissions. The emissions are instead carried by the country of residence of the passenger (the party reaping the most utility benefits). This allocation option has previously been dismissed due to a lack of availability of data (Faber et al., 2006; D.S. Lee et al., 2005; R. Wit et al., 2005). However, in this paper we have developed a new methodology which is mainly based on official statistics from different sources combined with data from travel surveys.

Applying this methodology for Sweden during the period 1990–2014 shows that the number of round trips increased on average by 3.6% per year. The average distance flown to the final destination has only marginally increased during this period. The number of long-distance trips to destinations in Asia or North America for example has increased, but so has the number of shorter trips from to Paris or London for example. The estimated emissions per PKM show an average reduction in emissions per PKM by 1.9% per year between 1990 and 2014. Emissions were about 190 g per km in 2014 if non-CO_2 effects are included. Looking solely at CO_2, emissions per PKM were 100 g of CO_2. Combining all the data indicates that the emissions caused by Swedish residents' international air travel were 11Mt CO_2 equivalents in 2014, including non-CO_2 effects.

Comparing the emissions per capita of Swedish residents to the global average showed that the Swedish number was seven times larger. This is a simple comparison that illustrates the uneven distribution of emissions globally, which is in line with several studies showing that only a very small share of the population causes large shares of aviation emissions in a typical year (Gössling et al., 2009; Larsson et al., 2015; Peeters et al., 2006).

The emissions from Swedish residents' international air travel are far greater than emissions from domestic air travel in Sweden. Emissions from Swedish residents' domestic air travel (calculated the same way as for international trips) were found to be 0.9 Mt CO_2 equivalents. Hence, 92% of GHG emissions from Swedish residents' air travel are caused by international trips.

What then are the possible scenarios for future emissions? With increasing private incomes and low ticket fares, it is likely that there will be a continued increase in demand for air travel among Swedish residents. IATA projects a global increase of 4% per year in the next 20 years (IATA, 2015a). The historical rate of increase (3.6% per year) in the number of international trips by Swedish residents would result in 260% more trips in 2050 compared with 2014. What this means for total emissions will depend on how the average distance and emissions per PKM changes. The average distance has not changed notably in the past, but the emissions per PKM have decreased by 1.9% per year on average. About half of this reduction is due to the increases in the load factor and since there is a theoretical maximal load factor of 100% this cannot continue much longer. Hence, the yearly decrease in emissions per PKM might be significantly lower in the future, as it has already slowed down in recent decades (IPCC, 2014a; Macintosh and Wallace, 2009; Owen et al., 2010). Introductions of low carbon fuels may however decrease the CO_2 emissions.

Future increases in demand of 3–4% per year thus risk increasing global emissions, which is problematic in relation to emissions targets. Sweden's goal is to reduce CO_2 emissions by 85% by 2045, compared with 1990 (Swedish Government, 2017). This goal does not include emissions from international air travel. If this goal is to be achieved along with a business-as-usual scenario for aviation – where emissions from international air travel by Swedish residents continues to rise by 2% per year – emissions from air travel will ultimately exceed land-based emissions by 2040.

As mentioned, we find that the emissions caused by Swedish residents' international air travel were 11Mt CO_2 equivalents in 2014, when both CO_2 and non-CO_2 effects are accounted for. This is in the same order as the emissions from all car driving in Sweden (Swedish Environmental Protection Agency, 2016), and emissions from car travel has declined the last decade emissions from aviation has risen during the same period. Although these calculations have different system boundaries and comparison should be done carefully, this could be an argument for having a similar climate governance in these two transport sectors. Many countries have a set of policies for the road sector aiming to deliver emission reductions in line with the two-degree target; e.g. carbon taxes, carbon emissions standards and policies for biofuels. The current policy pressure in the aviation sector is much lower.

The international aviation climate policies CORSIA and EU ETS will not deliver absolute reductions in global emissions since they do not cover non-CO_2 emissions and since they do not at all cover domestic aviation emissions in countries outside the EU. This policy deficit in relation to the two-degree target can be addressed through nationally decided policies, covering both domestic and international flights. One option that several European countries have adopted is air passenger taxes, which has been confirmed to reduce demand for air travel in the UK where such a tax was introduced in 1994 (Seetaram et al., 2016). To gain acceptance for substantially higher air travel taxes an NGO have suggested a “frequent flyer levy” where the tax level would increase for every extra flight that a person takes per year.[6] The introduction of low carbon fuels is an option for reducing GHG emissions which is put forward by the aviation industry (IATA, 2009, 2015b). Since the prices for biofuels are much higher than for fossil fuels strong policies are needed. One option that Norway is implementing is a quota obligation for low-carbon fuels, which stipulates that companies selling jet fuels must have an increasing share of low carbon fuels (Samferdselsdepartementet, 2017). A third example is policies for addressing the non-CO_2 climate impact which is in the same order of magnitude as the CO_2 emissions from aviation (Azar and Johansson, 2012; David S Lee et al., 2010). These emissions depend strongly on the altitude, geographic location and time of the emissions. One suggested policy is called “climate restricted airspaces” which implies that certain areas of the airspaces shall be closed based on weather forecasts three days in advance (Niklaß et al., 2017).

In order to follow the effects of any policies over time it is important to have ways of measuring emissions that are sensitive to various policies (Kander et al., 2015). The existing territorial based measure for CO_2 emissions from domestic aviation is sensitive to policies that are relevant for national travel, e.g. carbon tax on jet fuel or a quota obligation on low-carbon fuels for domestic aviation. The existing territorial based measure for CO_2 emissions from international aviation is problematic in many ways. It allocates substantial emissions to countries with large transit airports, and only minor to other countries. Another problem is that when a country gets more direct flight connections with other countries, this measure would show increasing emissions. This is due to the longer distances in comparison to the distance to the transit airport, while the emissions in reality would decrease since extra distances caused by the transfer is avoided. These problems indicate that it is problematic to only measure emissions from international air travel with the territorial perspective. Therefore, we suggest our residential approach as a complementary measure. It captures the emissions caused by air travel conducted by the population, without including the effect of e.g. increased number of incoming tourists. It covers all of the residents' air-travel, also trips that are starting at airports in neighboring countries. It is sensitive to policies aiming at making the residents reduce their number of international flights (regardless of starting airport) or choose closer destinations, e.g. through information-based policies or passenger taxes based on distance. It is also sensitive to policies aiming at reducing the non-CO_2 effects of aviation.

When designing policies and in order to gain public support for new policies, reliable data is thus an important aspect (Gössling et al., 2016). We argue that this paper provides a reliable methodology for reflecting a country's GHG emissions from international air travel. In order to do annual calculations of emissions from Swedish residents' international air travel, certain data needs to be kept and we recommend that policy is put in place to facilitate this. The state-owned enterprise Swedavia, which operates the major airports in Sweden, are conducting short interviews with about 150,000 respondents yearly. This can be the data source for both the share of Swedish residents as well as for average distance to the final destination. The availability of this data from Swedavia could be stipulated by the government. Another data option for the latter figure is the annual surveys for long distance travel which Statistics Sweden started to conduct in 2017 (Swedish Agency for Economic and Regional Growth, 2018).

The Swedish Environmental Protection Agency published preliminary results from our research (SEPA, 2017), showing that GHG emissions from international air travel is on par with car emissions, and this data has been frequently quoted in Sweden, e.g. by the Swedish Minister for Climate (Löwin, 2017). As such, this research has already partly reached one of its objectives by providing straightforward data for policy makers, something which is crucial for the development of responsible climate policies for international air travel.

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Appendix A. Supplementary data

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