Reconstructing high-resolution in-situ vertical carbon dioxide profiles in the sparsely monitored Asian monsoon region

Bärbel Vogel, C. Michael Volk, Johannes Wintel, Valentin Lauther, Rolf Müller, Prabir K. Patra, Martin Riese, Yukio Terao and Fred Stroh

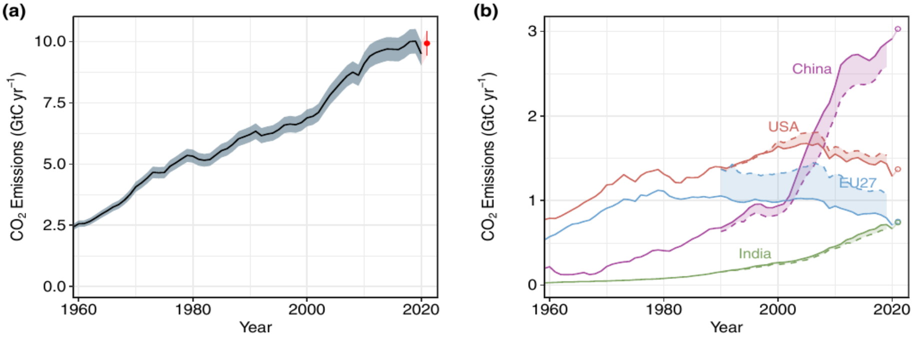
Kathmandu in Nepal summer 2017

courtesy of Armin Afchine

Transport of air pollution and greenhouse gas from surface into the lower stratosphere?

CO_2 is chemically inert in the troposphere and stratosphere $\rightarrow$ can be used as an age tracer.

Fossil CO_2 emissions

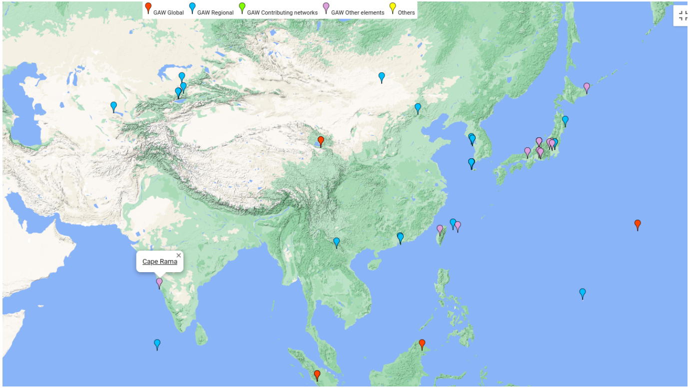


Friedlingstein et al., 2022, Global Carbon Budget 2021

(a) Fossil CO_2 emissions for the globe
(b) Territorial (solid lines) and consumption (dashed lines) emissions for the top country emitters (USA, China, India) and for the European Union

Ground-based CO_2 measurement sites in Asia

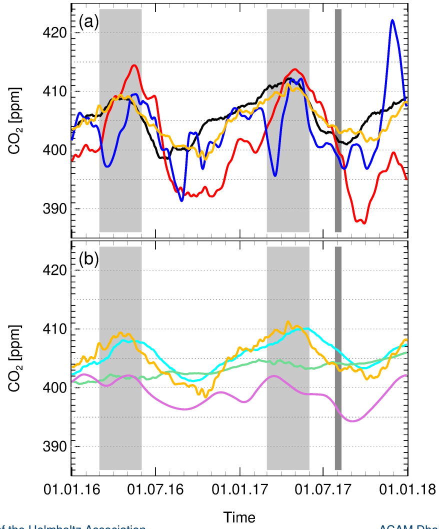
World Data Centre for Greenhouse Gases (WDCGG)

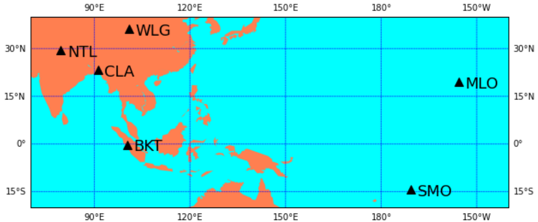


https://gaw.kishou.go.jp

➥ Only a limited number of continuous ground-based measurements of CO_2 and also other Greenhouse Gases are available in South Asia, in particular on the Indian subcontinent.

Ground-based CO_2 measurements in Asia



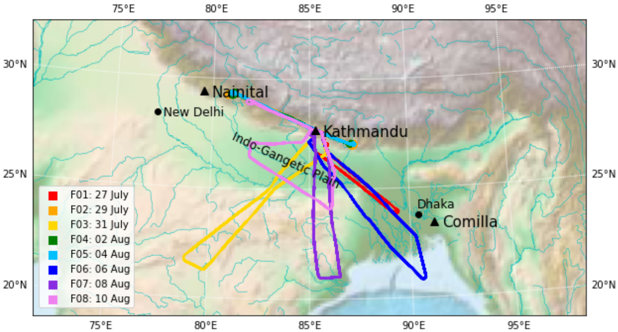


Nainital (India)
Comilla (Bangladesh)
Mt. Waliguan (China)
GOSAT Indian subcontinent
Mauna Loa (Hawaii)
Cape Matatula (Samoa)
Bukit Kototabang (Indonesia)

GOSAT-L4B: mean value between 20–30°N and 75–95°E at 975 hPa

Nomura et al., ACP, 2021; World Data Center for Greenhouse Gases

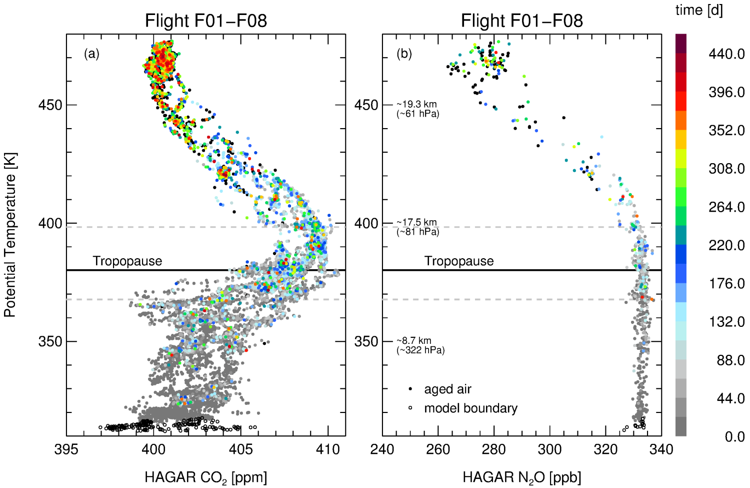
StratoClim aircraft measurement campaign
in Kathmandu (Nepal) in summer 2017



High-altitude aircraft Geophysica

➥ The StratoClim measurements constitute a unique data set in the Asian monsoon region up to $\sim$ 20 km ($\sim$55 hPa or $\sim$475 K)

CO_2 and N_2O aircraft measurements and transport time



- HAGAR = multi-tracer in situ instrument (University Wuppertal)
- high-resolution CO_2 measurements (3–5 seconds)
- CO_2 profiles reflect CO_2 variability at ground level
- N_2O profiles above 400 K indicates mixing with older stratospheric air
- transport time from CLaMS back-trajectories to 1 June 2016 driven by ERA5 reanalysis

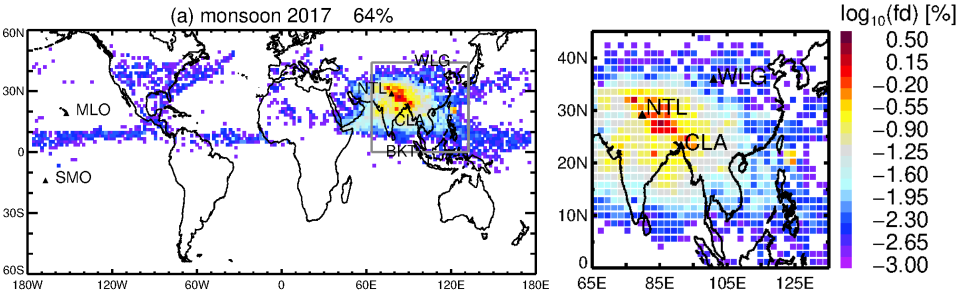
Time periods and age of air of considered seasons

on Indian subcontinent

Season	Time period	Start Time	Age of air
Monsoon 2017	June–September 2017	1 June 2017	$\sim$ 2 months
Pre-monsoon 2017	March–May 2017	1 March 2017	$\sim$ 2-5 months
Winter 16/17	December 2016 – February 2017	1 Dec 2016	$\sim$ 5-8 months
Post-monsoon 2016	October–November 2016	1 Oct 2016	$\sim$ 8-10 months
Monsoon 2016	June–September 2016	1 June 2016	$\sim$ 10-14 months
Aged air	older than 1 June 2016		$>$ 14 months

- Time when CLaMS back-trajectories driven by ERA5 (started along the flight tracks) reach the model boundary layer (BL) ($\sim$2-3 km above surface) corresponds to the age of air of measured air parcels.
- 90% of the air is younger than 1 June 2016, the other 10% is aged air

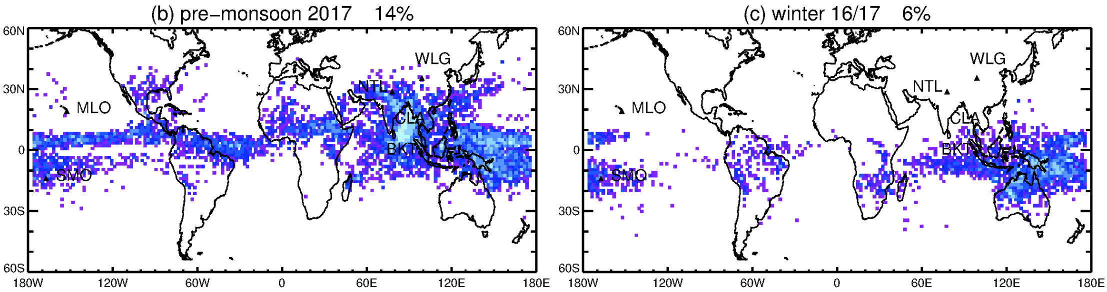
Air mass origin at Earth's surface during monsoon 2017



Frequency distribution (fd) of the air mass origins at the model boundary layer using CLaMS ERA5 back-trajectories

- Most air parcels were released at the model BL during monsoon 2017 (64%)
- from the northern part of the Indian subcontinent, the Tibetan Plateau, Bay of Bengal and eastern China

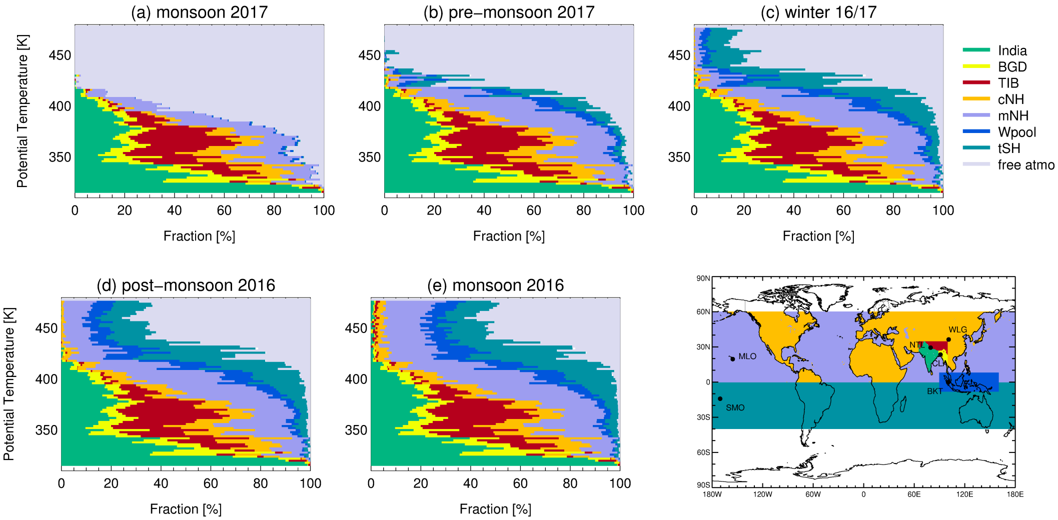
Air mass origin at Earth's surface during pre-monsoon 17 and winter 16/17



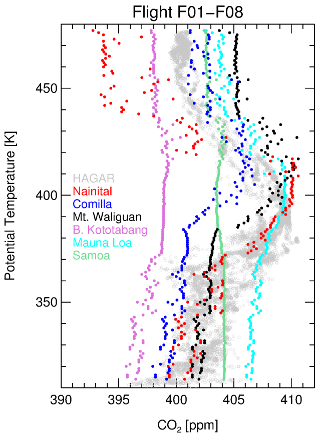
Frequency distribution (fd) of the air mass origins at the model boundary layer using CLaMS ERA5 back-trajectories

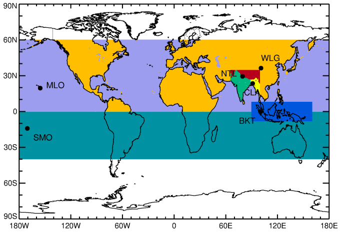
- Pre-monsoon 2017 (14%) and winter 16/17 (6%)
- During pre-monsoon 2017 the origins are shifted towards the tropics to the northern Inter-Tropical Convergence Zone (ITCZ)
- During winter 16/17 to the southern ITCZ

The fraction of air from the model BL and the free atmosphere



Sensitivity of CO_2 reconstruction on observation sites

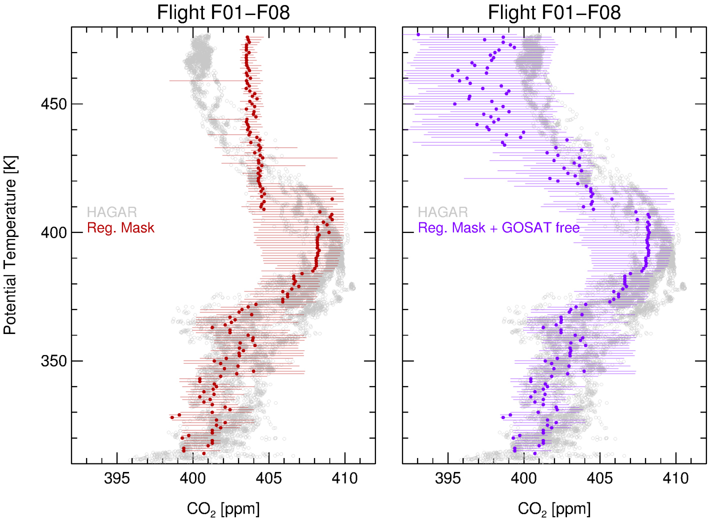




Model BL Region	Site
Indian subcontinent (India)	NTL
Bangladesh (BGD)	CLA
Tibetan Plateau (TIB)	NTL
continental northern hemisphere (cNH)	WLG
maritime northern hemisphere (mNH)	MLO
Warm Pool region (Wpool)	BKT
tropical southern hemisphere (tSH)	SMO

- HAGAR CO_2 airborne measurements
- Reconstructed CO_2 from ground-based measurements
- CO_2 mixing ratios from ground-based measurements are prescribed at the time when each trajectory reach the model BL
- Reconstructed CO_2 values are shown as median in 1 K intervals
- Reconstructed CO_2 profiles reflect CO_2 variability at ground level
- Aged air is not considered

Reconstructed CO_2 using back-trajectories until 1 Dec 2016



- HAGAR CO_2 airborne measurements
- Reconstructed CO_2 is shown as median calculated from all trajectories
- Bars indicate the range between the 25 and 75 percentile
- CO_2 reconstructed by using a regional mask (observation sites)
- GOSAT-L4B CO_2 data used for stratospheric background
- The statistic treatment represents mixing between different air masses

Conclusions

- Atmospheric concentrations of CO_2 have increased substantially because of human activities, however their sources in South Asia are poorly quantified.
- Lagrangian model simulations successfully reconstruct vertical CO_2 profiles obtained by high-resolution aircraft measurements up to 20 km during the Asian summer monsoon 2017.
- Reconstructed CO_2 profiles reflect CO_2 variability at ground level.
- Ground-based CO_2 signals rapidly propagate to approximately 13 km with slower ascent above.
- A greater number of continuous ground-based measurements of CO_2 and also other GHGs in South Asia, in particular on the Indian subcontinent, would be a great asset for atmospheric and climate modelling.

Vogel et al, 2023, communications earth & environment

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- the NOAA Earth System Research Laboratory for providing CarbonTracker
- the European Centre for Medium-Range Weather Forecasts (ECMWF) for providing ERA5 reanalyses

additional material

Comparison with GOSAT-L4B and CarbonTracker