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National Emissions of Greenhouse Gases and Air Pollutants from Commercial Aircraft in the Troposphere over South Korea

Sang-Keun Song[1] and Zang-Ho Shon[2,*]

[1] *Department of Earth and Marine Sciences, Jeju National University, Jeju, Republic of Korea*
[2] *Department of Environmental Engineering, Dong-Eui University, Busan, Republic of Korea*

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ABSTRACT

This study estimated greenhouse gas (GHG) and air pollutant emissions from aircraft in the troposphere (aircraft cruise altitudes, 1 - 12 km) over South Korea over a two-year period (2009 - 2010) using an activity-based (Landing and Take-Off (LTO) cycle) methodology. Both domestic and international LTOs covering 4 major airports and 11 smaller airports in South Korea were considered. The annual mean GHG emissions (CO_2, N_2O, CH_4, and H_2O) in the troposphere (1 - 12 km) over South Korea during the study period were approximately 3.5×10^3, 3.4×10^{-2}, -6.6×10^{-2}, and 1.4×10^3 kiloton (kt) yr^{-1}, respectively. The tropospheric air pollutant emissions (CO, NO_x, VOCs, and $PM_{2.5}$) were approximately 3.0, 20, 1.0, and 0.2 kt yr^{-1}, respectively. The monthly GHG and air pollutant emissions showed no significant variations. The GHG and air pollutant emissions during cruises over the South Korean airspace were significant contributors to (e.g., about 80% for NO_x and about 75% for CO_2) the total national aviation emissions including the emissions at airports, boundary layer and the free troposphere.

Key words: Troposphere, Aircraft Emission, Greenhouse gas, Air pollutants

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1. INTRODUCTION

The emissions of air pollutants [nitrogen oxides (NO_x), volatile organic compounds (VOCs) and particulate matter (PM)] and greenhouse gases (GHGs) from land transportation, such as roads, rail and inland shipping have been reported to have a significant impact on the atmosphere and climate change (Uherek et al. 2010). Although aviation emissions [2.7 Teragram (Tg) yr^{-1} of NO_x in 2006; Wilkerson et al. 2010] comprise a small fraction of the global NO_x emissions from man-made and natural sources, NO_x emissions from subsonic aircraft might have a pronounced impact on the atmospheric chemical composition (Lee et al. 1997; Gauss et al. 2006). Aviation also plays an important role in long-range transportation and is expected to grow gradually in the future. The annual passenger traffic growth rate between 2000 and 2007 was 5.3% yr^{-1}, showing a 38% increase in passenger traffic (Lee et al. 2009). This growth trend is expected to continue over the next 20 years with world passenger traffic growing at 5% annually due to the large demand in the Asia Pacific, Middle East and Latin American air transportation markets (Boeing Commercial Airplanes 2012). In 2006 the global emissions of CO_2, H_2O, NO_x, and CO from aircraft were estimated to be 162 (Tg-C), 233, 2.7, and 0.68 Tg yr^{-1}, respectively, with 93% of the world's aviation fuel consumption in the Northern Hemisphere (69% between 30 and 60°N) and 75% above 7 km for geographic coverage (Wilkerson et al. 2010). CO_2 emissions in East Asia account for 11% of global aviation CO_2 emissions (Wilkerson et al. 2010).

Accurate estimations of aircraft traffic air pollutant emissions, such as NO_x, VOCs, and PM, are essential for examining their impact on the air quality in surface source regions, such as the vicinity of large cities even in the free troposphere where other emission sources are less significant. The ozone (O_3) concentrations in the boundary layer and free troposphere can be affected by NO_x and VOCs emissions from aircraft, depending on the sensitivity of O_3 precursors (e.g., NO_x and VOCs) to O_3 concentration (NO_x-limited

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* *Corresponding author*
E-mail: zangho@deu.ac.kr

vs. VOC-limited) (Kleinman et al. 1997; Sillman 1999). The maximum impact of aircraft emissions on the O_3 surface concentration might occur near airports within the surface layer during the night due to the rapid O_3 titration by NO emitted from aircraft, which is a more important impact of NO_x emissions than VOC emissions on O_3 destruction (Pison and Menut 2004). In the cruising altitudes in the upper troposphere and lower stratosphere, NO_x emissions from aircraft are expected to increase the O_3 concentration (Hidalgo and Crutzen 1977; Johnson et al. 1992; Schumann 1997; Dameris et al. 1998; Kentarchos and Roelofs 2002; Grewe et al. 2002; Gauss et al. 2006). For example, Gauss et al. (2006) reported an aircraft-induced maximum increase in the zonal-mean O_3 concentrations ranging from 3.1 (in September) to 7.7 ppb (in June), accompanying that in the zonal-mean total reactive nitrogen (NO_y) from 156 (August) to 322 ppt (May). In addition, environmental concerns regarding the increase in fine PM emissions from the aircraft around large airports have recently increased (Webb et al. 2008; Lobo et al. 2012).

In contrast to other major anthropogenic emission sources, aircraft largely emit air pollutants and GHGs at flight altitudes in the free troposphere and lower stratosphere, where the lifetimes of the exhaust products as well as secondary photochemical products, e.g., O_3, are much longer than those at the surface. Aviation emissions including contrails combined with this relatively longer lifetime can contribute to a change in the radiative forcing (RF) in the climate (Travis et al. 2002; Lee et al. 2010). This impact also occurs through direct (i.e., warming by CO_2 and H_2O) and indirect (via atmospheric chemistry: O_3 formation and CH_4 reduction) effects. The total aviation RF has increased by 14% (excluding induced cirrus) from 2000 to 2005. The total aviation RF in 2005 was approximately 55 mW m^{-2}, which comprised 3.5% of the total anthropogenic forcing (Lee et al. 2009).

Compared to Europe and the USA (Wilkerson et al. 2010 and references therein), only a few studies have examined the regional aircraft emission data in Asia (Fan et al. 2012; Song and Shon 2012). This study used an activity-based methodology to estimate the national emissions of GHGs (CO_2, N_2O, H_2O, and CH_4) and air pollutants (NO_x, CO, VOCs, and PM) in the South Korean airspace over a two-year period (2009 - 2010). To the best of the authors' knowledge this study provides the first landing and takeoff (LTO)-based aircraft emission estimates of both GHGs and air pollutants in the highly expanding air traffic regions in East Asia, covering both the surface and free troposphere (aircraft cruise altitudes, 1 - 12 km). The spatiotemporal distribution (including geographical and monthly emissions) of these emissions was also characterized.

2. METHODS

2.1 Study Location

The emissions of GHGs (e.g., CO_2, N_2O, CH_4, and H_2O) and air pollutants (NO_x, CO, VOCs, and PM) from aircraft were calculated based on four major international airports in South Korea: Incheon (International Civil Aviation Organization (ICAO) code: RKSI), Gimpo (RKSS), Gimhae (RKPK), and Jeju International Airports (RKPC) (Fig. 1). Detailed information on these four airports can be found in the report by Song and Shon (2012). For domestic flights, thirty domestic air traffic routes involving 4 major airports were considered for the geographical distribution of aircraft emissions in Korean airspace (Fig. 1). For international flights, twelve international air traffic routes involving 4 major airports were considered (Fig. 1 and Table 1).

2.2 Estimation Methods of Aircraft Emissions

Aircraft emissions depend on the following factors: the number and types of aircraft operations; types and efficiency of aircraft engines; fuel used; length of flight; power setting; time in operation mode; and to a lesser degree, the aircraft exhaust gases emission altitude (IPCC 2006). To calculate the aircraft emissions, aircraft operations were divided into LTO cycles (taxi-in and out, start-up, approach, take-off and climb-out) and cruising. In general, the methods for estimating the emissions from aviation sources can be categorized into 3 types (Tier 1 - 3). Briefly, the Tier 1, 2, and 3 methods are based on the aggregate fuel consumption quantity data, the number of LTOs, and actual flight movement data including the number of LTOs, respectively [IPCC 2006; European Environment Agency (EEA) 2009]. A detailed description of these methods can be found in EEA (2009). In this study the LTO cycles in the boundary layer and actual flight pathways in the free troposphere (Tier 2) were used to estimate the national aircraft emissions in the boundary layer and at cruising altitudes (1 - 12 km) in the South Korean airspace. This method is generally more accurate than the fuel consumption based method (Tier 1) because the activity (LTO) based method represents actual aviation situations (aircraft type, flight route, etc.). However, there are some limitations in applying Tier 2 methodology to obtain the correct data on fuel use and emission factors. The emission factors and fuel use factors are based on the fuel use of average aircraft. In fact, the average aircraft is different from the specific aircraft type and engine used in Korea. This can cause uncertainty in the aircraft emissions. The limitations in the fuel use and emission factors are discussed further below.

The aircraft emissions in cruise were calculated using Eq. (1):

$$E_{ij} = S(LTO_i \times F_i \times EF_{ij}) \tag{1}$$

E_{ij} = Emission (kg yr^{-1}) of species (j) for the aircraft type (i).

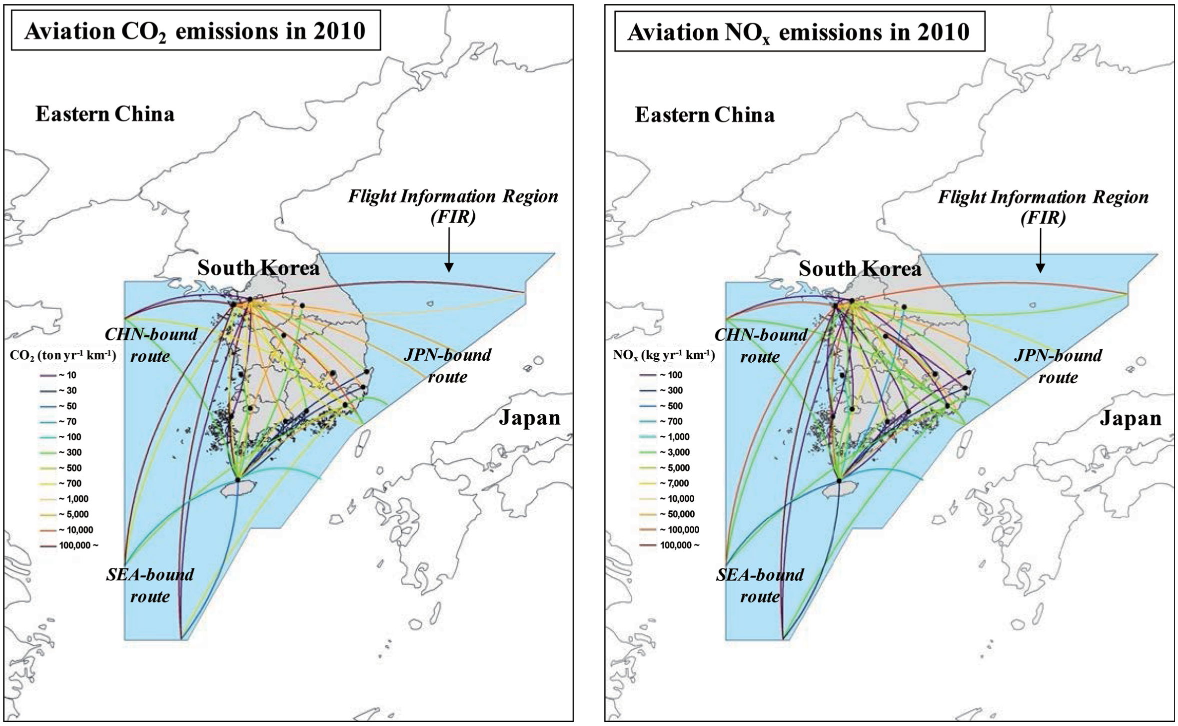

Fig. 1. Air routes for domestic and international flights and geographical distribution of CO_2 and NO_x emissions (in 2010) for flight routes over South Korea. CHN-bound, JPN-bound, and SEA-bound routes indicate international routes to China, Japan, and Southeast of Asia, respectively. Flight information region (FIR) represents the airspace over South Korea.

Table 1. Twelve international air traffic routes, including one or several sub routes, in the airspace over South Korea.

Route		
RKSI-JPN	Four sub routes	RKSI-Fukuoka
		RKSI-Narita
		RKSI-Chitose
		RKSI-Akita
RKSI-CHN	Two sub routes	RKSI-Beijing
		RKSI-Pudong
RKSI-SEA	A single route	RKSI-SEA
RKSS-JPN	Two sub routes	RKSS-Fukuoka
		RKSS-Narita
RKSS-CHN	Two sub routes	RKSS-Beijing
		RKSS-Pudong
RKSS-SEA	A single route	RKSS-SEA
RKPK-JPN	Two sub routes	RKPK-Fukuoka
		RKPK-Narita
RKPK-CHN	Two sub routes	RKPK-Beijing
		RKPK-Pudong
RKPK-SEA	A single route	RKPK-SEA
RKPC-JPN	A single route	RKPC-JPN
RKPC-CHN	Two sub routes	RKPC-Beijing
		RKPC-Pudong
RKPC-SEA	A single route	RKPC-SEA

Note: RKSI: Incheon airport, RKSS: Gimpo airport, RKPK: Gimhae airport, and RKPC: Jeju airport. JPN: Japan; CHN: China; and SEA: Southeast Asia.

LTO_i = Number of LTO for the aircraft type (i).

F_i = Fuel consumption for the aircraft type (i) and cruising route (1000kg).

EF_{ij} = Weighted-average emission factor (kg/1000kg-fuel) of species (j) for the aircraft type (i) associated with the total number of engine models.

The yearly chemical species emissions at each airport (E_{ij}) were calculated from the monthly emission summation for all aircraft types based on monthly LTOs. The numbers of LTOs at the three airports, RKSS, RKPK and RKPC, and the RKSI airport were obtained from the Korea Airport Corporation (KAC, http://www.airport.co.kr/) and Incheon International Airport Corporation (IIAC, http://www.airport.kr/), respectively. The fuel consumption (use) for the specific aircraft type in the flight route was calculated using regression analysis using the standard flight distances (e.g., 125, 250, 500, 750, and 1000 nm), their corresponding standard fuel uses and the actual cruising distances (Table 2). The standard flight distances (in nm) and their corresponding fuel uses for the specific aircraft type are available from the European Monitoring and Evaluation Programme (EMEP)/EEA Guidebook website (http://www.eea.europa.eu/emep-eea-guidebook, EEA 2009). The flight distance for each domestic and international route in Korean airspace was estimated using the coordinates (latitude, longitude) of transit fixes in flight routes between two airports obtained from the Enroute Chart-ICAO (Office of Civil Aviation Ministry of

Table 2. Regression analysis for fuel consumption and NO_x, VOCs, and CO emission factors using standard flight distances.

	A310	A320	A330	A340	B737
Reg. Ana.[a] (fuel use)	$y = 4.534x + 241.53$	$y = 2.638x + 326.84$	$y = 6.455x + 124.92$	$y = 7.321x - 416.92$	$y = 3.033x - 11.94$
r^2 (fuel use)	1.0	0.9994	0.9992	0.9996	0.9995
Reg. Ana. (EF_{NOx})[b]	$y = -6.124\ln(x) + 57.39$	$y = -2.341\ln(x) + 31.79$	$y = -7.393\ln(x) + 68.96$	$y = -3.069\ln(x) + 40.08$	$y = -1.208\ln(x) + 18.49$
r^2 (EF_{NOx})	0.9663	0.897	0.9398	0.9986	0.9461
Reg. Ana. (EF_{VOC})[c]	$y = -0.040\ln(x) + 0.449$	$y = -0.001\ln(x) + 0.185$	$y = -2.57E-7x^2 + 2.44E-4 x + 1.03$	$y = -8E-6x^2 + 7.0E-3x + 4.03$	$y = -0.056\ln(x) + 0.507$
r^2 (EF_{VOC})	0.9894	0.960	1	1	0.9837
Reg. Ana. (EF_{CO})[d]	$y = -0.283 \ln(x) + 2.815$	$y = -0.170 \ln(x) + 2.172$	$y = -2E-6x^2 + 1.6E-3x + 1.90$	$y = -9E-6x^2 + 8.7E-3x + 3.56$	$y = -0.787\ln(x) + 7.469$
r^2 (EF_{CO})	0.9858	0.9150	1	1	0.9848

	B747	B757	B767	B777	DC10
Reg. Ana.[a] (fuel use)	$y = 9.621x + 971.85$	$y = 3.746x + 304.19$	$y = 4.786x + 395.41$	$y = 7.908x + 94.99$	$Y = 8.054x + 596.71$
r^2 (fuel use)	0.9991	0.9998	0.9996	0.9997	0.9998
Reg. Ana. (EF_{NOx})[b]	$y = -3.151\ln(x) + 38.6$	$y = -7.922\ln(x) + 72.42$	$y = -2.216\ln(x) + 30.87$	$y = -1.7E-7x^4 + 7.5E-8x^3 + 1.2x^2 + 7.0E-2x + 6.4$	$y = -2.443\ln(x) + 36.68$
r^2 (EF_{NOx})	0.990	0.9560	0.9612	1	0.9403
Reg. Ana. (EF_{VOC})[c]	$y = -0.407\ln(x) + 3.683$	$y = -0.036\ln(x) + 1.256$	$y = 0.131\ln(x) - 0.562$	$y = -1.02E-5x^2 + 7.85E-3x + 2.20$	$y = -1.00E-6x^2 + 4.10E-3x + 6.02$
r^2 (EF_{VOC})	0.9656	0.9630	0.9624	1	0.9785
Reg. Ana. (EF_{CO})[d]	$y = -1.144\ln(x) + 10.59$	$y = -0.257\ln(x) + 3.474$	$y = -0.556\ln(x) + 5.683$	$y = -9.88E-6x^2 + 1.09E-2x + 5.60$	$y = -6.0E-7x^2 + 2.90E-3x + 5.07$
r^2 (EF_{CO})	0.9661	0.9652	0.9710	1	0.9646

Note: [a] *Regression equation.*
[b] *Emission factor for* NO_x.
[c] *Emission factor for VOCs.*
[d] *Emission factor for CO.*

Land, Transport and Maritime affairs, 2012, Aeronautical Information Services, http://ais.casa.go.kr/). Chemical species emission factors such as CO, NO_x, and VOCs for each aircraft type were calculated based on fuel use. The emission factor for specific flight distance between two airports was estimated using regression analysis (Table 2) using standard flight distances and their corresponding emission factors (http://www.eea.europa.eu/emep-eea-guidebook, EEA 2009). Since the emission factors for certain types of aircraft such as A300, A319, and A321 were not available, those factors were replaced with A310, A320, and A320, respectively. This might cause a limitation in accurate aircraft emission estimation. The emission factors for CO_2 and $PM_{2.5}$ were adopted from Table 3-3 of EEA 2009. The emission factors for N_2O and CH_4 were adopted from Santoni et al. (2011) and that for H_2O was obtained from Vay et al. (1998). The emission factors used in this study are summarized in Table 3. An estimation of military aircraft emissions was excluded for national security reasons. Furthermore, the GHG and air pollutant emissions with altitude (surface to 12 km) were discussed using this study (1 - 12 km) and our previous study (Song and Shon 2012). The airport ground-level (apron, taxi, and runway) emissions were adopted from Song and Shon (2012), while the emissions within the boundary layer (between ground level and 1km) were adopted using the emissions for approach and climb-out modes.

3. RESULTS AND DISCUSSION

3.1 Emissions of GHGs in the Free Troposphere

Table 4 lists the number of monthly LTOs according to the aircraft cruising route in the free troposphere during the study period, 2009 - 2010. The busy domestic routes were the routes between SS (RKSS) and PC (RKPC) and between SS (RKSS) and PK (RKPK) airports (Table 4a). For example, the number of LTOs for the route between SS and PC were 55543 and 58599 in 2009 and 2010, respectively, which was 38 - 40% of the 30 domestic routes. A slight variation in monthly LTOs was observed during the study period, showing the highest values in August (2009) or October (2010) and the lowest in February. The busiest international route based at the 4 major international airports (RKSI, RKSS, RKPK and RKPC) was the route between SI (RKSI, Incheon) and China, followed by the route between SI and Japan (Table 4b). The number of LTOs for these China and Japan routes were 38 - 39% and 28 - 29% of the total international routes, respectively, due to the rapid increase in tourism and trade between the two countries. Detailed information on the LTOs and aircraft types at 4 international airports was reported by Song and Shon (2012). Briefly, the dominant aircraft type was B737 at RKSS, RKPK and RKPC (accounting for 56 - 69% of the total LTOs). The dominant types at RKSI were A330 (17 - 18%), B747 (18 - 19%) and B777 (16%).

Tables 5a and 6a present the GHG emissions, such as CO_2, N_2O, CH_4, and H_2O, in the free troposphere for

Table 3. GHG and air pollutant emission factors for aircraft types (in g kg^{-1} of fuel).

Aircraft type	**CO**	**NO_x**	**VOC**	**$PM_{2.5}$**	**N_2O**	**CH_4**	**CO_2**	**H_2O**
B737	2.66	11.11	0.16	0.20	0.031	-0.06	3150	1228
B747	3.63	19.36	1.24	0.20	0.031	-0.06	3150	1228
B757	1.95	24.03	1.07	0.20	0.031	-0.06	3150	1228
B767	2.32	17.36	0.24	0.20	0.031	-0.06	3150	1228
B777	2.70	20.48	0.73	0.20	0.031	-0.06	3150	1228
A300	1.10	20.00	0.20	0.20	0.031	-0.06	3150	1228
A310	1.10	20.00	0.20	0.20	0.031	-0.06	3150	1228
A319	1.19	17.49	0.18	0.20	0.031	-0.06	3150	1228
A320	1.19	17.49	0.18	0.20	0.031	-0.06	3150	1228
A321	1.19	17.49	0.18	0.20	0.031	-0.06	3150	1228
A330	1.95	23.80	1.09	0.20	0.031	-0.06	3150	1228
A340	5.34	21.38	5.56	0.20	0.031	-0.06	3150	1228
A380	5.34	21.38	5.56	0.20	0.031	-0.06	3150	1228
AN12	2.65	8.64	0.70	0.20	0.031	-0.06	3150	1228
AN124	0.47	26.42	0.14	0.20	0.031	-0.06	3150	1228
AN225	0.47	26.42	0.14	0.20	0.031	-0.06	3150	1228
DC10	4.29	21.76	4.42	0.20	0.031	-0.06	3150	1228
DC8F	1.29	15.55	0.05	0.20	0.031	-0.06	3150	1228
E190	1.32	14.23	0.37	0.20	0.031	-0.06	3150	1228
G1159	0.48	15.54	0.12	0.20	0.031	-0.06	3150	1228
IL76	5.07	9.77	0.69	0.20	0.031	-0.06	3150	1228
IL96	0.47	26.46	0.14	0.20	0.031	-0.06	3150	1228
MD11 or Q400	1.67	15.42	0.57	0.20	0.031	-0.06	3150	1228
MD80 or BB-CRJ-200	1.67	15.42	0.57	0.20	0.031	-0.06	3150	1228
MD90	1.67	15.42	0.57	0.20	0.031	-0.06	3150	1228
TU154	4.96	10.30	0.64	0.20	0.031	-0.06	3150	1228
TU204	0.48	15.92	0.03	0.20	0.031	-0.06	3150	1228
Q400	10.96	3.73	0.07	0.20	0.031	-0.06	3150	1228
Others	0.08	9.23	0.07	0.20	0.031	-0.06	3150	1228

Note: Values represent emission factors calculated from the cruise distance of 450 km, which covers the highest number of LTOs during the study period.

Table 4. The number of monthly LTOs for the aircraft cruising route in the free troposphere during the study period of 2009 - 2010.

(a) Domestic cruise.

	2010 (2009)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
SS-PC	4545 (3935)	4288 (3466)	4772 (4189)	5050 (4389)	5181 (5173)	4686 (4701)	4704 (4920)	4992 (5442)	4843 (4652)	5523 (5099)	5085 (4705)	4930 (4872)	58599 (55543)
SS-PK	1698 (1912)	1661 (1711)	1836 (1896)	1726 (1956)	1809 (1963)	1672 (1995)	1682 (1987)	1751 (1942)	1708 (1765)	1737 (1842)	1638 (1737)	1770 (1871)	20688 (22577)
PK-PC	1307 (987)	1179 (870)	1327 (991)	1504 (1131)	1513 (1223)	1321 (1333)	1253 (1423)	1341 (1544)	1291 (1297)	1387 (1539)	1346 (1545)	1406 (1420)	16175 (15303)
SS-PU	715 (789)	690 (682)	741 (774)	741 (730)	702 (756)	692 (734)	682 (714)	688 (755)	678 (754)	716 (769)	667 (742)	712 (784)	8424 (8983)
PC-TU	738 (649)	714 (594)	795 (661)	748 (642)	692 (679)	635 (715)	650 (804)	657 (810)	613 (719)	637 (795)	605 (762)	612 (792)	8096 (8622)
PC-TN	471 (511)	444 (465)	496 (528)	480 (464)	490 (501)	470 (479)	494 (503)	485 (504)	471 (482)	504 (500)	480 (480)	485 (497)	5770 (5914)
PC-JJ	464 (489)	428 (428)	477 (496)	467 (460)	466 (484)	423 (475)	435 (477)	430 (496)	414 (465)	466 (495)	480 (480)	471 (491)	5421 (5736)
SS-JY	438 (475)	426 (380)	472 (478)	441 (449)	416 (470)	466 (464)	468 (441)	468 (472)	469 (470)	476 (469)	418 (448)	479 (484)	5437 (5500)
SS-JJ	380 (441)	407 (363)	429 (421)	414 (414)	426 (428)	411 (420)	423 (427)	421 (434)	410 (413)	404 (442)	388 (414)	397 (393)	4910 (5010)
SS-TH	278 (370)	258 (316)	278 (356)	276 (302)	282 (312)	276 (300)	288 (274)	286 (266)	274 (284)	302 (282)	226 (272)	300 (302)	3324 (3636)
Other*	860 (776)	809 (670)	872 (812)	846 (901)	875 (963)	811 (877)	787 (924)	809 (1028)	737 (897)	851 (965)	792 (871)	735 (874)	9784 (10558)
Total	11894 (11334)	11304 (9945)	12495 (11602)	12693 (11838)	12852 (12952)	11863 (12493)	11866 (12894)	12328 (13693)	11908 (12198)	13003 (13197)	12125 (12456)	12297 (12780)	146628 (147382)

(b) International cruise.

	2010 (2009)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
SI-JPN	5614 (5478)**	5158 (4907)	5720 (5461)	5559 (5320)	5828 (5511)	5695 (5342)	6085 (5627)	6246 (5721)	5889 (5441)	5895 (5627)	5698 (5535)	5859 (5560)	69246 (65530)
SI-CHN	7235 (7389)	6809 (6685)	7559 (7516)	7605 (7238)	8267 (7517)	8034 (6985)	8506 (7619)	8623 (7847)	8303 (7302)	8455 (7430)	7920 (7279)	8070 (7189)	95386 (87996)
SI-SEA	3490 (3449)	3185 (3023)	3280 (3107)	3225 (2940)	3324 (2969)	3127 (2763)	3487 (3056)	3730 (3276)	3385 (2817)	3519 (2911)	3614 (2933)	4034 (3296)	41400 (36540)
SS-JPN	977 (666)	906 (616)	985 (682)	960 (660)	994 (742)	961 (720)	992 (741)	992 (744)	960 (720)	995 (753)	1192 (884)	1249 (991)	12163 (8919)
SS-CHN	245 (246)	229 (227)	248 (252)	242 (240)	251 (249)	240 (240)	248 (244)	245 (248)	236 (239)	248 (249)	240 (240)	262 (247)	2934 (2921)
SS-SEA	0 (0)	2 (1)	0 (0)	2 (2)	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	3 (0)	26 (0)	34 (3)
PK-JPN	709 (824)	608 (733)	662 (794)	753 (706)	899 (736)	801 (693)	862 (719)	867 (753)	801 (688)	836 (732)	785 (712)	853 (745)	9436 (8835)
PK-CHN	583 (558)	518 (478)	559 (572)	595 (553)	638 (602)	677 (516)	723 (563)	740 (645)	709 (574)	798 (574)	587 (516)	548 (531)	7675 (6682)
PK-SEA	520 (513)	481 (445)	477 (455)	391 (433)	444 (448)	379 (339)	498 (388)	565 (420)	494 (334)	543 (355)	580 (414)	652 (444)	6024 (4988)
PC-JPN	166 (149)	152 (135)	186 (164)	191 (153)	216 (208)	190 (182)	210 (193)	197 (192)	208 (200)	212 (200)	189 (198)	198 (170)	2315 (2144)
PC-CHN	185 (80)	146 (75)	126 (135)	190 (152)	234 (169)	215 (149)	243 (186)	278 (212)	256 (169)	236 (230)	160 (197)	154 (182)	2423 (1936)
PC-SEA	16 (42)	24 (24)	20 (29)	40 (71)	38 (95)	59 (66)	76 (60)	77 (63)	62 (53)	61 (57)	40 (36)	24 (38)	537 (634)
Total	19740 (19394)	18218 (17349)	19822 (19167)	19753 (18468)	21134 (19246)	20378 (17995)	21930 (19396)	22560 (20121)	21303 (18537)	21798 (19118)	21008 (18944)	21929 (19393)	249573 (227128)

Note: SS: Gimpo airport, SI: Incheon airport, PC: Jeju airport, PK: Gimhae airport, PU: Ulsan airport, TU: Cheongju airport, TN: Daegu airport, JJ: Gwangju airport, JY: Yeosu airport, and TH: Pohang airport. JPN: Japan; CHN: China; and SEA: Southeast of Asia.

* *Other: 20 routes.*

** *The number in parenthesis is LTO in 2009.*

Table 5. GHG and air pollutant emissions for domestic cruise (1 - 12 km) during the study period (ton yr^{-1}).

(a) GHGs.

	N_2O		CH_4		CO_2		H_2O	
	2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
SS-PC	3.1	3.2	-6.1	-6.3	300432	329507	124553	128455
SS-PK	1.0	0.9	-1.9	-1.7	99347	88805	38730	34620
PK-PC	0.5	0.5	-1.0	-1.0	52326	54001	20399	21052
SS-PU	0.4	0.4	-0.9	-0.8	44802	40993	17466	15981
PC-TU	0.4	0.4	-0.7	-0.7	38433	35779	14983	13948
PC-TN	0.3	0.3	-0.5	-0.5	26301	25425	10253	9912
PC-JJ	0.1	0.1	-0.3	-0.2	13900	12878	5419	5020
SS-JY	0.2	0.2	-0.5	-0.5	24463	23616	9537	9207
SS-JJ	0.2	0.2	-0.3	-0.3	18273	17405	7124	6785
SS-TH	0.1	0.1	-0.3	-0.2	12981	11536	5060	4497
Other*	0.4	0.5	-0.8	-0.9	40884	49386	15894	19103
Total	6.8	6.8	-13	-13	672143	689331	269417	268580

(b) Air pollutants.

	CO		NO_x		VOC		$PM_{2.5}$	
	2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
SS-PC	235	238	1590	1637	43	41	20	21
SS-PK	79	69	522	465	14	12	6	6
PK-PC	40	42	270	274	7	8	3	3
SS-PU	34	31	229	209	6	5	3	3
PC-TU	25	22	189	178	3	3	2	2
PC-TN	17	16	130	126	2	2	2	2
PC-JJ	10	9	78	74	1	1	1	1
SS-JY	19	18	127	123	3	3	2	1
SS-JJ	15	14	99	94	3	2	1	1
SS-TH	11	9	71	62	2	2	1	1
Other*	30	42	203	276	4	10	3	3
Total	514	510	3509	3518	89	88	44	44

Note: * *Other: 20 routes.*

Table 6. GHG and air pollutant emissions for international cruise (1 - 12km) during the study period (ton yr^{-1}).

(a) GHGs.

	N_2O		CH_4		CO_2		H_2O	
	2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
SI-JPN	8	9	-16	-17	849979	883346	331357	344365
SI-CHN	9	10	-18	-19	939996	1000379	366449	389989
SI-SEA	7	8	-14	-16	732461	814925	285544	317691
SS-JPN	0.5	0.7	-1	-1	54354	70936	21189	27654
SS-CHN	0.3	0.3	-0.5	-0.5	26919	26471	10494	10320
SS-SEA	< 0.1	< 0.1	< -0.1	< -0.1	8	215	3	84
PK-JPN	0.1	0.1	-0.2	-0.2	9505	9629	3706	3754
PK-CHN	0.4	0.4	-0.7	-0.8	37949	42936	14794	16738
PK-SEA	0.3	0.3	-0.5	-0.6	26464	31364	10317	12227
PC-JPN	0. 1	0.1	-0.1	-0.1	5138	5493	2003	2141
PC-CHN	0.1	0.1	-0.2	-0.3	9648	13254	3761	5167
PC-SEA	< 0.1	< 0.1	-0.1	< -0.1	2729	2240	1064	873
Total	27	29	-51	-55	2695151	2901188	1050681	1131003

Table 6. (Continued)

(b) Air pollutants.

	CO		NO_x		VOC		$PM_{2.5}$	
	2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
SI-JPN	783	809	5203	5402	276	285	54	56
SI-CHN	903	955	5745	6107	342	363	60	64
SI-SEA	599	664	4119	4579	262	292	47	52
SS-JPN	39	50	265	347	7	9	3	5
SS-CHN	17	16	120	117	3	3	2	2
SS-SEA	< 1	< 1	< 1	1	< 1	< 1	< 1	< 1
PK-JPN	8	9	62	62	1	1	1	1
PK-CHN	26	30	175	195	4	6	2	3
PK-SEA	18	22	125	145	3	4	2	2
PC-JPN	4	4	29	31	< 1	< 1	< 1	< 1
PC-CHN	6	8	45	61	1	1	1	1
PC-SEA	2	1.454	13	11	< 1	< 1	< 1	< 1
Total	2405	2569	15901	17059	900	964	171	184

domestic and international routes during the study period. The GHG emissions from international routes were a factor of 4 higher than those from domestic routes. As shown in Table 5a the highest domestic GHG emissions occurred in the route between SS and PC. No significant changes in the yearly GHG emissions were observed between the two years (≤ 4%). The negative CH_4 emissions suggest a decrease in atmospheric CH_4 concentration through chemical reactions in the atmosphere involving NO_x emissions. The highest international route of GHG emissions were observed in the route between SI and China followed by the route between SI and Japan (Table 6a). The GHG emissions for the route between SI and China ranged from 940 to 1,000 for CO_2, 0.0093 to 0.0098 for N_2O, -0.018 to -0.019 for CH_4, and 366 to 390 kilogram (kt) yr^{-1} for H_2O. The yearly variations in emissions from the domestic and international routes were insignificant in the two year monitoring period (< 8%).

The magnitude of total CO_2 emission (4.8 Tg yr^{-1}) estimated from aircraft (in 2010) in the boundary layer and free troposphere over South Korea in this study was similar to that (3.8 Tg yr^{-1}) estimated for domestic civil aviation in China in 2010 (Fan et al. 2012) and in the boundary layer of UK airports (2.4 Tg yr^{-1}) in 2005 (Stettler et al. 2011). The present estimate of national CO_2 emission from civil aviation in 2009 was 0.8% of the global civil aviation (162 Tg-C yr^{-1}) in 2006 (Wilkerson et al. 2010). Note that the Chinese emissions estimated using fuel consumption and domestic flights considered only the cruise phase and did not include international cruises. The UK emissions [estimated using the activity (LTO)-based methodology] considered the emissions from airports only. The total aircraft CO_2 emissions at all four major airports in 2009 derived from the current study accounted for approximately 0.84% of the national annual CO_2 emissions (540 Tg yr^{-1} in 2009) in South Korea, estimated using the 1996 IPCC Guidelines for National Greenhouse Gas Inventories (GIR 2011, http://www.gir.go.kr/og/hm/gs/a/OGHMGSA010.do). Note that the national GHG inventory excludes international air traffic emissions (and ground support equipment (GSE) emission) and includes the emissions throughout the full domestic flight path (cruise phase).

Table 7a and Fig. 2 present the monthly GHG emissions in the free troposphere for both domestic and international routes during 2009 - 2010. The monthly variations in 2009 were similar to those in 2010. In general, the monthly emission variations in the domestic routes (≤ 32%) were slightly higher than that in the international routes (≤ 10%). The monthly GHG emissions were highest in August (2009) or October (2010) for the domestic route, whereas the international routes were highest in January (2009) or August (2010) due to a temporal difference in the number of international passengers. The mean monthly CO_2, N_2O, CH_4, and H_2O emissions for the domestic routes in 2009 (and 2010) were 56 ± 7 (58 ± 4) kt $month^{-1}$, 566 ± 42 (571 ± 37) kg $month^{-1}$, -1097 ± 81 (-1105 ± 71) kg $month^{-1}$, and 22 ± 2 (23 ± 1) kt $month^{-1}$, respectively. The mean monthly CO_2, N_2O, CH_4, and H_2O emissions for the international routes in 2009 (and 2010) were 225 ± 9 (242 ± 10) kt $month^{-1}$, 2210 ± 90 (2379 ± 103) kg $month^{-1}$, -4278 ± 174 (-4605 ± 200) kg $month^{-1}$, and 88 ± 4 (94 ± 4) kt $month^{-1}$, respectively. A distinct seasonal difference in GHG emissions was observed between domestic and international routes due to the different demands for flights. For example, the GHG emissions for the domestic route were highest in summer, whereas those for the international route were highest in winter.

The emissions of GHGs (and air pollutants) differed according to the aircraft type (Fig. 3). Moreover, the aircraft type that emitted the dominant amount of GHG emissions differed according to the cruise type. For example, the aircraft type emitting the highest GHG emissions for the domestic routes was the B737 (e.g., 517 - 536 kt yr^{-1} for CO_2, 5.2 - 5.3 ton yr^{-1} for N_2O, -10 ton yr^{-1} for CH_4, 205 - 209 kt yr^{-1} for H_2O) followed by A300 and A321. The GHG emissions for the B737 comprised 47% of the total emissions. For the international route, the aircraft type emitting the highest

Table 7. Monthly GHG and air pollutant emissions for cruise (1 - 12 km) (ton yr^{-1}).

(a) GHGs.

		N_2O		CH_4		CO_2		H_2O	
	Month	**Domestic**	**International**	**Domestic**	**International**	**Domestic**	**International**	**Domestic**	**International**
2009	1	0.53	2.3	-1.0	-4.5	54156	234882	21112	91567
	2	0.47	2.0	-0.9	-4.0	47485	208006	18597	81089
	3	0.55	2.2	-1.1	-4.4	55973	228522	21821	89087
	4	0.55	2.2	-1.1	-4.2	55862	219632	21777	85622
	5	0.61	2.2	-1.2	-4.3	61675	223552	24044	87150
	6	0.58	2.1	-1.1	-4.0	58672	208972	22453	81466
	7	0.59	2.3	-1.2	-4.4	60206	228834	23471	89209
	8	0.63	2.3	-1.2	-4.5	64063	234542	24975	91434
	9	0.56	2.2	-1.1	-4.2	56522	218673	22035	85248
	10	0.60	2.2	-1.2	-4.3	60773	227921	23692	88853
	11	0.56	2.3	-1.1	-4.4	37970	229016	22235	89280
	12	0.58	2.3	-1.1	-4.4	58785	232789	22788	90751
	Total	6.80	27	-13.2	-51	672143	2695340	268998	1050755
2010	1	0.55	2.3	-1.1	-4.5	55729	234946	21726	91592
	2	0.52	2.1	-1.0	-4.1	52794	217337	20581	84727
	3	0.57	2.3	-1.1	-4.5	58170	237768	22677	92692
	4	0.59	2.3	-1.1	-4.5	60322	234466	23516	91405
	5	0.60	2.4	-1.2	-4.6	61203	243801	23859	95044
	6	0.55	2.3	-1.1	-4.5	56147	236065	21888	92028
	7	0.56	2.5	-1.1	-4.8	56512	251932	22031	98214
	8	0.58	2.5	-1.1	-4.9	58902	255901	22963	99761
	9	0.56	2.4	-1.1	-4.7	56681	246345	22097	96035
	10	0.66	2.5	-1.3	-4.7	67468	249121	26152	97118
	11	0.55	2.4.	-1.1	-4.6	55945	242906	21810	94695
	12	0.55	2.5	-1.1	-4.8	56027	250599	21842	97694
	Total	6.85	29	-13.3	-55	695900	2901188	271141	1131003

(b) Air pollutants.

		CO		NO_x		VOC		$PM_{2.5}$	
	Month	**Domestic**	**International**	**Domestic**	**International**	**Domestic**	**International**	**Domestic**	**International**
2009	1	40	210	281	1384	7.2	79	3.4	15
	2	35	185	245	1227	6.4	70	3.0	13
	3	41	204	293	1350	7.7	77	3.6	15
	4	41	196	287	1298	7.4	73	3.5	14
	5	45	198	316	1321	8.1	74	3.9	14
	6	44	186	299	1235	7.7	70	3.7	13
	7	45	204	304	1349	7.9	76	3.8	15
	8	47	208	324	1381	8.1	78	4.1	15
	9	43	196	283	1292	7.0	73	3.6	14
	10	46	204	303	1347	7.4	76	3.9	14
	11	43	207	284	1350	6.9	76	3.6	15
	12	44	208	290	1369	7.2	77	3.7	15
	Total	514	2405	3509	15903	89	900	44	171

Table 7. (Continued)

(b) Air pollutants.

		CO		NO_x		VOC		$PM_{2.5}$	
	Month	Domestic	International	Domestic	International	Domestic	International	Domestic	International
2010	1	41	208	280	1380	7.3	78	3.5	15
	2	40	193	266	1276	6.8	72	3.4	14
	3	44	212	294	1399	7.4	79	3.7	15
	4	45	209	311	1377	7.9	78	3.8	15
	5	45	217	315	1433	8.1	81	3.9	15
	6	42	211	287	1389	7.3	80	3.6	15
	7	42	223	291	1483	7.3	84	3.6	16
	8	44	224	304	1504	7.7	85	3.7	16
	9	42	218	291	1451	7.5	82	3.6	16
	10	50	220	344	1468	8.4	84	4.3	16
	11	41	214	285	1429	6.5	80	3.6	15
	12	41	219	284	1469	6.5	82	3.6	16
	Total	515	2569	3553	17059	89	964	44	184

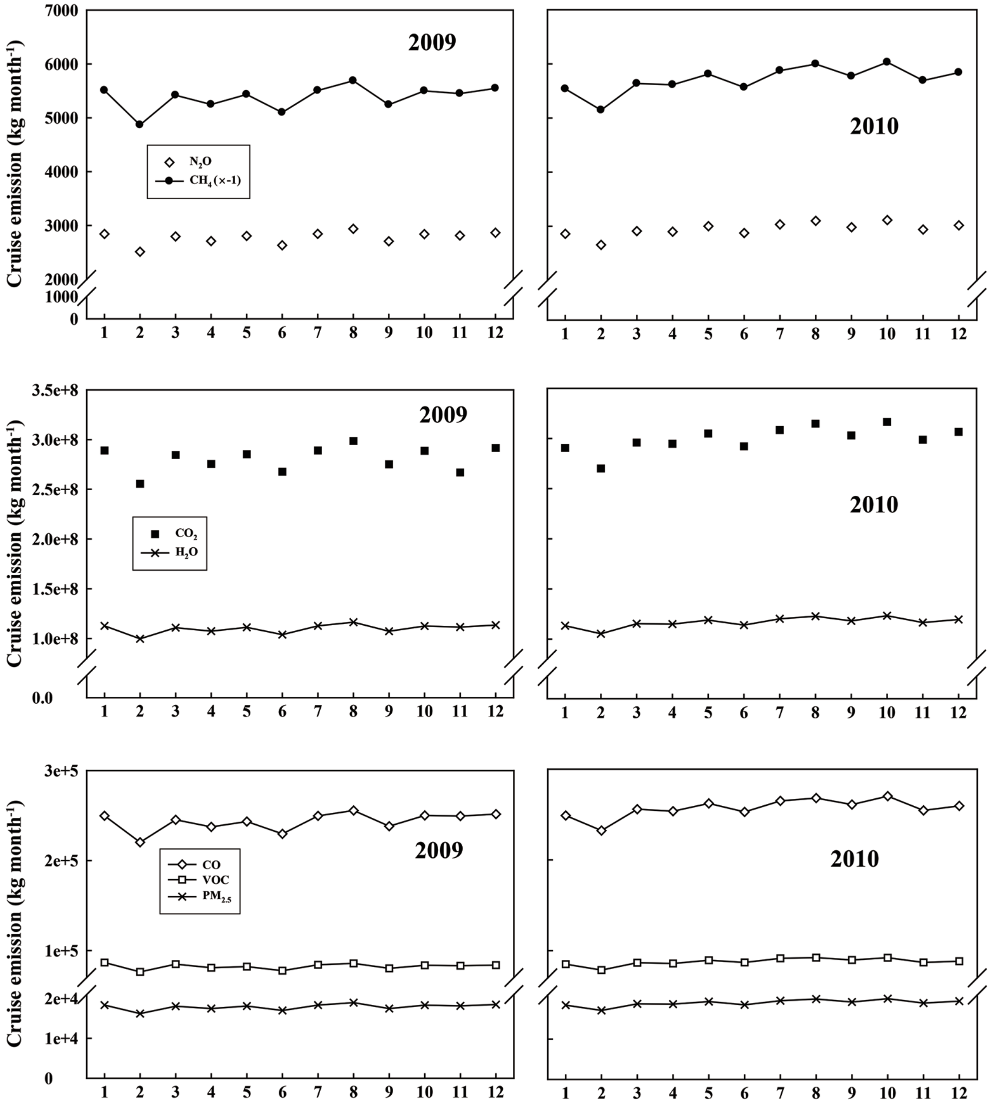

Fig. 2. Monthly distribution of GHG and air pollutant emissions calculated from both domestic and international cruise modes.

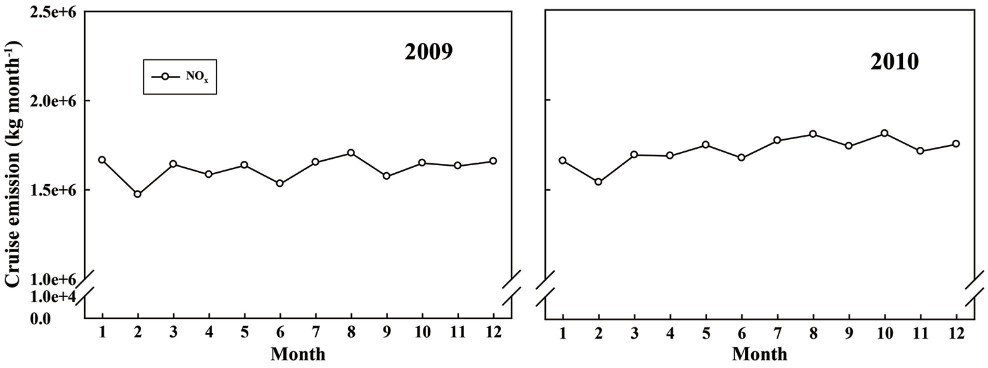

Fig. 2. (Continued)

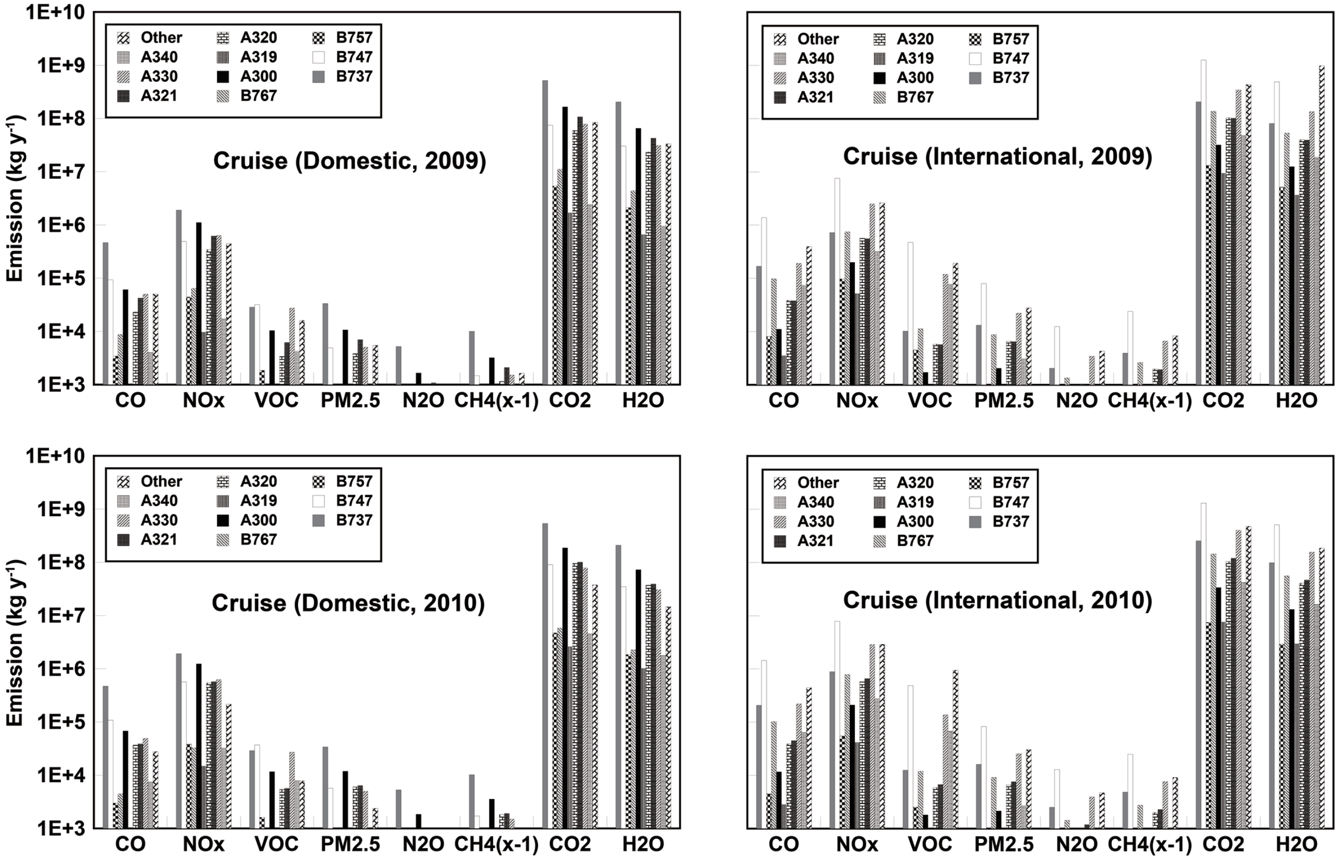

Fig. 3. GHG and air pollutant emissions for aircraft type in cruise mode.

GHG emissions was the B747 (e.g., 1258 - 1306 kt yr^{-1} for CO_2, 12 - 13 ton yr^{-1} for N_2O, -24 to -25 ton yr^{-1} for CH_4, 490 - 509 kt yr^{-1} for H_2O). The GHG emissions for the B747 were 26 - 47% of the total amount of emissions.

3.2 Air Pollutant Emissions in the Free Troposphere

Tables 5b and 6b list the air pollutant emissions, such as CO, NO_x, VOCs and $PM_{2.5}$, in the free troposphere for domestic and international routes during the study period. The air pollutant emissions from international routes were a factor of 4 - 11 higher than those from domestic routes. Similar to GHGs, the highest domestic route of air pollutant emissions occurred in the route between SS and PC, where the domestic air pollutant emissions ranged from 235 to 238 for CO, 1590 to 1637 for NO_x, 41 to 43 for VOCs, and 20 to 21 ton yr^{-1} for $PM_{2.5}$. The yearly amount of air pollutant emissions remained relatively constant over the two years (≤ 1%) (Table 5b). In the case of international routes, the highest air pollutant emissions also occurred in the route between SI and China followed by the route between SI and Japan (Table 6b). Compared to the emissions from domestic routes, the yearly variations in emissions from the international routes were slightly larger between the two years (7 - 8%). The NO_x to VOCs emission ratios in the free troposphere ranged from 18 to 40.

Compared to the previous pollutant emissions from aviation, the air pollutant emissions, such as CO, VOCs, and NO_x, estimated in the boundary layer and free troposphere over South Korea in 2010 were similar to those in China (Fan et al. 2012) and UK airports (Stettler et al. 2011). For example, the total CO, VOCs, and NO_x emissions in China were 40, 4.6, and 154 kt yr^{-1}, respectively, whereas those in UK airports were 11.7, 1.8, and 10.2 kt yr^{-1}, respectively. Current estimates of national CO, VOCs, and NO_x emissions from civil aviation in 2009 were 1.1, 1.9, and 0.93% that of global civil aviation (0.679, 0.098, and 2.656 Tg yr^{-1}) in 2006, respectively (Wilkerson et al. 2010).

Table 7b and Fig. 2 present the monthly air pollutant emissions in the free troposphere for both domestic and international routes during 2009 - 2010. The monthly emissions from the international routes were a factor of 4 - 11 higher than those from the domestic routes. The monthly variation trend in 2009 was similar to that in 2010. In general, monthly emission variations in the domestic routes (≤ 18%) were slightly higher than those in the international routes (≤ 11%). Like GHGs, the monthly air pollutant emissions showed the highest values in August (2009) or October (2010) for domestic routes, whereas those for the international routes were observed in January (2009) or August (2010). The mean monthly CO, NO_x, VOCs, and $PM_{2.5}$ emissions for domestic routes in 2009 (and 2010) were 43 ± 3 (43 ± 3), 292 ± 20 (296 ± 20), 7.4 ± 0.5 (7.4 ± 0.6), and 3.7 ± 0.3 (3.7 ± 0.2) ton $month^{-1}$, respectively. The mean monthly CO, NO_x, VOCs, and $PM_{2.5}$ emissions for international routes in 2009 (and 2010) were 200 ± 8 (214 ± 9), 1325 ± 53 (1422 ± 62), 7.4 ± 0.5 (7.4 ± 0.6), and 14 ± 1 (15 ± 1) ton $month^{-1}$, respectively. A distinct seasonal difference in air pollutant emissions was observed between domestic and international routes. For example, the air pollutant emissions for the domestic routes were highest in summer, whereas those for the international routes were highest in winter.

The air pollutant emissions emitted from both domestic and international routes differed according to the aircraft type (Fig. 3). For example, the aircraft type emitting the highest CO emission for domestic routes was the B737 (e.g., 464 - 471 ton yr^{-1}, 58% of total emissions) followed by the B747 and A300, and that emitting the highest NO_x emission was also the B737 (e.g., 1885 - 1919 ton yr^{-1}, 33%) followed in order by the A300 and A330. For VOCs, the aircraft type emitting the highest emission was the B747 (e.g., 32 - 37 ton yr^{-1}, 22%) followed in order by the B737 and A330. The B737 showed the highest $PM_{2.5}$ emissions (33 - 34 ton yr^{-1}, 47%) followed in order by the A300 and A321. For the international route, the aircraft type emitting the dominant emission was different from that for the domestic route. The aircraft type emitting the highest air pollutant emissions was the B747 followed by the A330. For example, the international cruise emissions for CO, NO_x, VOCs, and $PM_{2.5}$ for B747 were 1381 - 1431, 7546 - 7825, 472 - 488, and 80 - 83 ton yr^{-1}, respectively.

3.3 Comparison of the Emissions Related to the Aircraft Flight Geographic Coverage

The air pollutant and GHG emissions from aircraft activities at four major international airports and 11 small-scale airports located in South Korea, including cruise mode in the free troposphere were compared during 2009 - 2010 (Fig. 4 and Table 8). Detailed discussion of the air pollutant and GHG emissions at four major international airports and 11 small-scale airports in the boundary layer were reported by Song and Shon (2012) and Shon et al. (2013), respectively.

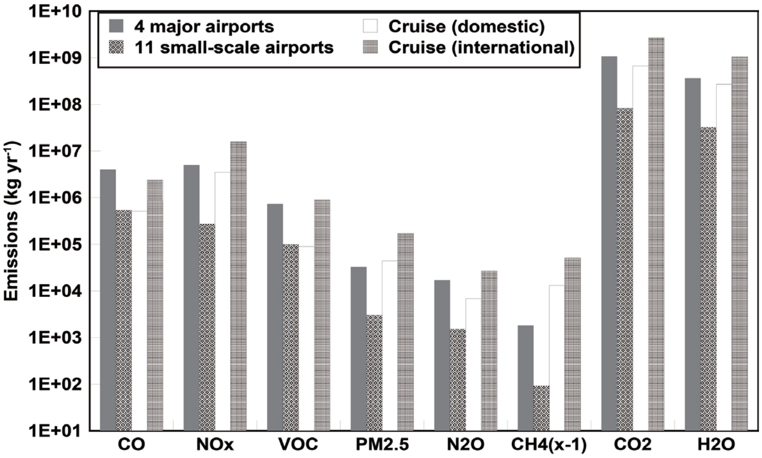

Fig. 4. Comparison of GHG and air pollutant emissions between the boundary layer and cruising altitude.

Table 8. Comparison of aircraft emissions between the boundary layer (≤ 1 km) and cruising altitude (1 - 12 km) (ton yr^{-1}).

(a) GHGs.

		N_2O		CH_4		CO_2		H_2O	
		2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
4 major airports (≤ 1 km)	RKSI	9	10	-1.3	-1.4	628465	674762	201786	219737
	RKSS	3	4	-0.2	-0.2	198921	205242	71572	77411
	RKPK	2	2	-0.1	-0.1	96433	97147	35744	37569
	RKPC	3	3	-0.2	-0.2	152209	168535	57209	65794
	Sum	17	18	-1.8	-1.9	1076028	1145686	366311	400512
11 small-scale airports (≤)		2	2	-0.1	-0.1	82703	93558	32320	36562
Cruise (1 - 12 km)	Domestic	7	7	-13	-13	672143	689331	269417	268580
	International	27	29	-51	-55	2695151	2901188	1050681	1131003
	Sum	33	35	-64	-68	3367294	3590519	1320098	1399583
Total		52	55	-66	-70	4526025	4829763	1718729	1836657

(b) Air pollutants.

		CO		NO_x		VOC		$PM_{2.5}$	
		2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
4 major airports (≤ 1 km)	RKSI	1606	1754	3407	3648	298	314	17	18
	RKSS	1022	1040	750	786	184	186	7	7
	RKPK	547	570	335	332	101	104	3	3
	RKPC	813	884	532	600	148	156	5	6
	Sum	3988	4249	5026	5366	731	761	33	35
11 small-scale airports (≤)		535	512	269	340	99	91	3	3
Cruise (1 - 12 km)	Domestic	514	510	3509	3518	89	88	44	44
	International	2405	2569	15901	17059	900	964	171	184
	Sum	2919	3079	19410	20577	989	1052	215	228
Total		7442	7839	24704	26284	1819	1904	251	266

The total air pollutant and GHG emissions at the 11 airports ranged from 4.8 to 12% at the four major airports. The GHG emissions, such as CO_2, N_2O, CH_4, and H_2O, in the cruise mode were predominant in the GHG emissions from aviation, accounting for more than 64% (52% for international route) of the national aircraft GHG emissions. The yearly CO_2, N_2O, CH_4, and H_2O emissions for the cruise mode were 3367 to 3590 kt yr^{-1}, 33 to 35 ton yr^{-1}, -64 to -68 ton yr^{-1}, and 1320 to 1400 kt yr^{-1}, respectively. The GHG emissions at the four international airports in the boundary layer (derived from approach, climb out, startup, takeoff taxi in, and taxi out modes) were significant (21 to 33% of national aircraft GHG emission), except for CH_4 (3%) (Song and Shon 2012). The total GHG emissions from the 11 small-scale airports in the boundary layer were insignificant (≤ 3%) (Shon et al. 2013).

The air pollutant emissions in cruise mode were dominant in the air pollutant emission from aviation, accounting for 39 to 86% (32 to 69% for international routes) of the national aircraft emissions. For example, the yearly emissions, such as CO, NO_x, VOCs, and $PM_{2.5}$ for the cruise mode were 2919 to 3078, 19409 to 20577, 989 to 1052, and 215 to 228 ton yr^{-1}, respectively. The air pollutant emissions at the four international airports in the boundary layer were significant (20 to 54% of national aircraft emission), except for $PM_{2.5}$ (13%). The total air pollutant emissions from the 11 small-scale airports in the boundary layer were small (≤ 7%).

Figure 5 shows the total CO_2, NO_x, and VOC emissions with altitude from international and domestic aircraft over South Korea in 2010. Strongly enhanced CO_2 and NO_x emissions occurred at flight altitudes of 10 - 12 km (the upper troposphere) where contrails predominantly form, whereas strongly enhanced VOC emissions occurred at both the surface and altitudes of 10 - 12 km. Unlike other emission gases, VOC emissions were significantly higher in the start-up operational mode so that the VOC emissions were also higher at the surface (Song and Shon 2012). The CO_2 and NO_x emissions within the boundary layer (approximately ≤ 1 km) accounted for approximately 30 - 32% and 19 - 31% of their peak emissions at the altitudes (10 - 12 km), respectively.

The current methodology for estimating aircraft emissions in the boundary layer presents two main sources of uncertainty (LTOs and LTO emission factors). Song and Shon (2012) reported a detailed discussion of the emission uncertainty in the boundary layer. Fuel consumption should be included in the aircraft emission uncertainty in cruise

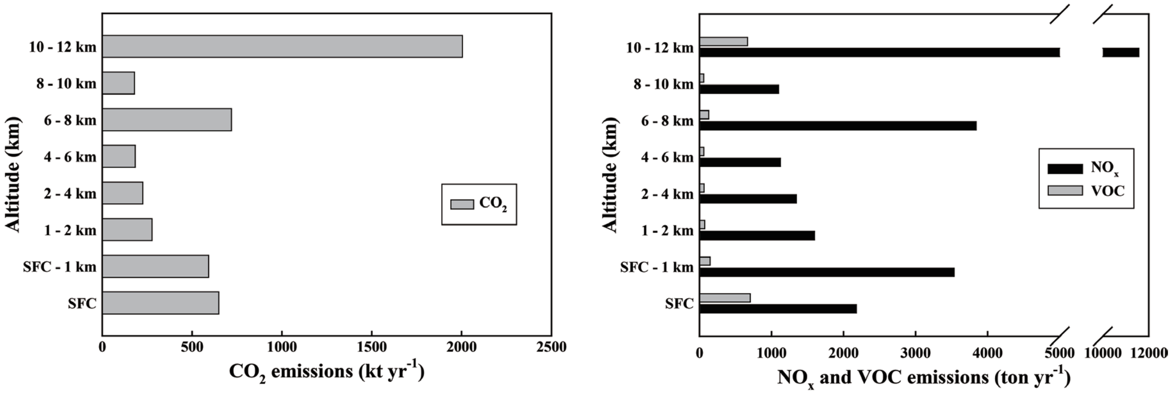

Fig. 5. Altitude profile of the total CO_2 (kt yr^{-1}), NO_x (ton yr^{-1}), and VOC (ton yr^{-1}) emissions from the international and domestic flights at both 4 major and 11 small airports over South Korea in 2010. "SFC" represents the surface at airport.

mode. As mentioned in section 2.2, estimating the cruise mode emissions involves calculating the aircraft type fuel consumption using regression analysis using the standard flight distance, corresponding standard fuel use and actual cruising distance. The fuel consumption error might be negligible due to the strong correlation coefficient ($r^2 > 0.92$) between the regression result and observations (actual fuel consumption).

4. SUMMARY AND CONCLUSIONS

The emissions of GHGs (e.g., CO_2, N_2O, CH_4, and H_2O) and air pollutants (NO_x, CO, VOCs, and PM) from aircraft in the boundary layer and free troposphere over South Korea in 2009 - 2010 were calculated using an activity-based (LTO) methodology. The busiest domestic and international routes showed the highest air pollutant and GHG emissions between Gimpo (Seoul) and Jeju (island) airports and the route between Incheon and China, respectively. The air pollutant and GHG emissions from the international routes were significantly higher than those from domestic routes (by a factor of 4 to 11). In general, there was no distinct emission difference between the two years (2009 - 2010). The month of highest air pollutant and GHG emissions differed according to the route (international vs. domestic). For example, for the domestic routes, the highest monthly air pollutant and GHG emissions occurred in August (2009) or October (2010), whereas those for the international routes occurred in January (2009) or August (2010). In the free troposphere air pollutant and GHG emissions were dominant from aviation, accounting for 64 - 97% and 39 - 86% of the national aircraft emissions (including 4 major international airports and 11 small-scale airports), respectively. Of the air pollutants and GHGs, the CO emissions were a dominant contributor only in the boundary layer from the 4 major international airports (54%) to the national aircraft CO inventory, whereas the emissions from other pollutants and GHGs were less than 40%.

The NO_x to VOC emission ratio from aircraft with different altitudes plays an important role in atmospheric chemistry (e.g., the production of loss of O_3) at different altitudes. The NO_x to VOC emission ratio (range of 3 - 12) in the boundary layer was somewhat lower than that (range of 18 - 40) in the free troposphere. This suggests that the impact of the emission difference between the altitudes on increases or decreases in O_3 concentrations can be very significant. The different magnitudes of GHGs at different altitudes might influence the atmospheric environment and climate change. Therefore, future studies should assess the impact of aircraft emissions on the air quality (e.g., O_3) near airports and free troposphere as well as climate change.

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