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Carbon dioxide in passenger cabins: spatial temporal characteristics and 30-year trends

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Highlights

1. A mean CO_2 concentration of 1253 ± 164 ppmv was measured across 52 randomly selected flights in economic classes during the cruising phase.

2. CO_2 concentrations in the boarding phase were 1680 ± 558 ppmv.

3. Spatial CO_2 concentrations in different positions of the same class were relatively uniform, whereas business classes had a lower CO_2 than economic classes.

4. Cabin CO_2 concentration trends over the last 30 years were analyzed.

Abstract

Carbon dioxide (CO_2) is an important environmental parameter in aircraft cabins. To understand the most recent, real-time CO_2 concentration levels and their key influencing factors in aircraft cabins, we conducted in-flight measurements of 52 randomly selected commercial flights with different aircraft types and durations from August 2017 to August 2019. The spatial temporal characteristics of CO_2 concentrations on board were analyzed and summarized. For the flight time scale, the CO_2 concentrations during the boarding phase (1680 ± 558 ppmv) were notably higher than that in other phases, whereas the condition of the cruising phase was the lowest in most flights. The flight average CO_2 concentrations of the cruising phase were 1253 ± 164 ppmv and the corresponding estimated outside airflow rates were 6.2 ± 1.3 L/s/p in the economic class across all flights. Single-aisle and double-aisle flights did not show noticeable differences for the same phases. Relatively uniform CO_2 concentrations were observed at different positions of the same class. By comparing the results of this study with those previously reported, CO_2 concentrations showed a slightly decreasing trend over the last 30 years. This suggested a slightly increased ventilation rate and potentially superior air quality on board.

Keywords: Carbon dioxide (CO_2); Aircraft cabin air quality; Ventilation; On-board measurements

Practical Implications

Onboard CO_2 concentrations represent an important parameter for evaluating the cabin air quality as both human bioeffluent and a ventilation proxy. This study provides a field investigation of the spatial temporal characteristics of real CO_2 concentrations and a summary of the CO_2 long-term trends on board. The results can be used to better understand CO_2 concentrations and ventilation conditions in cabins and improve cabin air quality through considering both the flight phases and the different classes.

1. Introduction

The aircraft cabin is a unique semi-enclosed environment for passengers and crew members. Cabin air quality has been a research hotspot and has received increasing attention from the public. Several studies have investigated cabin air quality onboard, including thermal comfort and different contaminants. These investigations help detail the current situation, improve control strategies, and develop standards and regulations.

Carbon dioxide (CO_2) is an important environmental parameter in closed environments. Earlier research found that a high CO_2 level environment may impact human breathing [1]. In consideration of health effects, standards for closed environments have established safety concentration limits. In the Occupational Safety and Health Administration (OSHA) and the American Conference of Government Industrial Hygienists (ACGIH), the maximum permissible occupational exposure limits are 5000 ppmv as an 8-h time-weighted average [2]. A series of studies recently noted the effects of CO_2, even at a lower concentration level. Satish et al. found that negative human cognitive functions were significantly associated with exposure to higher CO_2 concentrations at a much lower level (600-2500 ppmv) [3]. Snow et al. also reported that the addition of pure CO_2 may influence aspects of cognitive performance after only short exposures [4]. Hence, CO_2 has unsurprisingly been selected as one of the most prominent air components with limitations in nearly all aviation regulations [5,6,7,8]. In 1996, the Federal Aviation Administration (FAA) revised the threshold limit of CO_2 to 5000 ppmv in the Federal Aviation Regulations Part 25 (FAR, regulations for the USA) based on OSHA standards and recommendations from the National Academy of Sciences [9]. However, this threshold limit only sets a bottom line that the aircraft cabin cannot exceed under any circumstances. The actual CO_2 levels during normal operation should be much lower than this limit.

In addition to possible health effects, CO_2 can be used as a proxy for ventilation. In the middle of the 19th century, Pettenkofer proposed a maximum CO_2 concentration of 1000 ppmv as a criterion for a well-ventilated room [10]. Ventilation is an important issue for cabin air quality. As the occupant density in an aircraft's cabin is much higher than that in residences, ventilation in the aircraft's cabin is most critical in reducing human bioeffluents and other air contaminants. The Aviation Regulations set the limitation of ventilation rate as 0.55 pound/min/p or 4.7 L/s/p [5,6,7,8] and a lower reference limitation was set by ASHRAE (3.5 L/s/p) [10]. Because the direct measurement of ventilation in an aircraft's cabin is extremely difficult, a method to estimate the cabin ventilation rate based on the CO_2 concentrations has been proposed and widely used [12,13,14,15,16].

The characteristics of CO_2 concentration in real aircraft cabins have been investigated by various researchers. For the flight time scale, the CO_2 concentration during the cruise phase was relatively stable because of the stable CO_2 generation and ventilation rate. The CO_2 concentrations in boarding and other phases were mentioned or discussed [16,17,18,19]. For the concentration distribution onboard, Mattson et al. found that the passenger cabin air is most thoroughly mixed in the economy class of single-aisle aircraft, whereas the concentrations in separate classes differed [20]. Lindgren et al. performed measurements at the working or resting areas of the flight crew (flight deck, forward galley, and rear galley), and the CO_2 concentration in resting areas was significantly lower than in the passenger seating area [21]. Haghighat et al. measured the CO_2 concentration near first-class cabins as 386-1091 ppm [22]. However, these investigations were mainly limited to single-aisle aircraft, whereas investigations of CO_2 concentration distributions in double-aisle aircraft and systematic comparisons with analyses are still lacking.

As an important cabin air indicator, onboard CO_2 concentrations have been measured by various groups from the early the 1980s to 2014. Data from more than 500 flights can be found in various publications or reports. In 2000, a study indicated that the designed ventilation capacity declined in newer types in the 20th century [12]. However, real onboard CO_2 concentrations still need to be systemically analyzed, especially regarding how they vary over several decades.

There are two purposes of this study. First, we further investigate the spatial and temporal characteristics of CO_2 distributions in aircraft cabins by conducting on-board measurements. Double-aisle aircraft data that were largely missing in the existing literature were obtained and compared with single-aisle aircraft. Second, we fill the experimental data gap in most recent years and analyze the 30-year trends of onboard CO_2 concentrations. The study can be used to better understand CO_2 concentrations and estimate ventilation conditions in cabins and their long-term trends.

2. Method

An onboard test campaign was undertaken to obtain CO_2 data in real aircraft cabins. The study covered the following three aspects. 1) Investigate the real-time CO_2 levels onboard and estimate the ventilation rate in different phases (temporal characteristics), 2) verify the uniformity of CO_2 concentrations in cabins and compare the differences of separate classes (spatial characteristics), 3) analyzing the 30-year trends of onboard CO_2 concentrations. Fig. 1 illustrates the outline of the study.

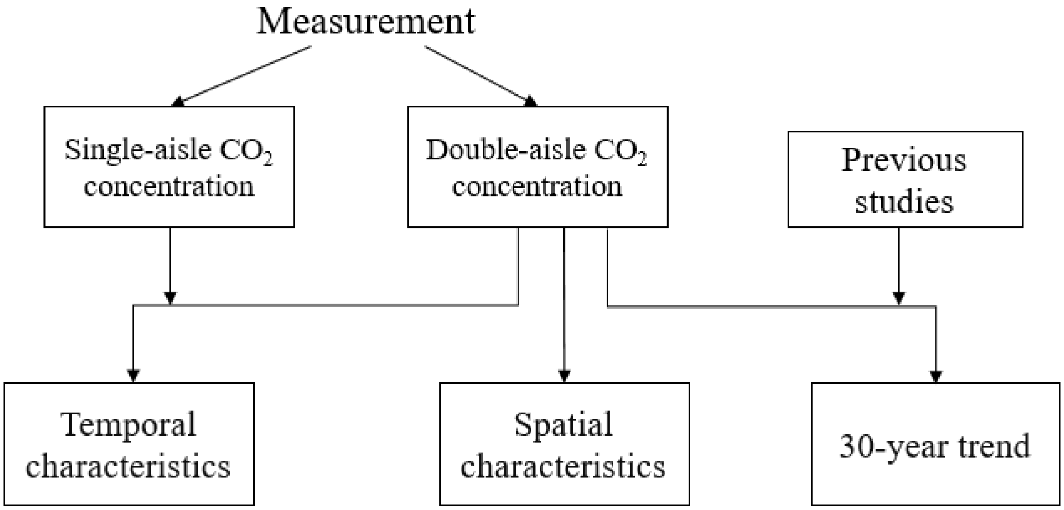


Figure 1. Outline of the study

2.1 Flight Selection

The selection of the types of aircraft and number of flights is the most important step needed to achieve the goals set by this investigation. For the aircraft type, previous studies have mainly covered the in-service single-aisle aircraft such as the B737 and A320 series. This study expands upon fleet types by covering more double-aisle aircraft such as the B777, B787, and A330 series. Regarding the number of flights for measurements, given the time and budget constraints, and considering the number of tested flights in other experimental studies, a total of 52 commercial flights were randomly selected for detailed tests when conducting the experiments. The flights included 16 single-aisle aircraft (N=16, 9 B737 series, 3 A320 series, and 4 A321 series) and 36 double-aisle aircraft (N=36, 10 A330 series, 15 B777 series, 10 B787 series, and 1 A350). Furthermore, to compare different classes, CO_2 concentrations in 26 double-aisle flights were measured in economic classes, and concentrations in 11 double-aisle flights were measured in business classes.

2.2 CO_2 measurement method

The CO_2 concentrations were measured using a Telaire 7001 and HOBO MX1102 (TELAIRE, USA) and recorded at intervals of 30 s or 60 s (non-dispersive infrared self-calibrating CO_2 sensor). The accuracy of the equipment is ± 50 ppmv or ± 5% of reading, whichever is greater. The detection limit and threshold of the instruments were 0 and 2500 ppmv, respectively. The instruments have their own pressure compensation curve with a compensated pressure range from 0.5 to 1.05 bar, which covers the real pressure on board. The pressure was continuously measured using a sensor (JXcBS-3001-QYJ, Jingxunchangtong, China, ± 1 mbar) and was used to compensate for the CO_2 concentration. The instruments were calibrated in the detection range of 500 to 2000 ppmv, which was the main range of the CO_2 concentration in the aircraft cabin [13,16]. Four standard mixed gases with different CO_2 concentrations of 500 ppmv, 1000 ppmv, 1500 ppmv, and 2000 ppmv were used to calculate the instruments before the experiment.

The entire flight process can be divided into several phases, including boarding, ascent, cruising, descent, and landing [1316]. The aircraft door closing to the flight taking off is the boarding phase. The ascent phase continues until the aircraft stops climbing. The cruising phase starts after the ascent phase until the flight begins to descend. The descent phase ends until aircraft landing. The landing phase is from landing to the door reopening. The time points were recorded according to the actual situation and referenced to the flight altitude and pressure data.

The measurement typically began when the door was closed after all passengers boarded and ended when the door opened after the flight arrived. In several flights, the test procedures could not be performed at certain times because of operational restrictions. The test points were set on the seat table or seatback pocket to measure the CO_2 concentration in the breath zone of the experimenters. The breathing zone is above the folding table plate and below the nose of the passenger.

The CO_2 concentrations in each class of single-aisle aircraft cabins are well-mixed [20]. However, this dynamic has yet to be verified in double-aisle flights. In this study, five double-aisle flights were selected to verify the uniformity of CO_2 concentrations in the cabin. The seats were divided into three different types, as shown in Fig. 2. The CO_2 concentrations of at least two different types of seats with re-circulated air at the outlets were tested on each flight. The verification of the uniformity was used to prove that the results for the breathing zone could represent the CO_2 concentration in the cabin.

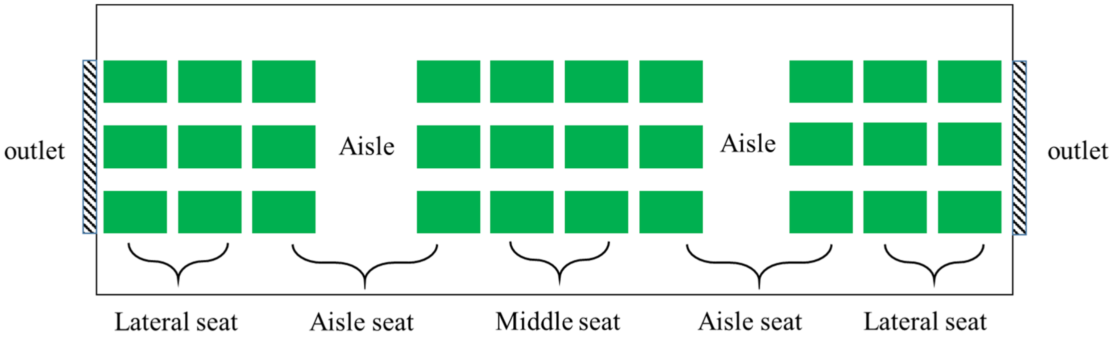


Figure 2. Top view of the aircraft cabin and seat types

2.3 Estimation of the ventilation rate based on CO_2 concentrations

It is difficult to measure the ventilation rate directly in a real cabin. Without considering other inessential CO_2 sources in the cabin and under fully mixed conditions, the ventilation rate can be estimated based on the breathing zone CO_2 concentrations and human generation rates of CO_2. The CO_2 concentration in the cabin can be described by the following equation [13,14,16,23]:

$$V\frac{dC_{b,j}}{dt}\times10^{-3}=NQ_j(C_{o,j}-C_{b,j})\times10^{-6}+\frac{N\dot{m}}{3600} \tag{1}$$

where V is the cabin volume (m^3) $C_{b,j}$ is the CO_2 concentration measured at the breathing zone at test point j (ppmv), t is time (s), N is the number of passengers and crew members in the aircraft cabin (-), Q_j is the outside (bleed air) flow rate per passenger at test point j (L/s/p), $C_{o,j}$ is the CO_2 concentration outside the aircraft cabin at test point j (ppmv), and $\dot{m}$ is the average CO_2 generation rate of the passengers and crew members (L/h).

Based on equation 1, with the assumption that all the parameters are at a steady state during a specific period ($dC_{b,j}/dt$ in equation 1 is zero), the ventilation rate can be estimated using the measured CO_2 concentration, as shown in equation 2 [12]; this was the most popular method used in previous investigations of flight ventilation performances [13,14,15,16].

$$Q_j = \frac{10^6 \dot{m}}{3600(C_{b,j} - C_{o,j})} \tag{2}$$

Equation 2 reveals that except for the CO_2 concentration and the assumptions of stability and full mixing, the main influential factors on the accuracy of the estimated ventilation rate are: 1) the human generation rate of CO_2 and 2) the concentration of fresh air (bleed air).

When seated, the human CO_2 generation rate is relatively stable in a closed environment [15]. The CO_2 generation rate was calculated as 18.2 L/h by Springer et al. based on the distribution of the passengers' height and weight [23]. This estimated value has also been used in many studies to calculate the ventilation rate [13,14,16,23,24]. There have also been different generation rates from laboratory measurements. Qi et al. tested the CO_2 intensity of 44 young Chinese subjects while seated, and the average emission intensity was 12.3 L/h [25]. Lee et al. tested the emission of 23 astronauts, and the emission intensity of CO_2 per person was 13.2 ± 1.2 L/h [26]. However, these results did not cover most of the population. In this study, to compare the estimated ventilation rate with previous results in the literature, the generation rate of CO_2 was set as 18.2 L/h.

The outside CO_2 concentration represented the atmospheric CO_2 concentration at high altitude. According to the results of NASA remote sensing satellite data, the CO_2 concentration is relatively uniform at an altitude of 8000–10000 m [27]. The CO_2 concentrations at different positions in the free troposphere from 0° N to 60° S in February 2017 were 403 ± 3 ppmv (mean ± SD) [27]. A previous study reported that seasonal and altitudinal effects on the variation of CO_2 concentration can be neglected at a higher altitude (>6000 m) [28]. Although the average CO_2 concentration increased at a rate of several ppmv per year, the approximation that the CO_2 concentration outside the cabin can be treated as a constant during a flight. In this study, the outside CO_2 concentration was estimated as 403 ppmv.

The above methodology was used to estimate the stable ventilation rate to obtain an overview of the flight. However, if the CO_2 concentration is changing rapidly, equation 3 will not be accurate because the left side of equation 1 cannot be ignored. In systemically analyzing the entire process of the flight, the assumption that $dC_{b,j}/dt$ was zero was not accurate, especially for the analysis of the boarding phase when the CO_2 concentration changed considerably. In this study, we use the slope of the CO_2 concentration curve to estimate the term. The most commonly used technique in chemistry for smoothing and differentiation is the SAVITZKY–GOLAY method, which is a local polynomial regression method requiring equidistant and exact x-values [2930]. The derivative can also be easily calculated using this method. In this study, the two parameters, the number of neighbors and the degree of the polynomial, were set as 21 and 4, respectively. Thus, the fresh air ventilation rate is as follows:

$$Q = \frac{10^6 \dot{m}}{3600(C_{b,j} - C_{o,j})} - \frac{10^3 V}{N(C_{b,j} - C_{o,j})} \frac{dC_{b,j}}{dt} \tag{3}$$

In equation 3, except for the aforementioned parameters (generation rate and outlet concentration), the cabin volume and the number of passengers and crew members are also needed. The cabin volumes were estimated using the public information of the types. The number of passengers on board was estimated using the occupancy rate and the maximum number of persons allowed.

2.4 Statistical analysis

The test results above were used to carry out the statistical analyses to explore the study questions (Table 1). The hypothesis was accepted with a p-value<0.05. Statistical tests were performed using SPSS (version 26.0, SPSS Inc., USA).

Table 1. Statistical treatments

Phase	Data used	Statistical Treatment	Hypothesis
Validation of the uniformity of CO_2 in a cabin	The CO_2 concentrations for difference phases at different test points in the five flights	Descriptive analysis of means.	Sufficient level of uniformity
Analysis of the distribution of mean CO_2 concentrations of phases	The mean CO_2 concentrations of phases across 42 flights with the same classes	Kolmogorov–Smirnov test for a normal distribution	Not obeying a normal distribution
Analysis of the difference between phases	The mean CO_2 concentrations of phases across 42 flights with the same classes	Descriptive analysis of means. Paired-samples t-test for each pair of two phases obeying a normal distribution. Wilcoxon signed-rank test for the pairs not obeying a normal distribution.	Comparing the differences of the means Significant differences in separate phases
Analysis of the difference between economic class and business class	The mean CO_2 concentrations of phases between 26 flights measured in economic class and 11 flights measured in business class	Mann Whitney test (nonnormally distributed data) for the groups	Significant differences between the economic and business classes
Analysis of the differences between separate types	The mean CO_2 concentrations of phases across 42 flights with the same classes of different types	Mann Whitney test (nonnormally distributed data) for the groups	Significant differences in different types
Fitting the CO_2 concentration with the measured time	The mean CO_2 concentration of the cruising phase across 42 flights with the same classes in this study and the mean concentration reported in literature	Linear weighted fitting method	The slope is significantly different from zero.

3. Results and Discussion

3.1 Temporal characteristics

Fig. 3 shows the distribution of the duration of different phases of the flights. The duration of the cruising phase varied from 20 min to more than 10 h. The durations of double-aisle flights were significantly higher than those of single-aisle flights. The durations of the boarding, ascent, and descent phases were relatively stable and mostly numbered 0.2–1 h. The landing phase was usually around or less than 0.5 h.

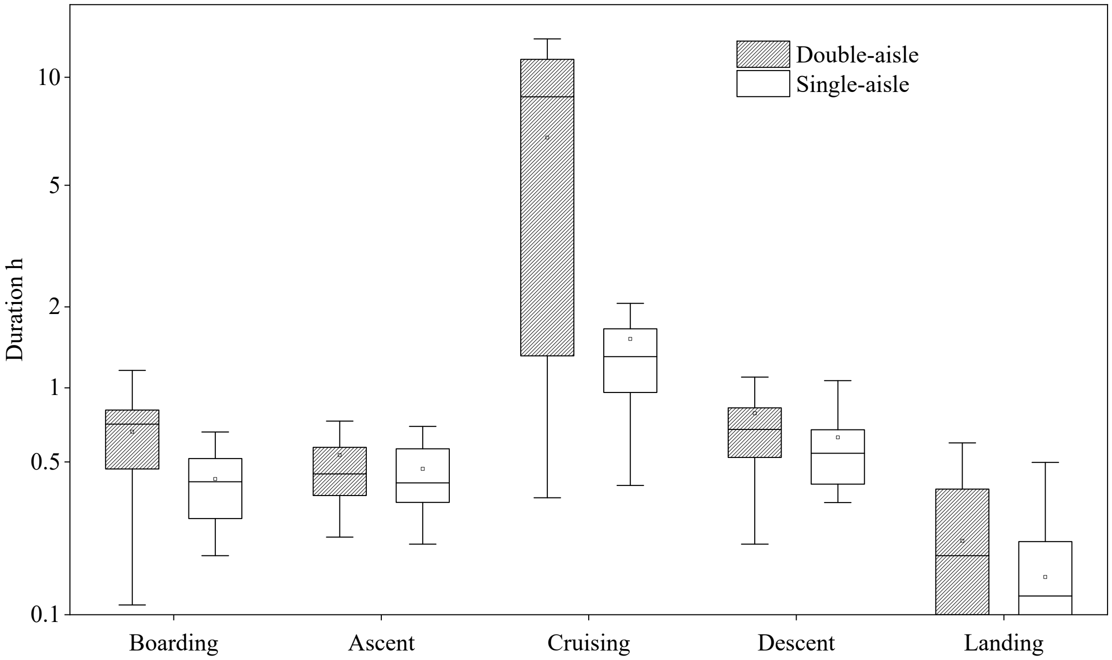
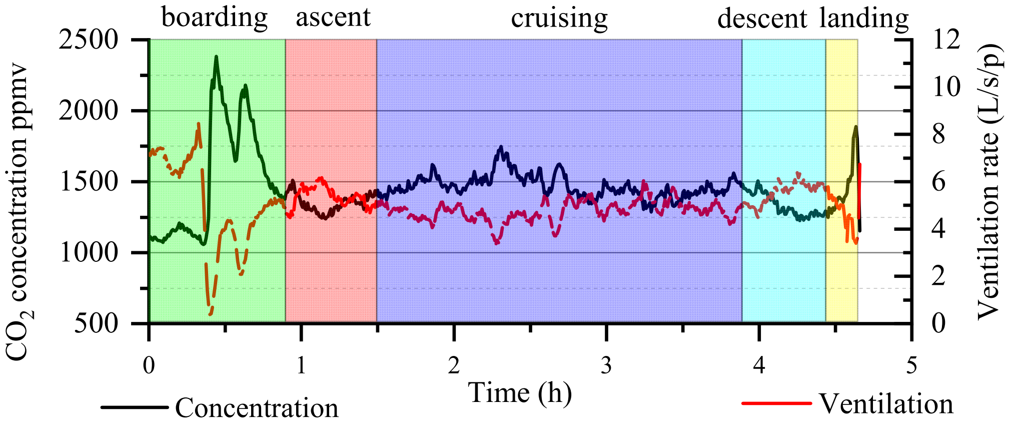
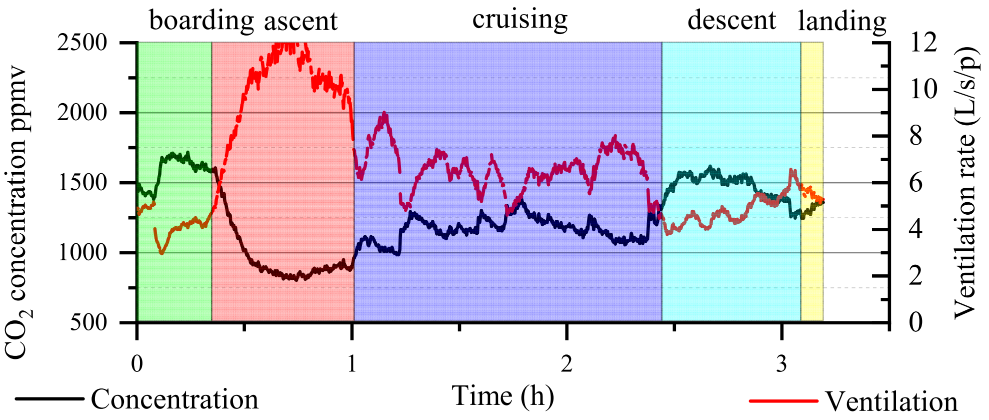


Figure 3 Box and whisker plot of durations according to different phases with economic class results. The line in the box is the median, the plots represent the mean, the boxes represent the 25th and 75th quartiles, and the whiskers represent the upper and lower bounds of the distribution (calculated as 1.5 times the interquartile range away from the 25th and 75th quartiles).

Fig. 4 shows the results of two typical single-aisle flights (A320, B737), and Fig. 5 shows three typical double-aisle flights (B777, A330, B787), including the CO_2 concentration and the estimated ventilation rate. The 0 time was the time at which the door closed. Changes in CO_2 concentrations showed some obvious and common characteristics.

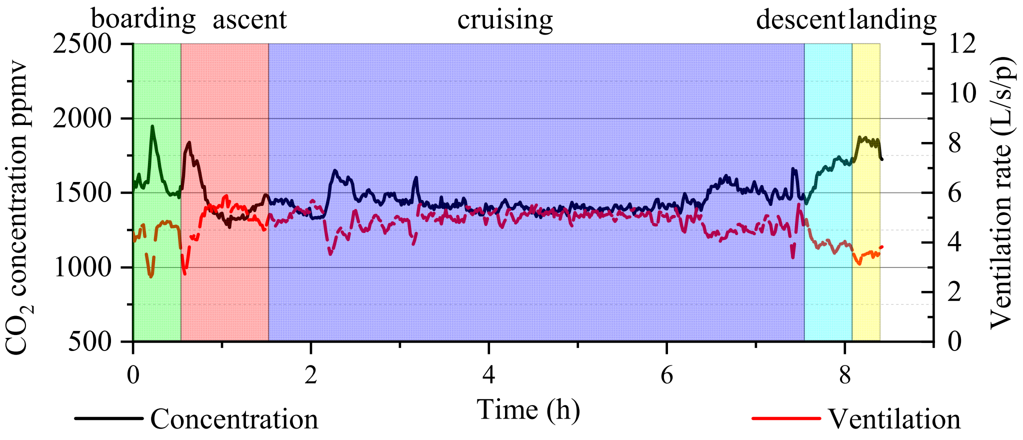


(a) A320

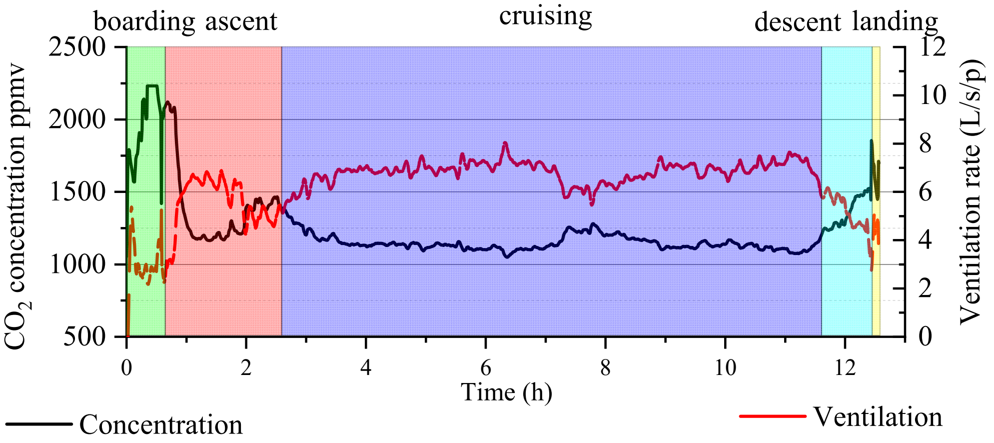


(b) B737

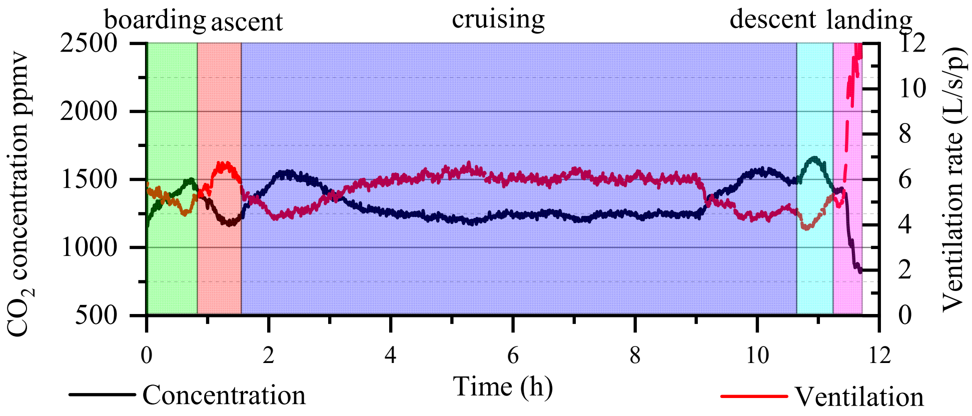
Figure 4 CO_2 concentrations and estimated ventilation rate of single-aisle flights



(a) B777



(b) B787



(c) A330

Figure 5 CO_2 concentrations and estimated ventilation rate of double-aisle flights

During the boarding phase, the CO_2 concentrations were relatively higher than the concentrations in other phases. There were two different characteristics in the boarding phase: (1) a relatively obvious fluctuation peak or peaks, and (2) a high concentration plateau than the cruising phase.

Multiple reasons may have caused this phenomenon. For the engine supply bleed air system (flights except for B787), the CO_2 peak may have been caused by the change in the bleed air supply from the ground assistant system (APU) to the self-supplying bleed air powered by the engine. Otherwise, as the power of the bleed air was supplied by the engine, when the aircraft accelerated during take-off, the bleed air supply power was likely insufficient and caused the peak and plateau. Electric bleed air systems are used on Boeing 787 series aircraft, which means that the bleed air supply was affected less by the change in flight status. Interestingly, there was no obvious difference between the B787 and its counterparts in the boarding phase (Table 2), and the B787 series did not fully utilize its advantages.

At the ascent phase, the CO_2 concentration decreased rapidly. The ventilation rate also was positively correlated with the bleed air. During the cruising phase, the CO_2 concentration remained relatively stable. The standard deviations of the CO_2 concentration during the cruising phase of the flights were all below 220 ppmv.

During the descent phase, the CO_2 increased and the ventilation rate decreased. For the landing phase, the CO_2 concentration also had peaks or plateaus as in the boarding phase. However, as the remaining time of the descent was the shortest, these characteristics were not observed clearly.

The statistics of mean CO_2 concentrations and estimated ventilation rates of different phases across economic classes are shown in Fig. 6. As the features of the CO_2 concentration changed in different phases, the parameter estimations were accordingly statistically analyzed by phases. The CO_2 levels on all flights were far below the exposure limit of 5000 ppmv. The two limitations of the ventilation rate were also marked, with the higher from Aviation Regulations (4.7 L/s/p) [6789] and the lower from ASHRAE (3.5 L/s/p) [10]. There were flights or phases that were not higher than the limit requirements. The mean CO_2 concentrations of phases obeyed a normal distribution except for the boarding phases (Table 2).

Table 2 The p-values of statistical test results of CO_2 concentrations in different phases

Hypothesis	Boarding	Ascent	Cruising	Descent	Landing
Not obeying a normal distribution	0.000*	0.2	0.2	0.2	0.2
Difference between boarding phase and others	-	0.000	0.000	0.000	0.002
Difference between cruising phase and others	0.000*	0.424	-	0.003	0.000
Difference between B787 and other airplane types	0.463	0.533	0.489	0.579	0.048*
Difference between single-aisle and double-aisle planes	0.003*	0.476	0.379	0.936	0.511
Differences between economic and business class	0.026*	0.053	0.000*	0.000*	0.001*

* Statistically significant and accepting the hypothesis.

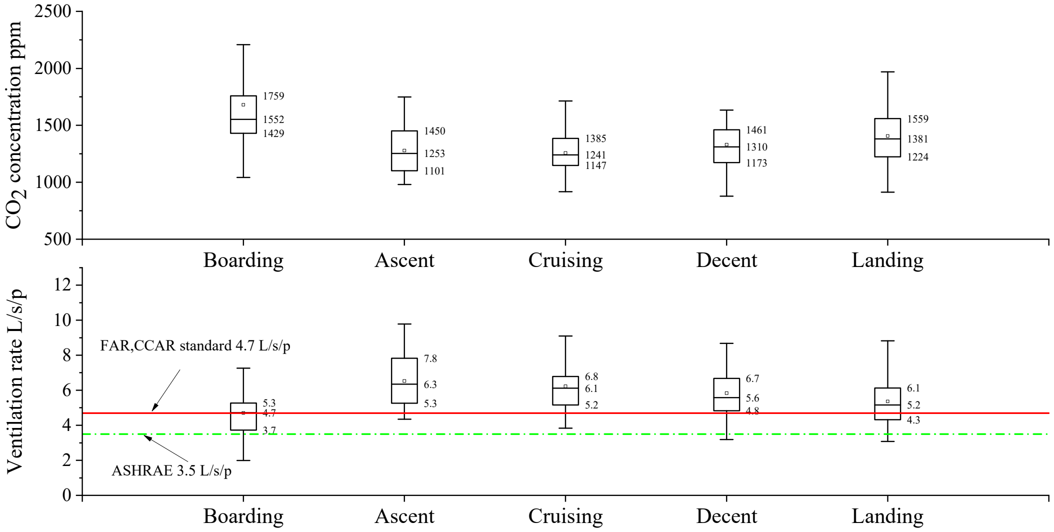


Figure 6 Box and whisker plot of mean CO_2 concentration and estimated ventilation rates in economic classes according to different phases. The line in the box is the median, the plots represent the mean, the boxes represent the 25th and 75th quartiles, and the whiskers represent the upper and lower bounds of the distribution (calculated as 1.5 times the interquartile range away from the 25th and 75th quartiles).

Statistically speaking, the CO_2 concentration in the boarding phase was significantly higher than that in other phases. The percentage of flights with phase estimated ventilation rates below 4.7 L/s/p and 3.5 L/s/p were 50% and 18%, respectively. The mean CO_2 concentrations of boarding phases across economic classes were 1680 ± 558 ppmv (mean ± SD).

For the cruising phase, the CO_2 concentration (1253 ± 164 ppmv, mean ± SD) was significantly lower than that in other phases except for the ascent phase (Table 2). The estimated ventilation rate was 6.2 ± 1.3 L/s/p (mean ± SD). All the flights met the 3.5 L/s/p limitation, whereas the percentage of flights with phase-estimated ventilation rates below 4.7 L/s/p was still 10%.

The test results showed that there were no significant differences between single-aisle flights and double-aisle flights in all phases, except for the boarding phase. Although there were obvious differences in the aircraft structure and the flow field between different types, the stable ventilation rates remained similar. The difference between double-aisle flights (1506 ± 268 ppmv, mean ± SD) and single-aisle flights (1947 ± 749 ppmv, mean±SD) in the boarding phase may have been because the volume of the double-aisle flights was higher than that of single-aisle flights. A higher volume provides more inertia to resist the fluctuation peaks of the CO_2 concentration.

3.2 Spatial characteristics

Fig. 7 shows the distribution of phase CO_2 concentrations at different positions in a B787 flight. The difference in the mean CO_2 concentration between different test points was within 8%, which was equivalent to the error of the instrument. All five flights had similar CO_2 concentrations at different test positions in the cruising phase (mean CO_2 concentration difference <15% at different phases). This indicates that the different positions of the same class of double-aisle aircraft, at least for the same line, had relatively uniform CO_2 concentrations. Li et al. also reported that at a high ventilation rate, the CO_2 concentration in the double-aisles cabin was relatively uniform as per CFD simulation results [31].

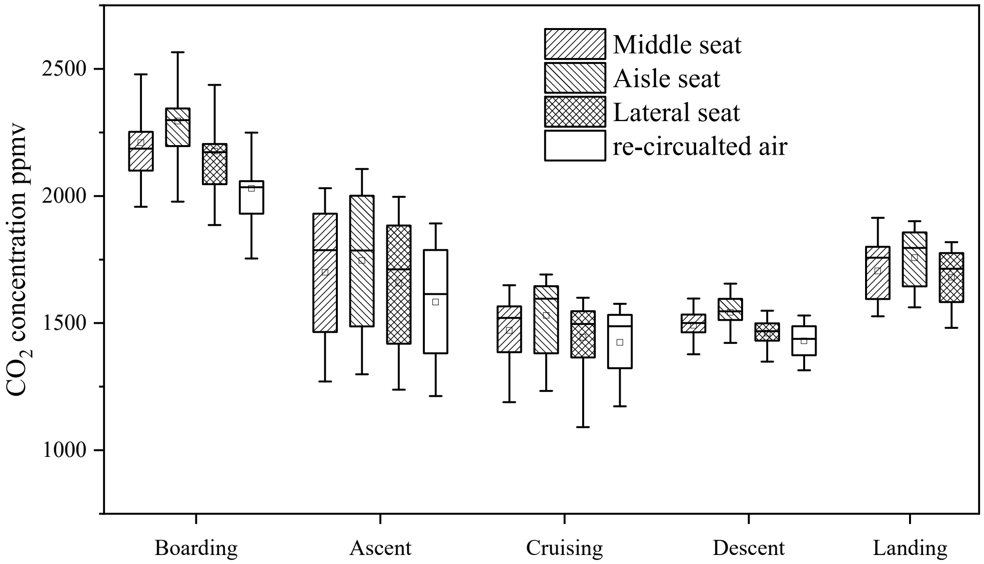


Figure 7 Box and whisker plot of CO_2 concentrations on a flight at different locations. The line in the box is the median, the plots represent the mean, the boxes represent the 25th and 75th quartiles, and the whiskers represent the upper and low bounds of the distribution (calculated as 1.5 times the interquartile range away from the 25th and 75th quartiles).

Fig. 8 shows the statistical results of the CO_2 concentration in different classes. There were significant differences between economic and business classes, especially in the cruising phase. Fig. 9 illustrates the CO_2 concentration of different classes for a B787 flight. The mean CO_2 concentration in the business class was over 100 ppmv higher than that in the economic class on this flight.

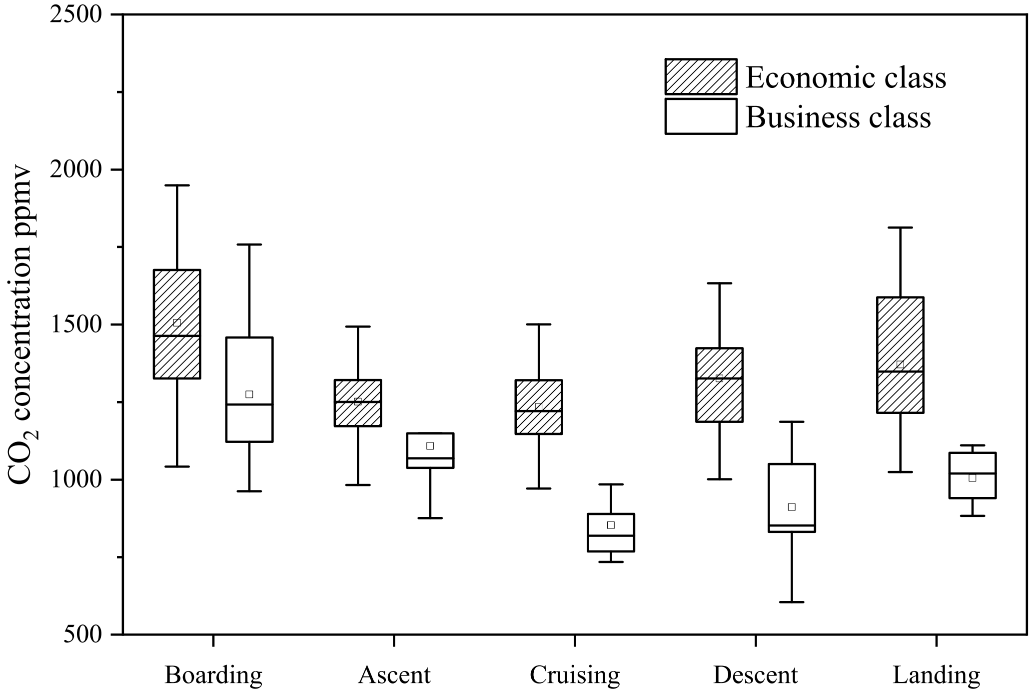


Figure 8 Box and whisker plot of mean CO_2 concentrations in different classes. The line in the box is the median, the plots represent the mean, the boxes represent the 25th and 75th quartiles, and the whiskers represent the upper and low bounds of the distribution (calculated as 1.5 times the interquartile range away from the 25th and 75th quartiles).

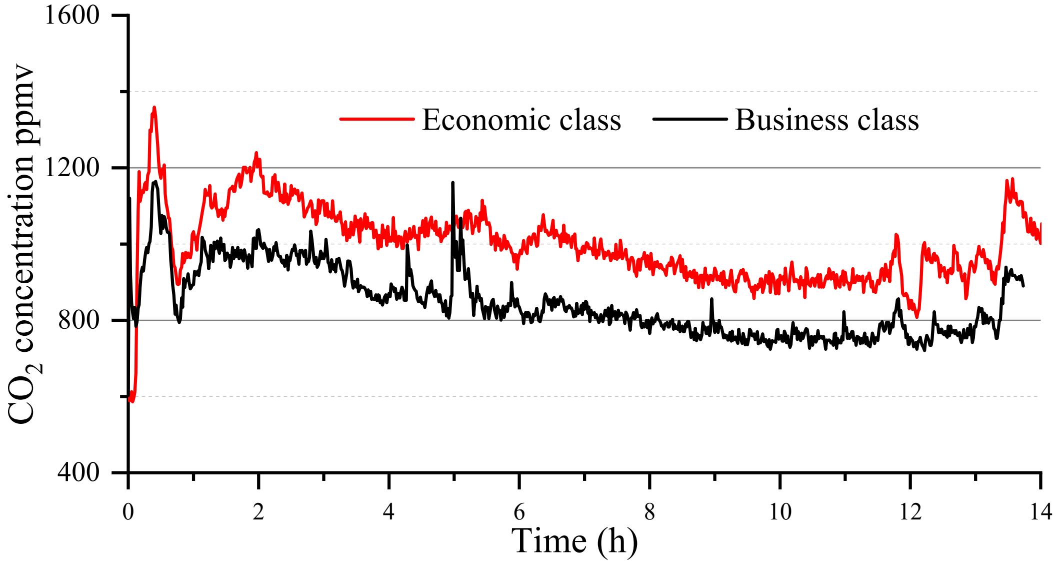


Figure 9 CO_2 concentrations for different classes in the B787 aircraft

A lower CO_2 concentration meant that the ventilation rate per person of the business class was larger than that of the economy class. This was mainly because the seat density of the business class was lower than that of the economy class. The B787 flight in Fig. 9 had four seats per row in business class and nine seats per row in the economic class. Row lengths in different classes were also diverse. Fig. 10 shows the estimated ventilation rates for unit length of the cabin at different classes, which were closer than the CO_2 concentrations.

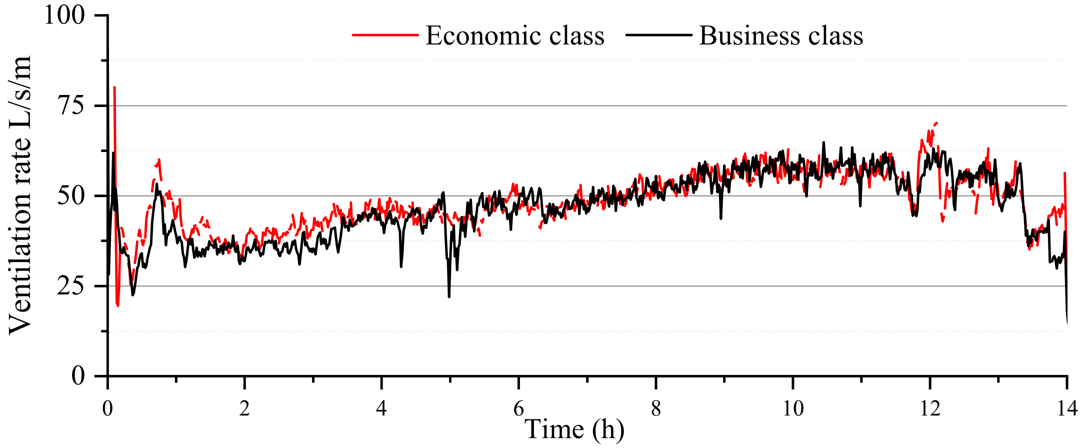


Figure 10 Estimated ventilation rate unit length of the aircraft cabin in different classes

3.3 Onboard CO_2 concentration trends over the past 30 years

Over 20 journal papers with widely different test methods have reported CO_2 concentrations over the past 30 years. Table 3 lists the onboard CO_2 concentration investigation results, including numbers of flights, test time, and flight types.

Table 3 Onboard CO_2 concentrations in aircraft cabins reported in the literature, as sequenced by the time of measurement (Unit: ppm). No.= Number of tested flights, SD=Standard Deviation, Min.=Minimum, Max.=maximum

Reference	NO.	Test position	Test time	Flight type	Mean	SD	Min.	Max.
Holcomb and NAS [32]	-	-	Early than 1983	-	-	-	550	1200
Malmfors et al. 1989 [20,12]	48*	Seat	1988	DC-9, MD-80	1265	80	850	1930
Nagda et al. 1992 [33,34,12]	69*	Economic class seat	1989	B727, B737 DC9, L1011, etc.	1562	685	597	4943
Nagda et al. 1992 [33,34,12]	23	Economic class seat	1989	B727, B737 DC9, L1011, etc.	1756	660	765	3157
O'Donnell et al. 1991[17,12]	45	-	1991	Short-haul aircraft	719	233	330	2170
CCS 1994 [34]	35**	-	-	-	1162			
Spengler 1997 [34]	6**	-	1996	-	1400		1200	1800
Haghighat et al. 1999 [22]	43**	Near first class	1996	A320,A340,B767,DC9	674	178	386	1091
Lee et al. 1999 [18]	3*	Business class seat	1996-1997	B747-400	925	70	868	1024
Lee et al. 1999 [18]	13	Business class seat	1996-1997	B747-400 A340 A330	937	239	683	1557
Pierce et al. 1999 [19]	8**	Economic class seat	1998	B777	1469	-	1252	1758

Water et al. 2002 [36]	36	Economic class seat	-	-	1387	351	664	4328
Lindgren et al. 2002 [21]	26*	AFT and forward galley	1995-1998	B767-300	734	151	415	1488
Nagada et al. 2001 [35]	10**	Economic class seat	1999-2000	B737, B767, B747	1380		800	2390
Water et al. 2002 [36]	36*	Economic class seat	-	-	1387	351	874	2328
Ross et al. 2003 [37]	8	Economic class seat	2002-2003	BAe 146 B737-300	1316		780	1806
Spicer et al. 2004 [38]	4	Economic class seat	2004	MD80, B757-800	1229	164	723	1896
Cao et al. 2018 [16]	179	Economic class seat	2007-2009	A319/320, B737, B757, B767, etc.	1353	290	514	2993
Spengler et al. 2012 [23]	86	Economic class seat	2008-2010	B737, B767, B777, etc.	1404	297	863	2056
Giaconia et al. 2013 [39]	14	Economic class ceiling	2011	A319	1192	151	734	2213
Li et al. 2014 [13]	5	Economic class seat	2013	B737	1079	70	976	1151

- No information
* Smoking allowed
** Smoking conditions not mentioned

With the improvement of CO_2 testing methods, large-scale on-board CO_2 measurements have been carried out since the 1980s. Many investigations were carried out on cabin air quality in the 1990s and the first 5 years of the 21 century. One of the widely discussed topics in the early 1990s was smoking on board. The purpose of many investigations was to determine the effect of smoking. Malmfors et al. found that smoking cabins have lower CO_2 concentrations and higher ventilation rates needed to remove pollutants, and concentrations of other pollutants were much higher [20].

Regulations on cabin air quality changed in the 1990s, as smoking was completely banned during this period. As a result, the smoking cabins disappeared in the new century. The fresh ventilation rate was 4.7 L/s/p (0.55pounds/min/p) in the aviation regulations in 1996 and has remained unchanged until now [12].

Although there were many differences between flights in the 1990s and now, studies still included flights with a ventilation rate and smoke-free strategies similar to those of modern flights; this has provided valuable information for onboard CO_2 concentrations. Nagda et al. measured 23 non-smoking flights, and the CO_2 concentrations were 935 ± 217 ppmv (mean ± SD) [33]. O'Donnell et al. measured 45 short-haul flights, with a CO_2 concentration of 935 ± 217 ppmv (mean ± SD) [17]. Lee et al. investigated 13 non-smoking flights in the business class, and the CO_2 concentration was 937 ± 239 ppmv (mean ± SD) [19]. The 1990s constituted a period of great change in standards and specifications, and different routes or airlines often adopted unique ventilation strategies. As a result, onboard CO_2 concentrations considerably changed in the 1990s.

Since 2000, additional studies have attempted to investigate onboard CO_2 concentrations, and all measured non-smoking flights had similar CO_2 sources. Spengler et al. carried out CO_2 concentration monitoring in the passenger cabin of 86 commercial flights from 2008 to 2010 [23]. The length of the flights varied from 1 h to 16 h, although most were short-haul flights. The average CO_2 concentrations were 1404 ± 297 ppmv (mean ± SD), and the concentration range was 863–2056 ppmv. Cao et al. measured onboard CO_2 concentrations of 179 US domestic flights in passenger cabins from 2007 to 2009 [16]. The average CO_2 concentrations were 1353 ± 290 ppmv (mean ± SD). Giaconia et al. and Li et al. also measured the CO_2 concentration of a small number of flights in 2011 and 2013, respectively.

The mean CO_2 concentrations were fitted with the test times to investigate the real change in the CO_2 trend. The distribution for mean CO_2 concentration across flights in a period can be treated as a normal distribution [16], so the concentrations in the literature were estimations of the distribution's expectation. Regarding the differences in flight numbers in the literature, the linear weighted fitted method was used to fit the mean CO_2 concentrations with the test times, and the flight numbers of each investigation represented the weighting.

Many factors likely influenced the onboard CO_2 concentrations, and results with these influencing factors should be eliminated to maintain the accuracy of the trend. 1) Many smoking flights were included in the literature in the 1990s. As there were significant differences between smoking and non-smoking flights for CO_2 concentrations, all with undistinguished smoking flights were eliminated to avoid their potential impact. 2) Because the different classes had significantly different CO_2 concentrations, all selected studies measured the CO_2 concentrations in the economic class, and the results measured at other classes, galleys, or not mentioned were eliminated. In this study, the mean CO_2 concentration of the cruising phase in the economic class (1253 ± 164 ppmv, mean ± SD) was compared with the previous results.

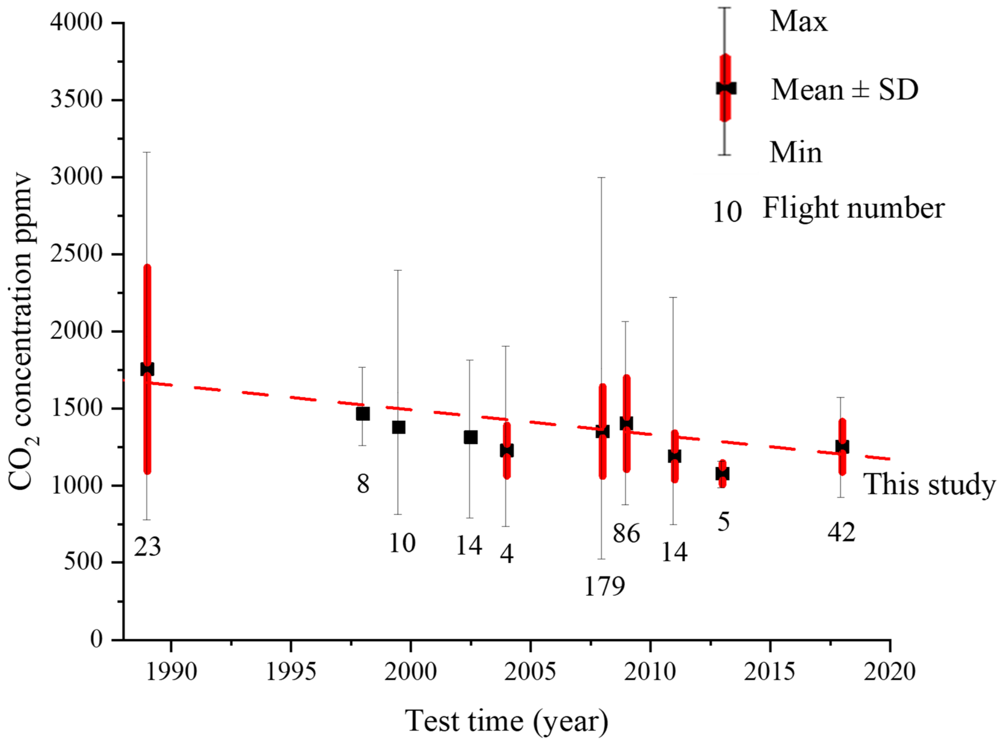


Figure 11 CO_2 concentration trend in non-smoking flights (--linear fitted line)

The in-service aircraft types were understandably diverse at different periods, although their impact was very limited. Water et al., Springer et al., and Mattson et al. found that CO_2

concentration had no significant difference in different aircraft types during the same period [20,2336], which means that the measured CO_2 concentration results represented the period within an aircraft type difference. In this study, single-aisle and double-aisle flights also did not show significant variations for typical phases in the same class.

Fig. 11 shows the CO_2 concentrations of non-smoking economic classes in the last 30 years, and all the previous results are presented in Table 3. The fitted curve of the average CO_2 concentration has a negative slope of -15.9 ppm/h and is different from 0 ($p = 0.002$), which means that onboard CO_2 concentrations have slightly decreased in the last 30 years.

The results meant that the ventilation rate was consistent growth in the last 30 years especially considering that the outside CO_2 concentration was also higher [28]. The best and safe way to reduce the risk of health effects is to increase the ventilation rate, which might cause a growth ventilation. With our deepening understanding of cabin air quality, a more suitable ventilation strategy considering both the outside and inside pollutant sources should be developed.

3 Conclusions

In this study, we measured CO_2 concentrations in the passenger cabins of 52 flights from boarding through deplaning. The spatial temporal characteristics of the CO_2 concentration on the board were analyzed and summarized. During the period before takeoff, the CO_2 concentration showed relatively obvious fluctuation peaks. During the cruising phase, the CO_2 concentration remained relatively stable. For the flight time scale, the CO_2 concentrations during the boarding phase (1680 ± 558 ppmv) were notably higher than in other phases, whereas the condition of the cruising phase was the lowest in most flights. The mean CO_2 concentrations during the cruising phase were 1253 ± 164 ppmv (mean ± SD) and the estimated outside airflow rates were 6.2 ±1.3 L/s/p across all flights in the economic class. Single-aisle and double-aisle flights did not show many variations for typical phases.

The positions of different classes represented the most important factor for CO_2 concentrations in aircraft cabins. Relatively uniform CO_2 concentrations were observed in the different positions of the same class (<15%). However, the CO_2 concentration in the business class was significantly lower than that in the economic class, whereas the ventilation rates per unit length of the cabin were similar.

Overall, onboard CO_2 concentrations have slightly decreased in the last 30 years. These results indicated that the ventilation rates slightly increased.

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