Harvard John A. Paulson School of Engineering and Applied Sciences

2023 International Emissions Inventory Conference

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Developing a high-resolution emission inventory of aviation sector using real-world flight trajectory data

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Aviation and its environmental impact

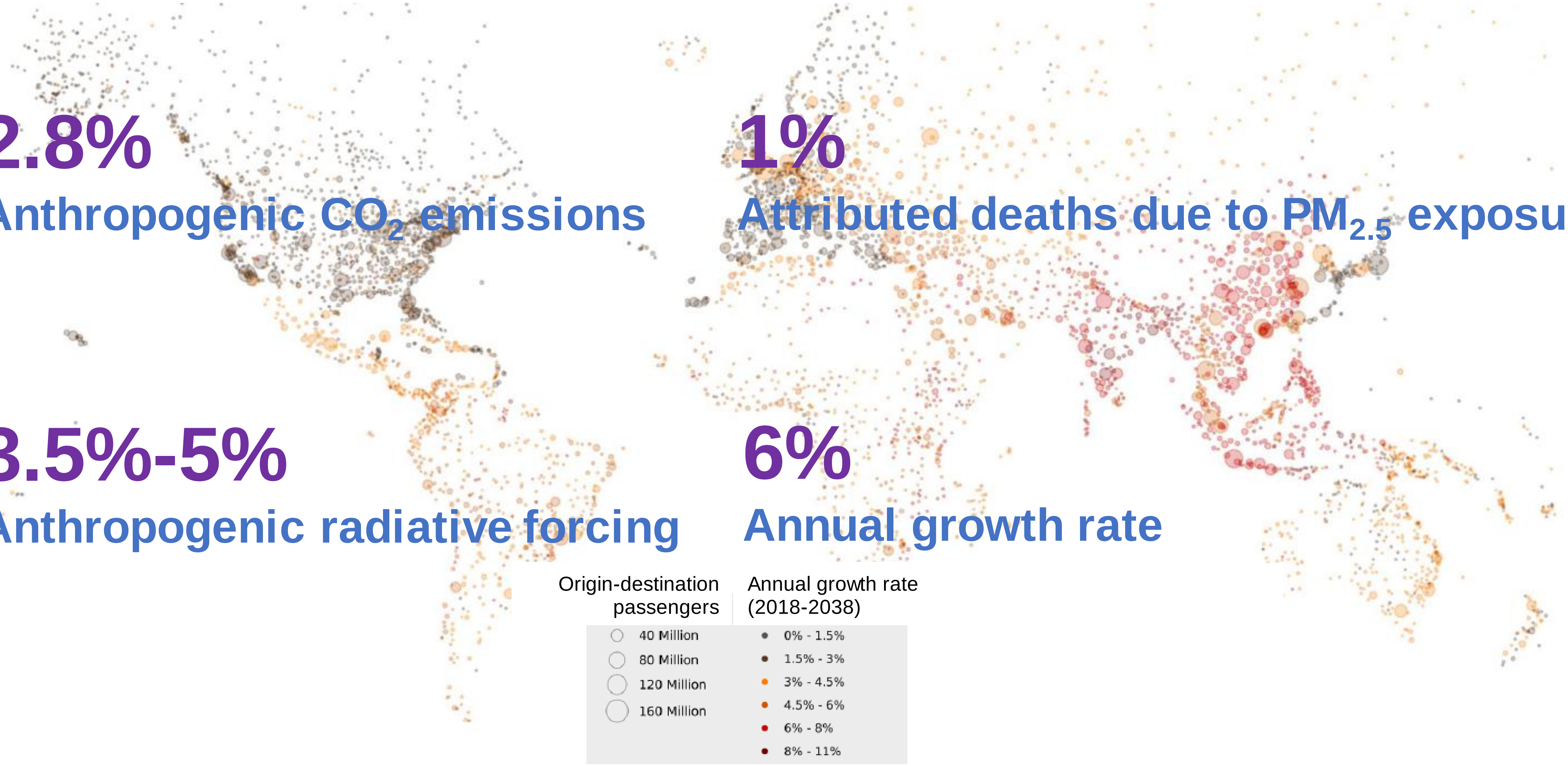
Economic growth has led to a surge in civil aviation transportation demand in the past twenty years.

2.8%
Anthropogenic CO_2 emissions

1%
Attributed deaths due to $PM_{2.5}$ exposure

3.5%-5%
Anthropogenic radiative forcing

6%
Annual growth rate

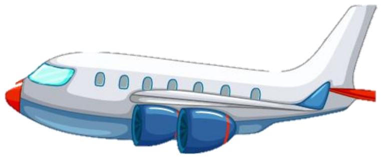


Airbus GMF 2019, Staples, M.D., et al.,2018, Lee, D.S., et al.,2021, Yim, S.H.L., et al.,2015 , Steven R. H. Barrett., et al.,2010

Aviation and its environmental impact

Compared with other transportation modes, research on the environmental impacts from aviation sector has developed relatively late.

Aviation



Emission Control

NO_X and fuel efficiency dilemma
PM standard began at 2016

New Energy

Biofuels < 1% Demand
Electric aircraft： <9 seats

Economic policy

CORSIA
Incentives for SAF in EU and US

Road

Emission Control

Tier Ⅵ
Advanced processing technology

New Energy

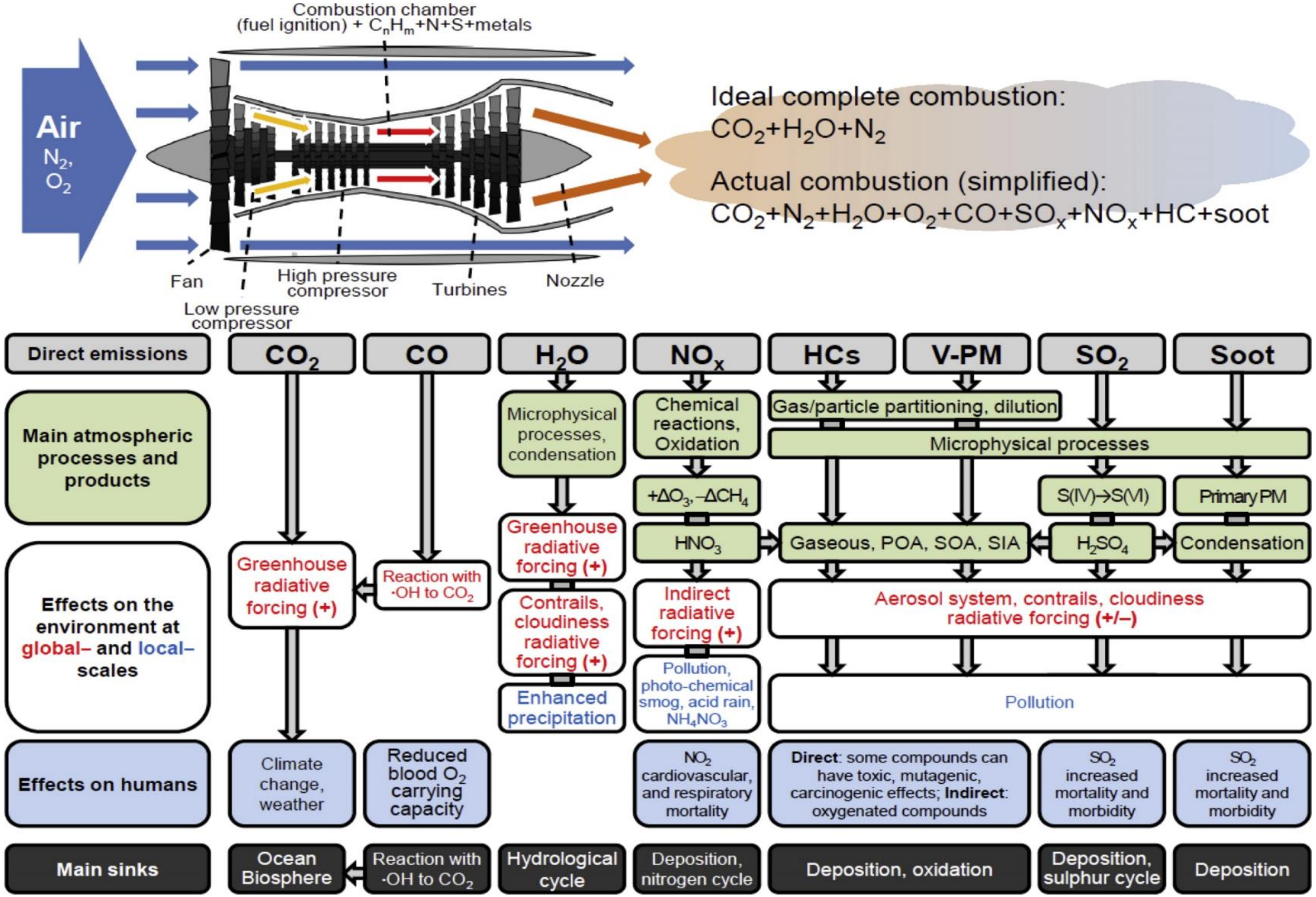
Blooming EV market
Hydrogen fuel cell technology has been promoted

Economic policy

Subsidy for elimination of old cars
Subsidy for new energy vehicle purchase

CORSIA: The Carbon Offsetting and Reduction Scheme for International Aviation, International Civil Aviation Organization (ICAO)

Aviation and its environmental impact

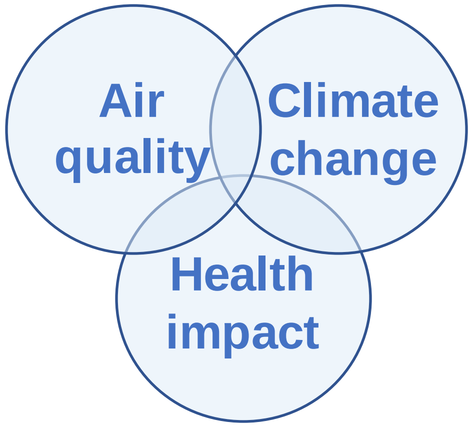


Activity

↓

Emission inventory

↓



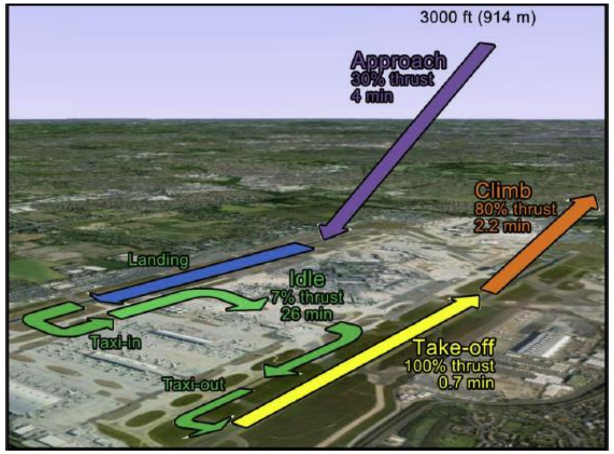
Masiol, Mauro, et al.2014

Characterization of aviation emissions of CO_2 and air pollutants

Emission inventory of the aviation industry developed relatively late, poor resolution and accuracy, weaken environmental impact analysis

Emission Inventory of Airports

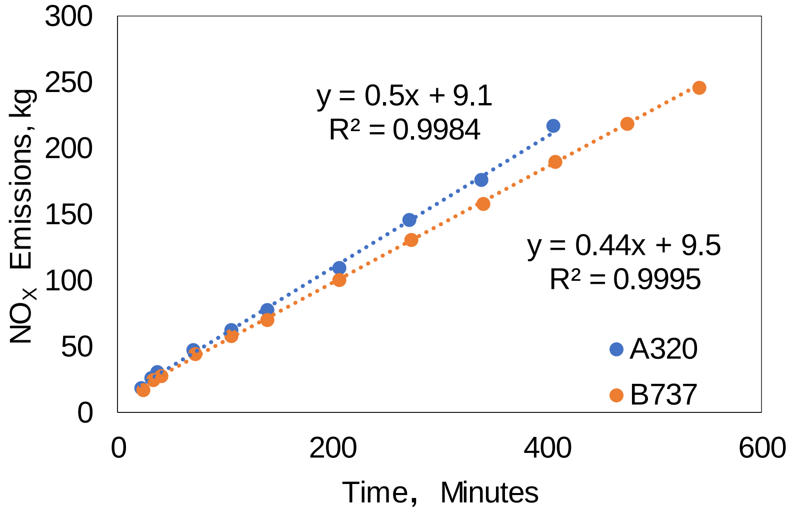
- Based on Landing takeoff times
- Do not distinguish aircraft type, incomplete coverage



Stettler M E J et al. UK. 2011
Xu H et al. Shanghai Hongqiao. 2020

Emission Inventory of flights

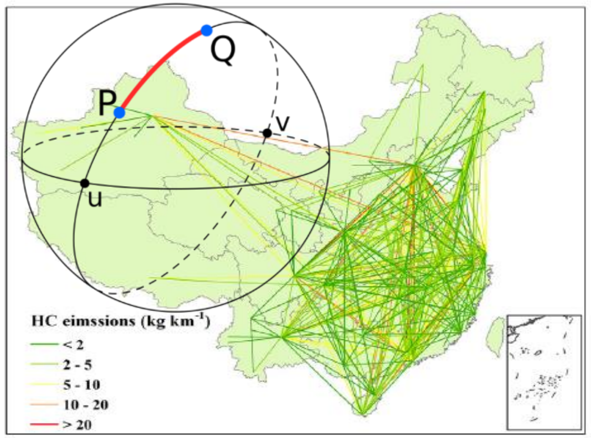
- Based on Flight information(aircraft and flight distance)
- No spatial resolution



H. Liu et al. 2019
European Environment Agency. 2020

3D Emission Inventory

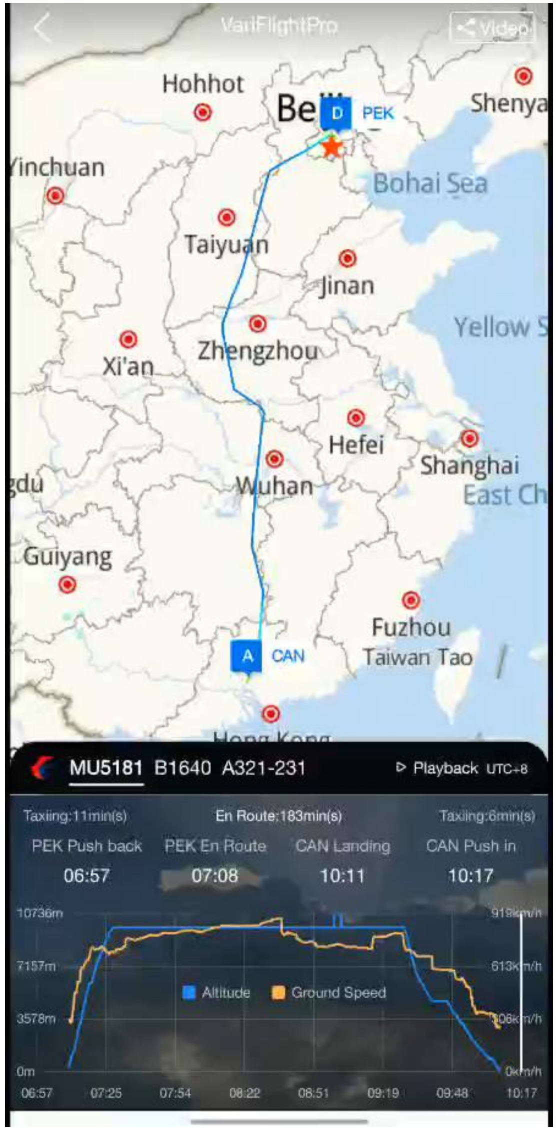
- Based on Great Circle method
- Gap between the Ideal model and real-world flight performance



Eyers C J et al. AERO2K. 2002
Wilkerson J T et al. AEDT. 2004/2006

The great-circle distance: shortest distance between two points on the surface of a sphere

Developing a high-resolution emission inventory of aviation sector using real-world flight trajectory data



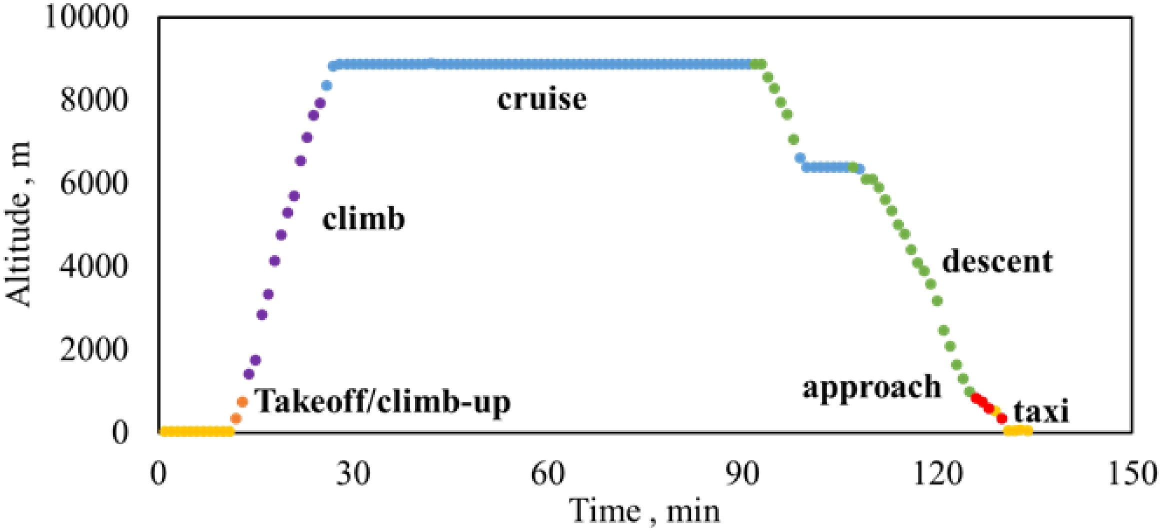
Open source data :
Automatic Dependent Surveillance–Broadcast (ADS-B)

Real-time position and speed

Latitude + Longitude + Altitude + Speed

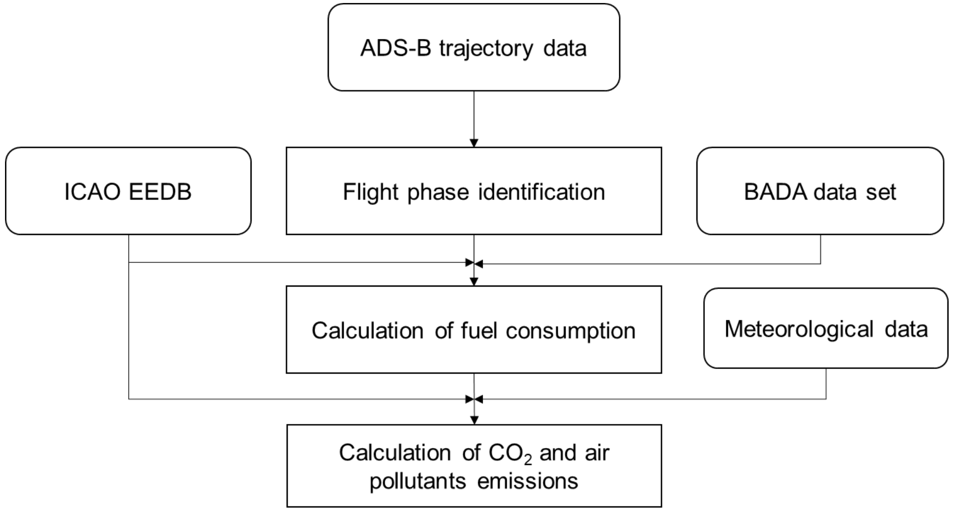
Landing and takeoff (LTO) includes Taxi + Take off + Climb up + Approach

Climb Cruise Descent (CCD) includes Climb + Cruise + Descent



Method: Emission calculation of each flight record

SO_2, PMS	**Principle of mass balance**
NO_X, HC, CO	**Boeing method**
PM, OC, BC	**FOA3+DLR**
BC number	**ETH**



$$Fuel = \sum FC_{f,i} \times EF_{f,i} \times EngineNum_f \times time_i$$

$$EF_{f,i} = f_{f,phase}(EFbase_{f,phase}, FC_{fi})$$

$$W_{ff} = \frac{W_f \theta_{amb}{}^{3.8} \exp(0.2Ma^2)}{\delta_{amb}}$$

$$EF_{NO_x} = REF_{NO_x} exp(-19.0 \times (\omega - 0.0063))(\theta_{amb}{}^{3.3}/\delta_{amb}{}^{1.02})^{-0.5}$$

Reference emission factors of the standard testing cycle phases

Reference fuel consumption at the sea level standard

Instantaneous flight performance: sub-phases

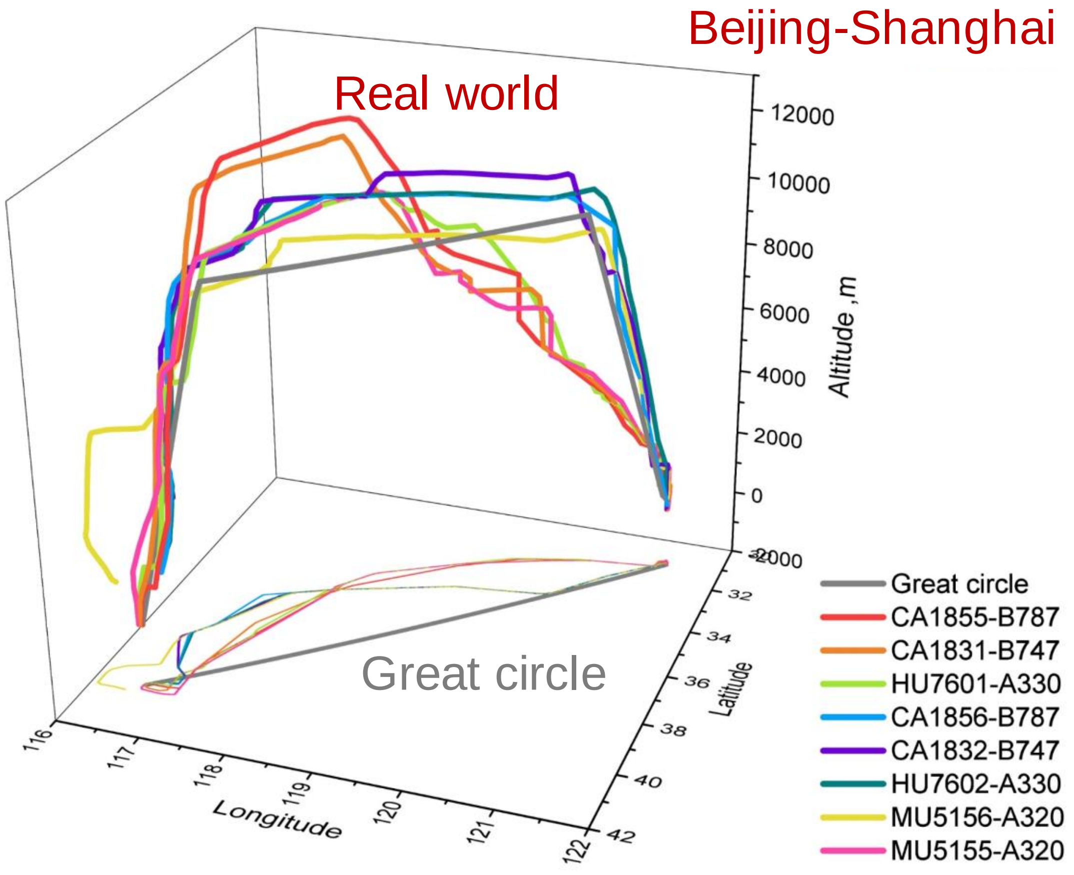
Instantaneous flight performance parameters

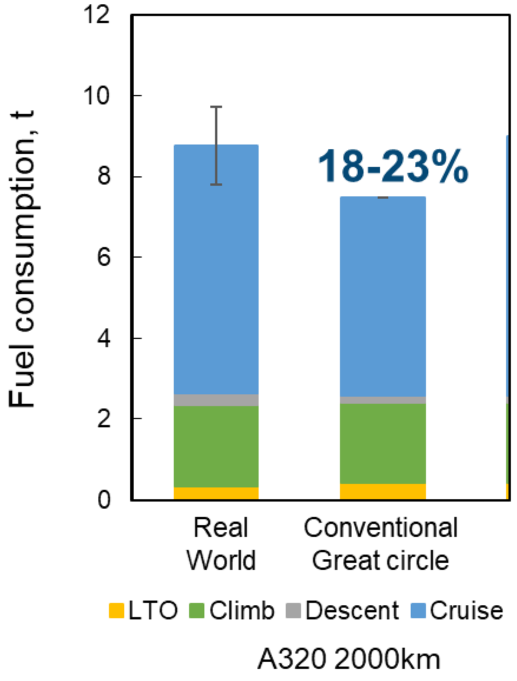
4D meteorological parameters

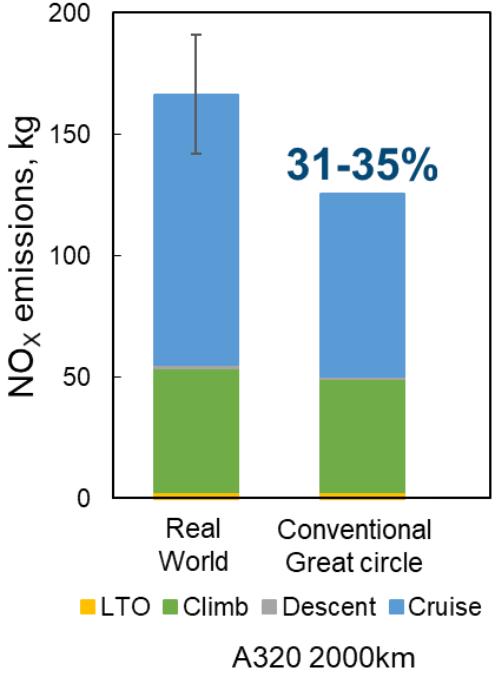
Improve the resolution and accuracy of emission inventory

Total emissions of CO_2 and air pollutants from short-distance domestic flights would be significantly underestimated by the conventional great-circle-based approach due to underrepresented calculation parameters (flight distance, duration, and cruise altitude).

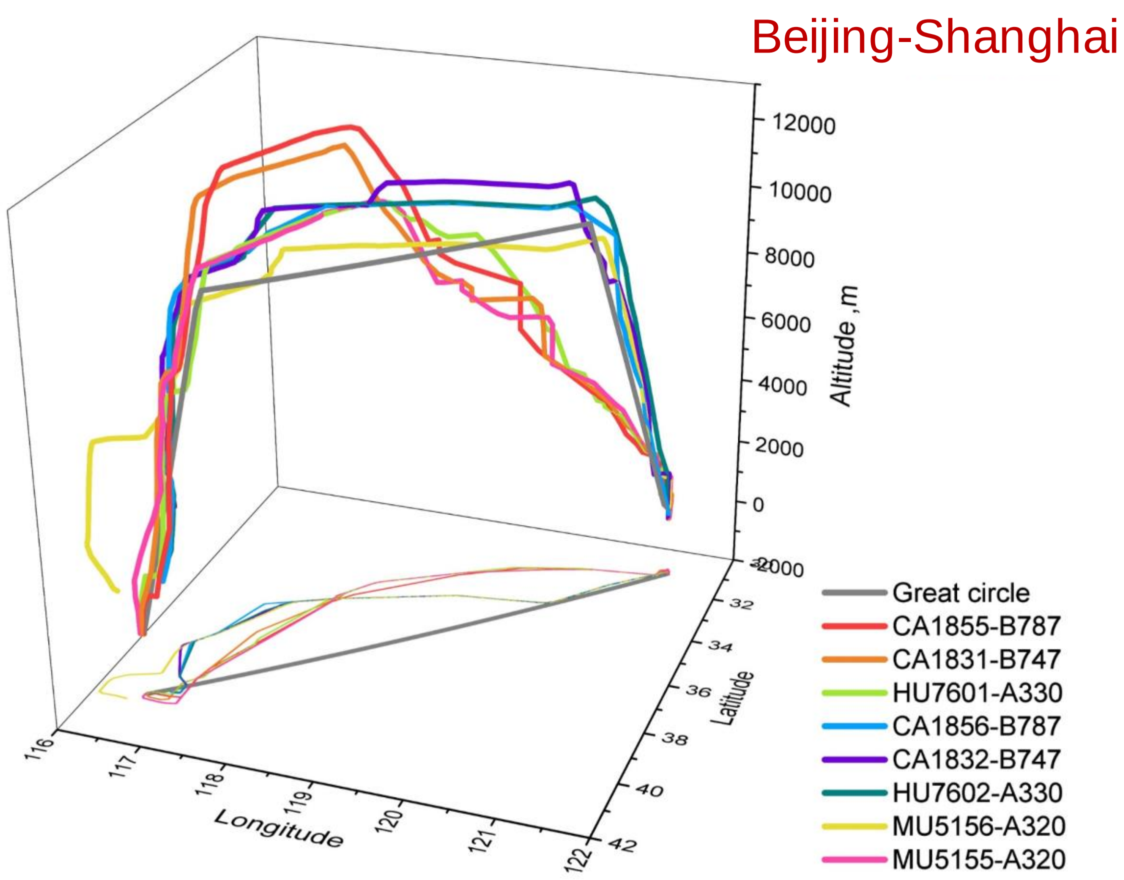
Cruising altitude → **Fuel consumption rate** → **Emission factors**







Improve the resolution and accuracy of emission inventory



◻ When :

Real time
1 min resolution

◻ Where :

High resolution latitude + longitude at any resolution

◻ How much :

The real flight performance and corresponding meteorological data to correct the emission factor

Results compared to previous studies

This study noted a significant underestimation of aviation emissions for short-distance flights based on the conventional great-circle-based approach compared with the results using real-world trajectory profiles.

	Model Year	Fuel Consumption	CO_2	NO_X	HC	CO	BC Mass	OC	PM	BC Number
		Mt	Mt	kt	kt	kt	kt	kt	kt	#
This Study	2019	290.60	915.4	4982	78	636	8.0	2.1	21.9	1.35×10^{26}
IATA	2019		914							
ICCT	2019	290.16	914							
AEDT	2006	205.68		2987	98	529	6.8	3	12.1	
AEIC	2005	180.6		2689	201	749				
Aero2k	2002	156		2060	63	507			3.9	4.03×10^{25}

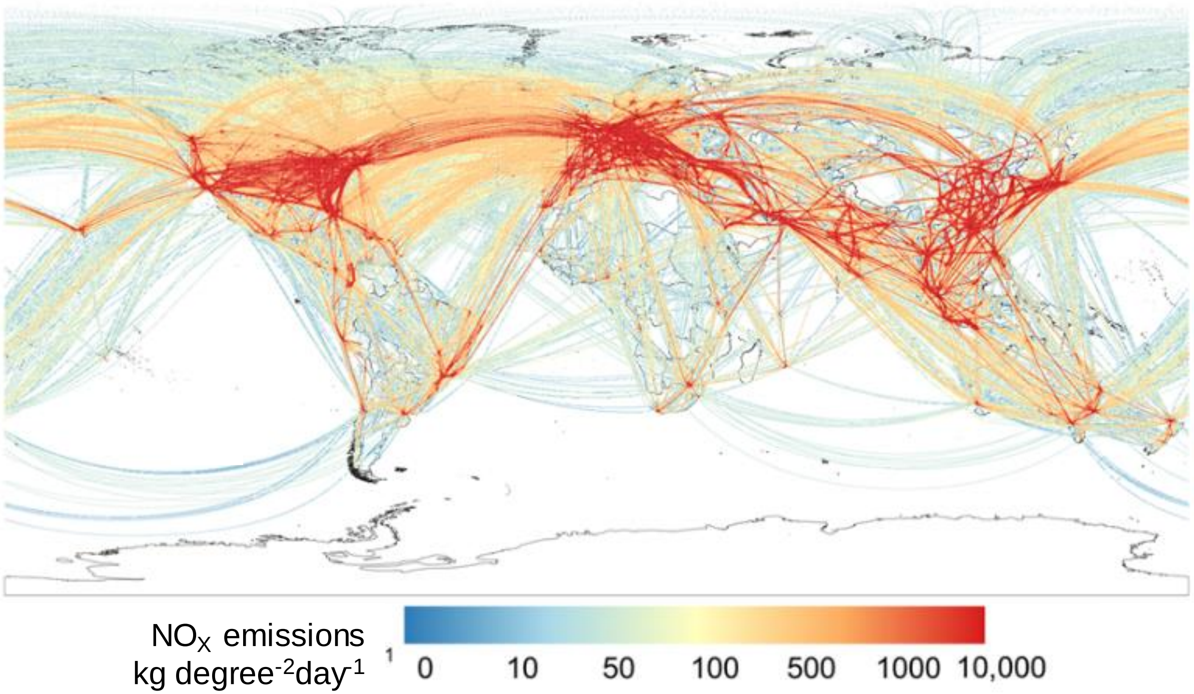
Compared with the statistical data of The International Air Transport Association, the difference in estimation fuel consumption is less than 0.2%

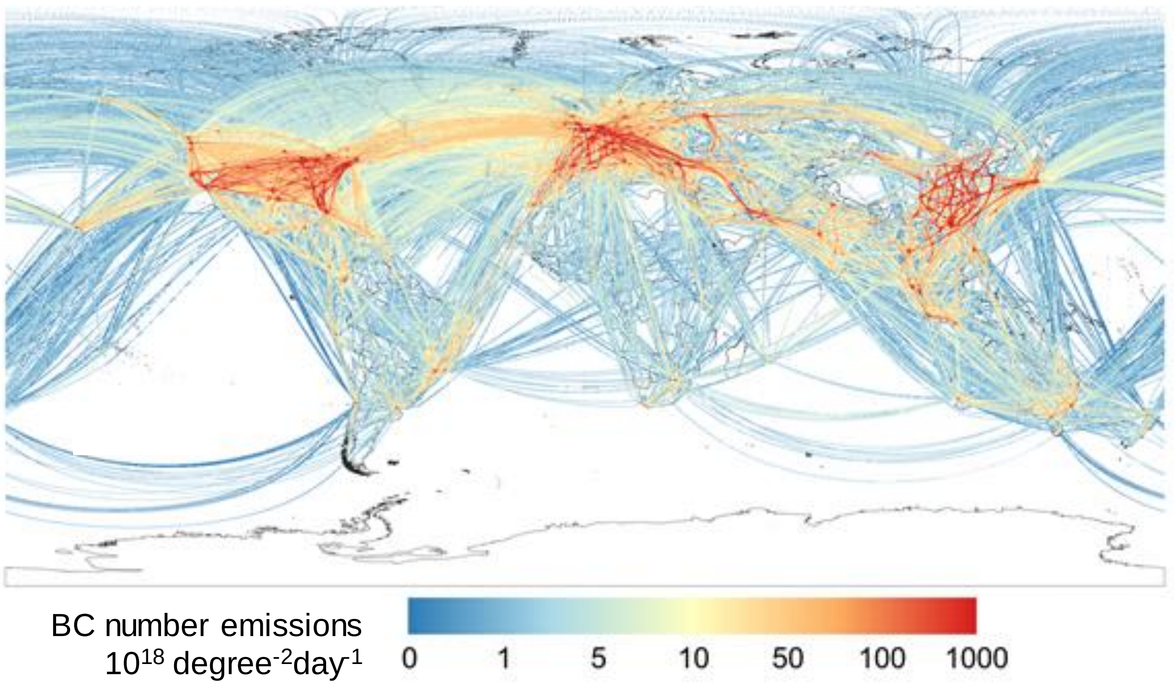
IATA,2020; ICCT,2020; Wilkerson J T et al., Atmospheric Chemistry and Physics, 2010; Simone N W et al., Transportation Research Part D,2013; Eyers C J, et al. 2004

The spatial distribution-Global scale

The total emissions of the global aviation sector were estimated to be 915 Mt of CO_2, 4981.8 kt of NO_X, 635.7 kt of CO, 77.8 kt of HC and 21.9 kt of PM, and 1.35×10^{26} of BC particle number in 2019.

Three active regions (Asia Pacific, North America and Europe) represented the majority of total aviation emissions, and a few regional hubs also were emission hotspots.





The altitude distribution-Global scale

CO_2

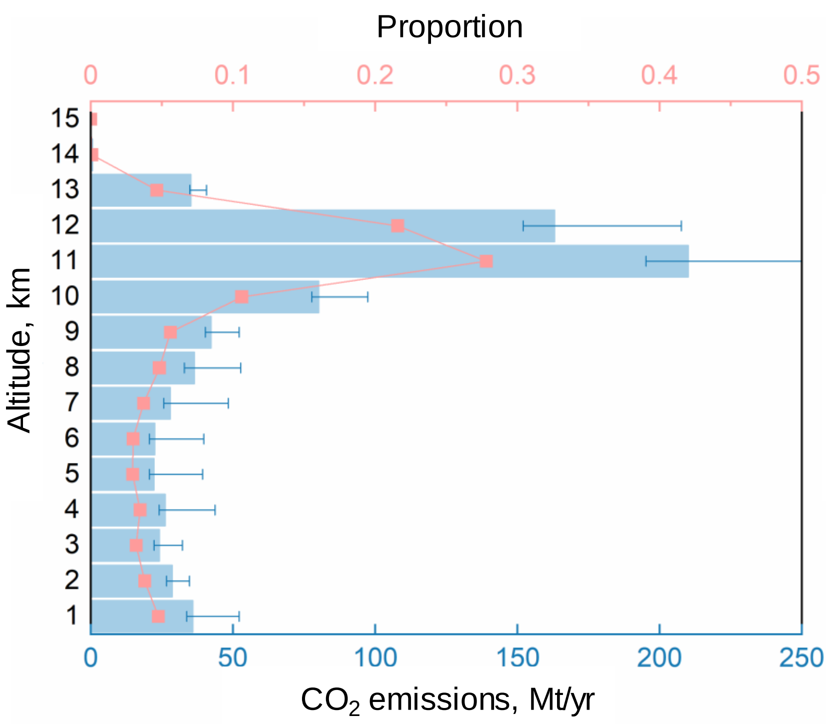
- Concentrated at 9-12 km
- Accounting for over 60%

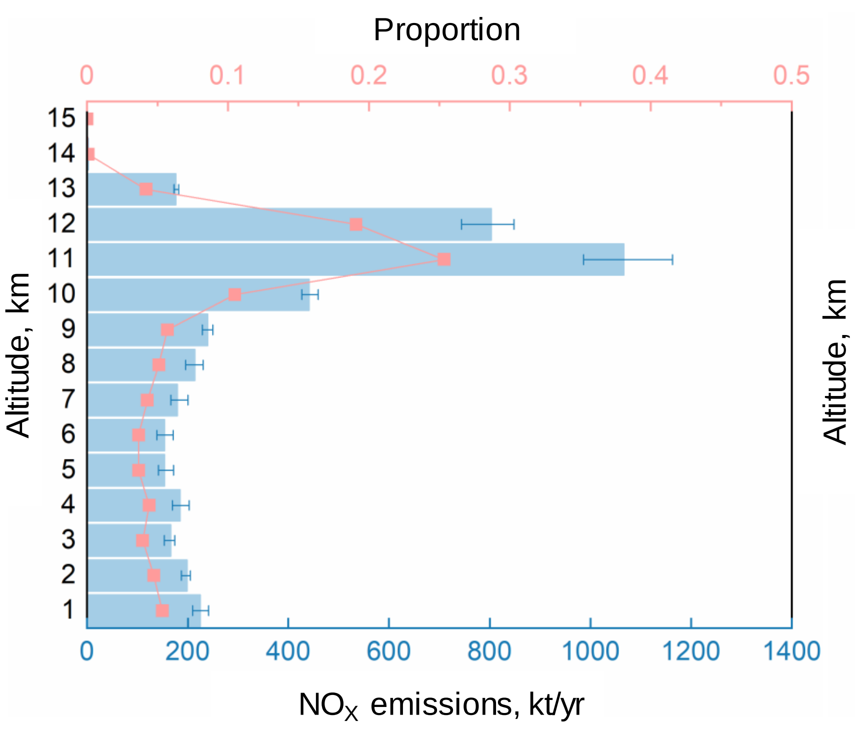
NO_X

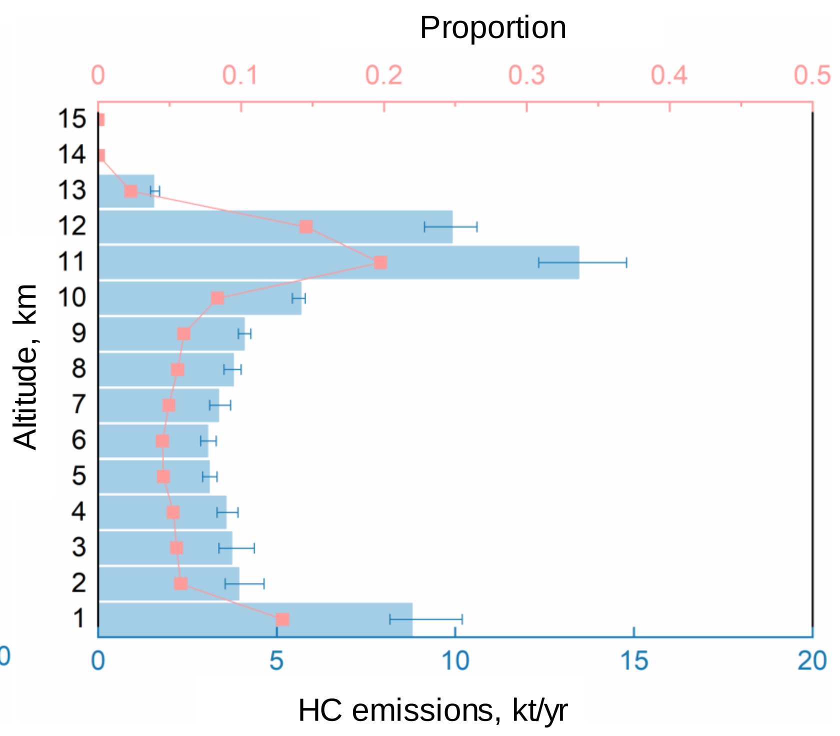
- Dominated by thermal reactions
- Generated with large thrust and rich combustion

HC

- Low altitude higher
- Incomplete combustion



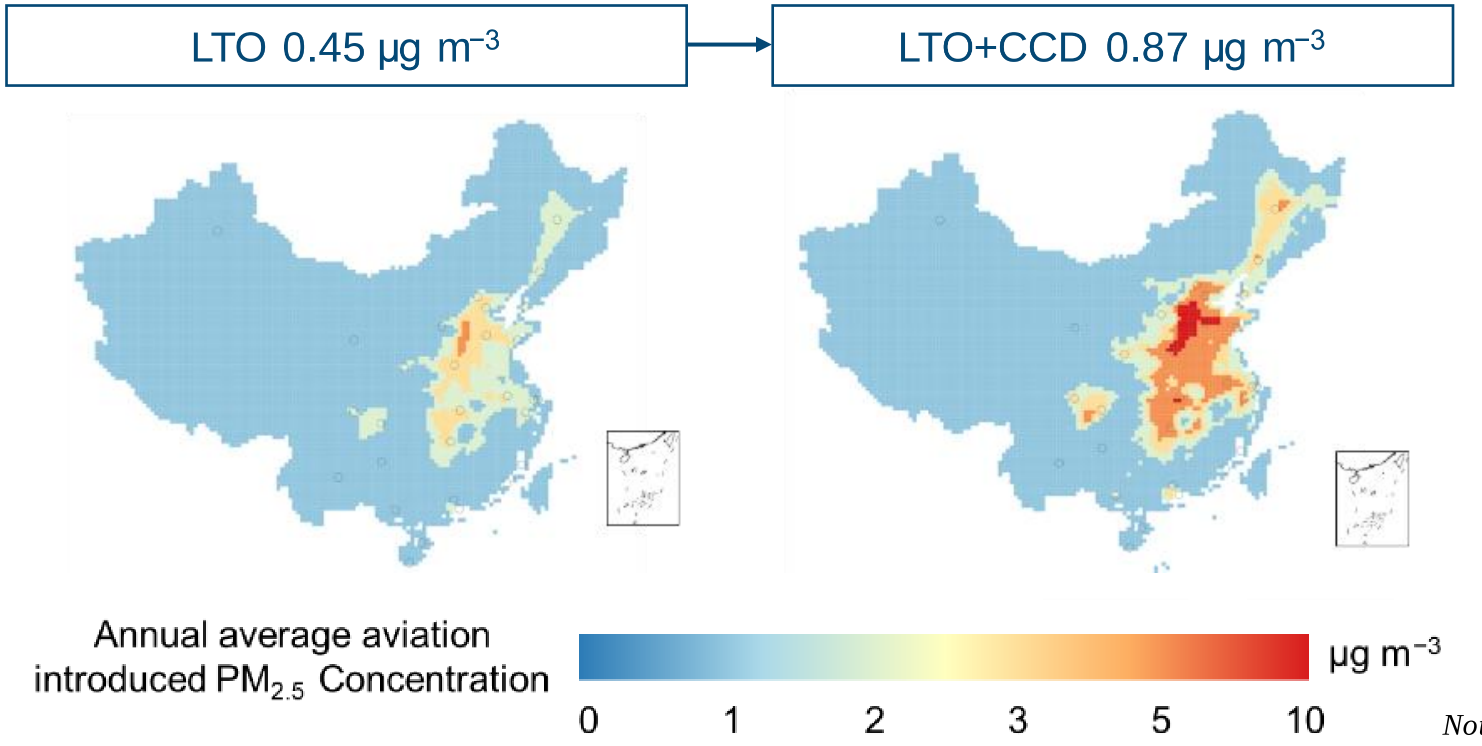




Today: Aviation attributed air pollution and health impact

Significant contribution of high-altitude cruising emissions

- Although the CCD (Climb Cruise Descent) emissions were mainly at altitudes higher than 1 km, their contribution to the ground-level pollution was comparable to that of LTO (Landing and takeoff).
- $PM_{2.5}$: CCD emissions resulted in a significant increase of the aviation-attributed ground-level $PM_{2.5}$ in eastern China, from 0.45 $\mu g \cdot m^{-3}$ to 0.87 $\mu g \cdot m^{-3}$ (2% to 3%).



Tomorrow: Rising impact from ‘hard-to-abate’ aviation sector

	Battery- electric	Hydrogen	Sustainable aviation fuel
			
PROS	• No environmental impact in flight • Reduced Costs • Noise Reduction	• No environmental impact in flight • Reduced Costs • Noise Reduction	• No limitation of range • No change to aircraft or infrastructure • Contributed to 65% of carbon mitigation target in 2050
CONS	• Limited range • Low mass density • Change to aircraft and infrastructure	• Limited range • Low volume density • Change to aircraft and infrastructure	• Limited non-CO_2 effects • No significant NO_X reduction • PM reduction limited to aromatics content requirement

Boeing, Airbus, Honeywell

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Thank you !

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