Supplementary information for:

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

Bärbel Vogel[1*], C. Michael Volk[2], Johannes Wintel[2,5], Valentin Lauther[2], Rolf Müller[1], Prabir K. Patra[3], Martin Riese[1], Yukio Terao[4] and Fred Stroh[1]

[1*]Institute of Energy and Climate Research (IEK-7), Forschungszentrum Jülich, Jülich, Germany.

[2]Institute for Atmospheric and Environmental Research, University of Wuppertal, Wuppertal, Germany.

[3]Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan.

[4]Center for Global Environmental Research, National Institute for Environmental Studies, Ibaraki, Japan.

[5]now at: Curt-Engelhorn-Centre of Archaeometry gGmbH, Mannheim, Germany.

[6]Department, Organization, Street, City, 10587, State, Country.

*Corresponding author(s). E-mail(s): b.vogel@fz-juelich.de;

Supplementary Discussion

Sensitivity of CO_2 reconstruction on the trajectory length

The sensitivity of CO_2 reconstruction (case S1, case S2a and case S2b; details see main paper) depending on the used length of the back-trajectories is also inferred (Fig. S1). Back-trajectories ending until the start time of monsoon 2017 and pre-monsoon 2017 are too short to reconstruct the vertical CO_2 profiles because the fraction of model BL is lower than 90% below 410 K.

The longer the back-trajectory calculations the higher the altitudes of the end points of the trajectories from the free atmosphere. Along latter trajectories CO_2 is reconstructed from GOSAT-L4B product providing CO_2 values up to 10 hPa. The longer the trajectories the more the altitudes of the end points exceeds the pressure level of 10 hPa and the CO_2 values are here extrapolated to higher pressure levels that increases the uncertainties of reconstructed CO_2. We decided to show back-trajectories to 1 December 2016 in the main paper, because here up to 410 K reconstructed CO_2 is determined solely by CO_2 prescribed at the model BL and by the transport of air parcels along the back-trajectories. Here, the uncertainties regarding the CO_2 extrapolation to higher pressure levels are negligible. Thus the longer the trajectories the higher are the uncertainties of the used CO_2-reconstruction approach for stratospheric altitudes, however also the fraction of

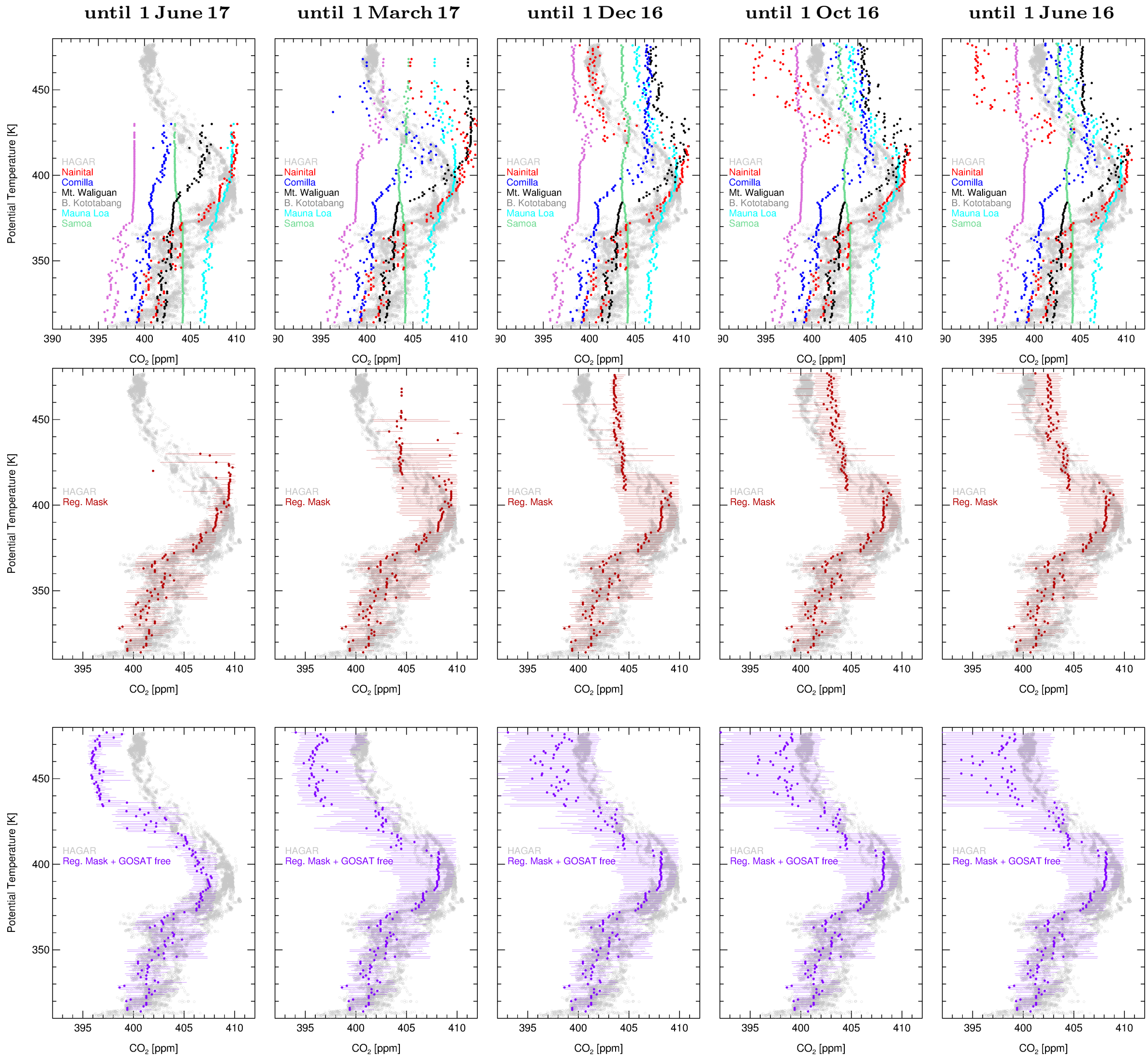

Fig. S1 Reconstructed CO_2 using back-trajectory calculations of different length. Same as Fig. 7a and Fig. 8a,b of the main paper showing case S1 (top), S2a (middle) and case S2b (bottom), but CO_2 is reconstructed using trajectories of different length until the start time of monsoon 2017, pre-monsoon 2017, winter 16/17, post-monsoon 2016 and monsoon 2016.

trajectories from the free atmosphere is decreasing (to 1 Dec 2016: 16%; to 1 June 2016: 10%; details see Fig. S1), these two effect working against each other and are to be taken into account for longer trajectories. Considering all these effects, we think that the selection of the back-trajectories until 1 December 2016 is a good choice for the used approach to reconstruct CO_2 profiles in the region of the Asian monsoon anticyclone.

Reconstructed CO_2 from GOSAT-L4B

To compare GOSAT-L4B data with the vertical CO_2 profiles measured by the HAGAR instrument CO_2 from GOSAT-L4B is interpolated along the Geophysica flight tracks (see Fig. S2). A good agreement in the lower troposphere is found, however in the upper troposphere and lower stratosphere CO_2 from GOSAT-L4B is in general lower than in situ CO_2 from HAGAR. In addition CO_2 is reconstructed similar as in case S2b, but CO_2 is used from the lowest level of GOSAT-L4B data

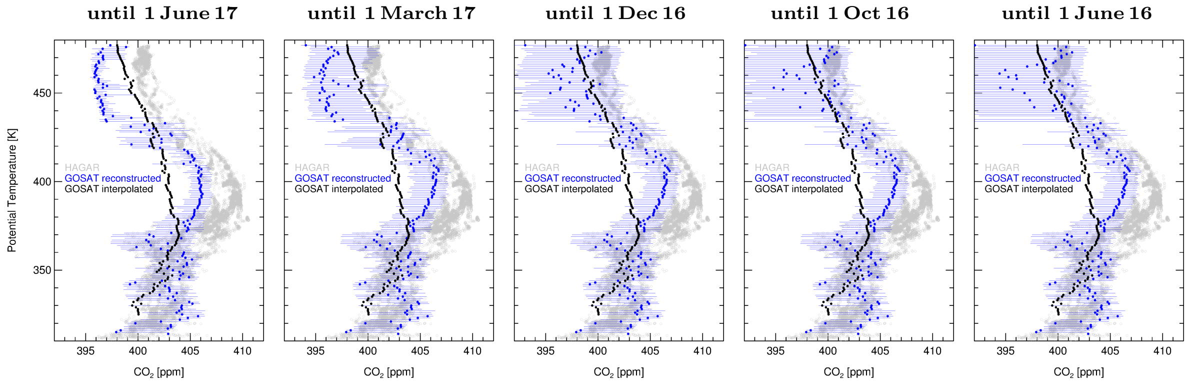

Fig. S2 Reconstructed CO_2 using GOSAT-L4B at the model BL. Same as Fig. S1 (case S2b), but CO_2 is used from the lowest level of GOSAT-L4B data to reconstruct CO_2 for trajectories that end in the model BL (case S3). In addition, CO_2 from GOSAT-L4B is also interpolated along the Geophysica flight tracks.

to reconstruct CO_2 for trajectories that end in the model BL (case S3). Also for case S3, the sensitivity of the quality of the reconstruction of CO_2 on the employed trajectory length is inferred (Fig. S2).

The longer the trajectories the better the measured CO_2 profile is reconstructed. The reconstructed CO_2 (case S3) is still lower than the measured CO_2 profile, but a better agreement is achieved than for GOSAT-L4B CO_2 interpolated along the Geophysica flight tracks. That confirms that the Lagrangian transport in CLaMS using diabatic vertical velocities and driven by high-resolution EAR5 reanalysis is very well suited for CO_2 reconstruction. Further this demonstrates that the lowest level of GOSAT-L4B CO_2 data inferred from CO_2 fluxes at the Earth surface (GOSAT-L4A data) is a useful data base at the Indian subcontinent to infer lower boundary conditions for atmospheric model simulations in the absence of ground-based CO_2 measurements.

Airborne CO_2 profiles compared to CarbonTracker and GOSAT

Figure 3 shows airborne CO_2 high-resolution measurements from the StratoClim campaign in Kathmandu (Nepal) during July and August 2017 for each research flight (F01-F08; details see main paper) depending on potential temperature and pressure. Vertical CO_2 profiles from CarbonTracker (Version CT2019B; available every 3 hours) and GOSAT-L4B (Version V02.07; available every 6 hours) for each flight day are shown using the closest vertical profiles to Kathmandu. Thus the original CarbonTracker and GOSAT-L4B CO_2 profiles are shown to avoid any interpolation or averaging of the CO_2 data. For each day several CO_2 profiles are available (8 for CarbonTracker; 4 for GOSAT-L4B). At the lowest model levels CarbonTracker CO_2 contains the diurnal variation of CO_2, therefore there is a larger variability of CO_2 compared to GOSAT-L4B data. Nevertheless, the comparison with aircraft CO_2 profiles demonstrates, that in the troposphere GOSAT-L4B agree much better with measured CO_2 profiles as CarbonTracker (which is in general too high), reflecting that GOSAT-L4B data are based on column-averaged satellite measurements compared to CarbonTracker that does not include ground-based measurements from the Indian subcontinent after 2013 (detail see main paper). Further, Fig. 3 shows that within the UTLS the vertical resolution of both CarbonTracker and GOSAT-L4B is too low to reproduce the vertical variability of CO_2 visible in the airborne measurements and caused by the seasonal variability of CO_2 at the ground (details see main paper). Despite GOSAT-L4B and CarbonTracker fail to reproduce HAGAR CO_2 in the UTLS, CO_2 values of the stratospheric background (above 450 K / 70 hPa) from GOSAT-L4B and CarbonTracker show a reasonable agreement with HAGAR.

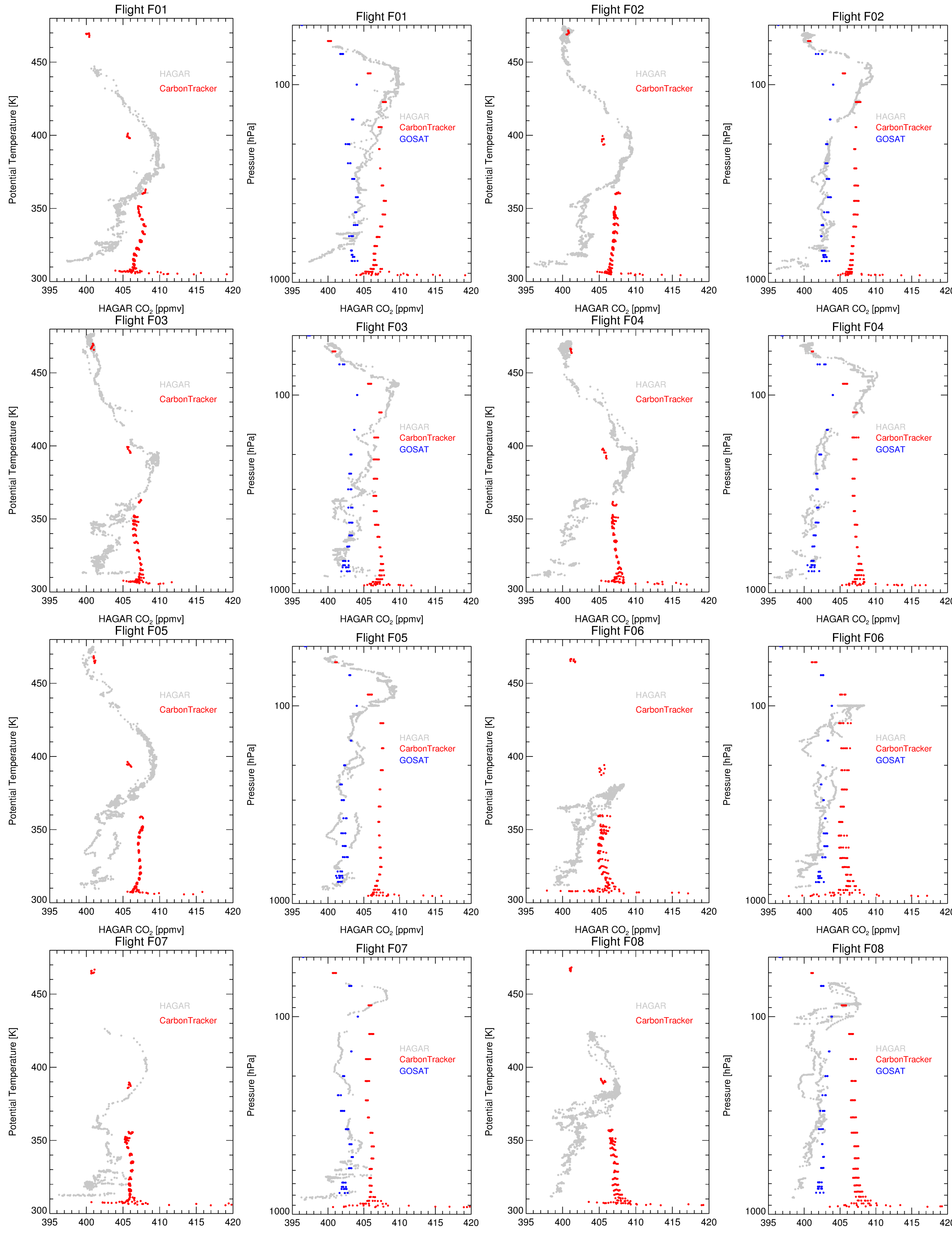

Fig. S3 Airborne CO_2 profiles from HAGAR instrument and simulated CO_2 profiles from CarbonTracker and GOSAT. Airborne CO_2 high-resolution measurements from the StratoClim campaign in Kathmandu (Nepal) during July and August 2017 for each research flight (F01-F08; details see main paper) are shown depending on potential temperature and pressure. Vertical CO_2 profiles from CarbonTracker (Version CT2019B; available every 3 hours) and GOSAT-L4B (Version V02.07; available every 6 hours) for each flight day are shown using the closest vertical profile to Kathmandu (shown is CO_2 at each model level). GOSAT-L4B data include no temperature data, therefore CO_2 profiles versus potential temperature are not shown.

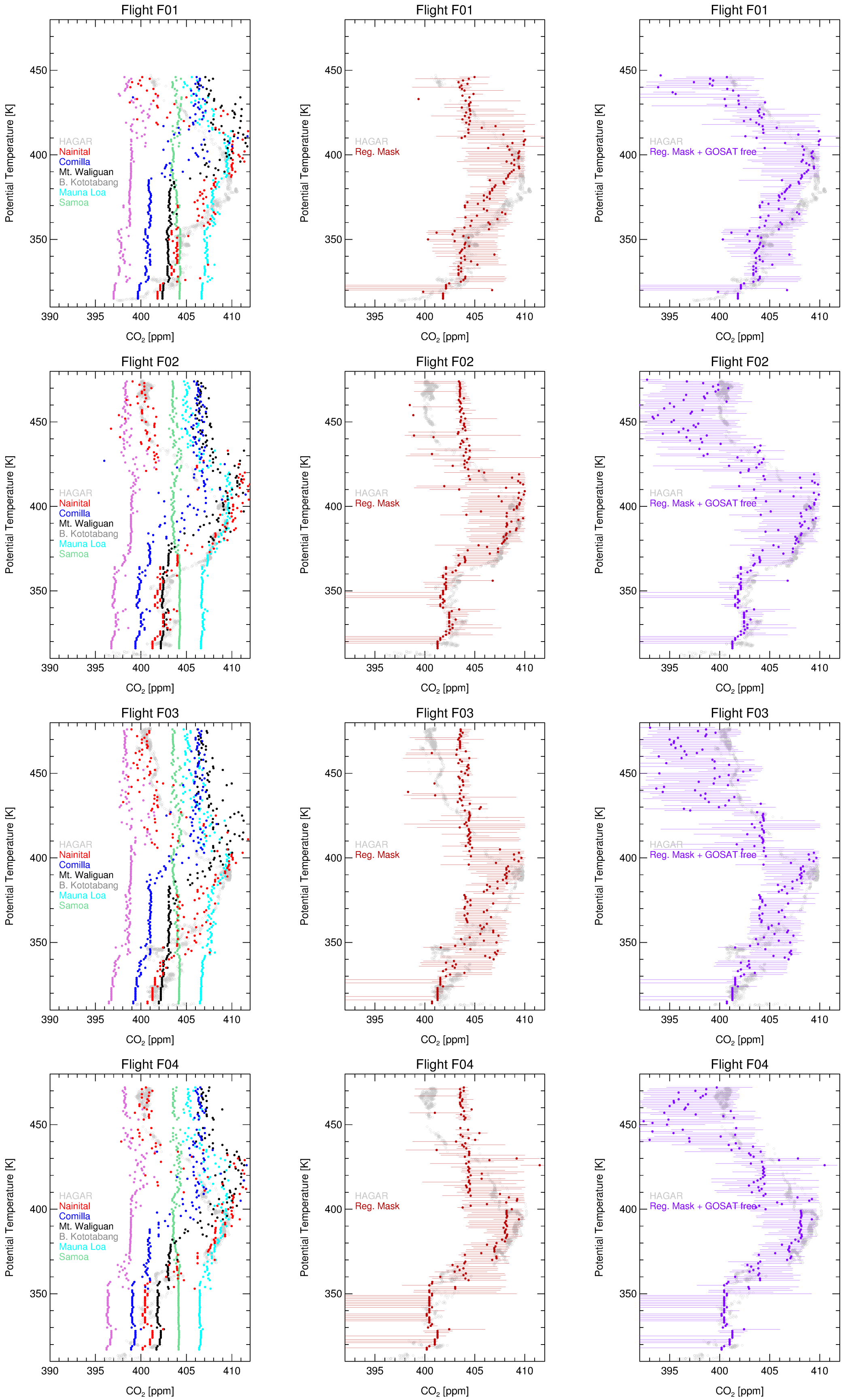

Fig. S4 Reconstructed CO_2 for Flight F01-F04. Same as Fig. 7 and Fig. 8a,b of the main paper showing case S1, S2a and S2b using a trajectory length until the start time of winter 16/17 (1 December 2016).

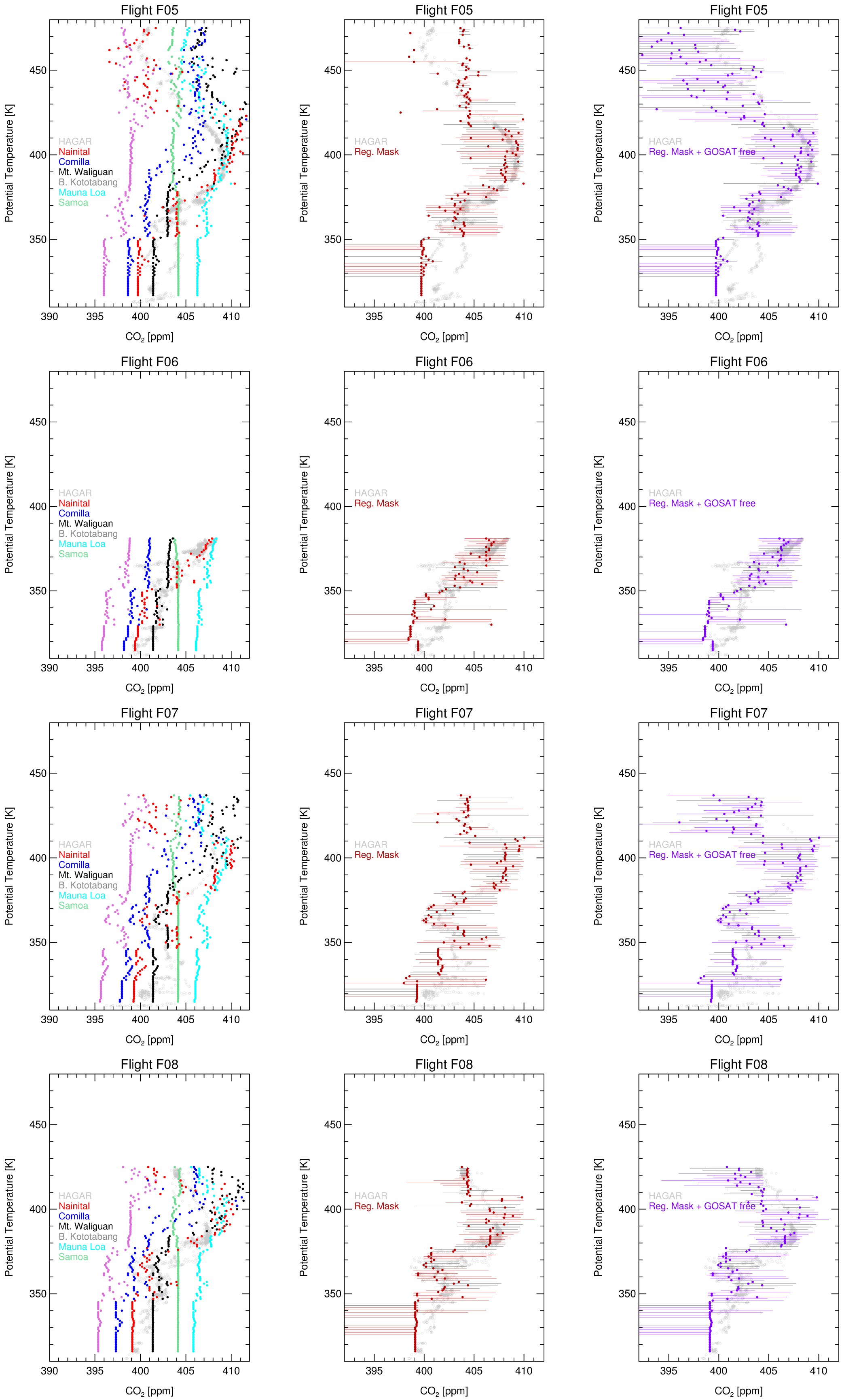

Fig. S5 Reconstructed CO_2 for Flight F05-F08. Same as Fig. 7 and Fig. 8a,b of the main paper showing case S1, S2a and S2b using a trajectory length until the start time of winter 16/17 (1 December 2016).