SOIL

Supplement of

Overcoming barriers in long-term, continuous monitoring of soil CO$_2$ flux: a low-cost sensor system

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S1. Supplementary materials and methods
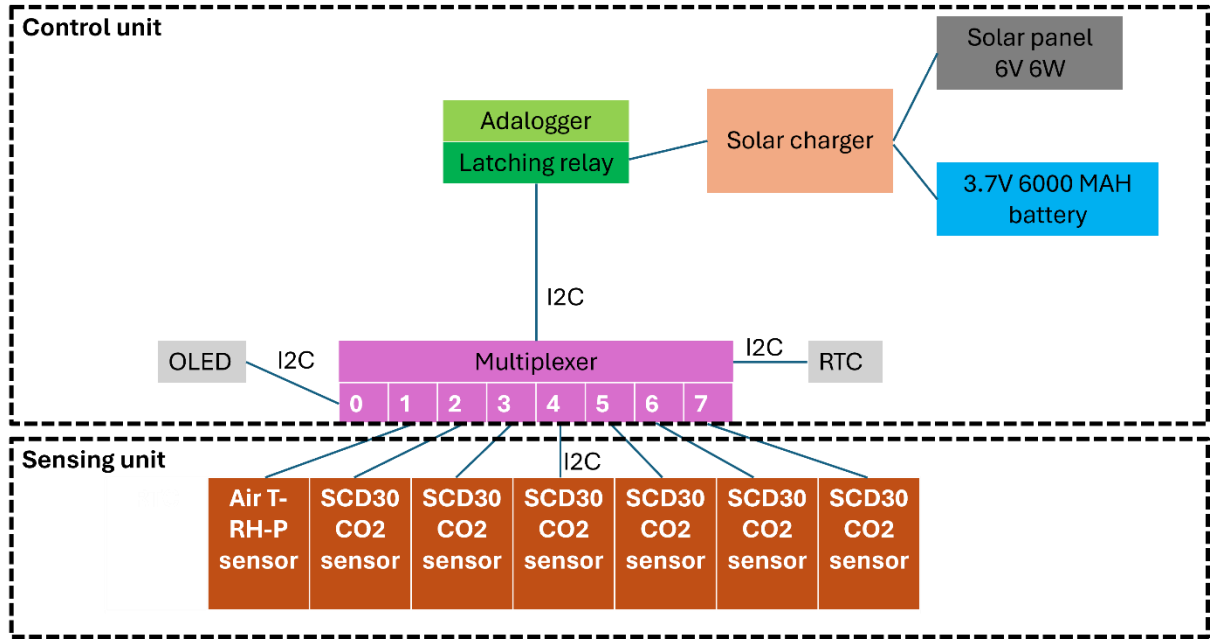
S1.1. Hardware

Figure S1: The schematic design of the low-cost sensor system with the control unit and the sensing unit.

S1.2. F_{GM} calculation

The low-cost CO_2 sensors are factory pre-calibrated at fixed pressure and temperature. To correct soil CO_2 concentration to in-situ environmental conditions according to ideal gas law (e.g., Chamizo et al., 2022) **Eq. S1** is applied.

$$C_v = C_{v0} \frac{P_c(273.2 + T_s)}{P_s(273.2 + T_c)} \qquad [S1]$$

where C_v [μmol mol^{-1} or ppm] is the corrected soil CO_2 concentration, P_c [hPa] is the atmospheric pressure during factory calibration (Pc = 1013 hPa), P_s [hPa] is the air pressure in soil (assume P_s = atmospheric pressure), T_c [ºC] is the air temperature during factory calibration (T_c = 25 ºC), and T_s is the soil temperature measured by the low-cost CO_2 sensors.

The CO_2 concentration or volume fraction (C_v [μmol mol^{-1} or ppm]) is converted to mole density (C_z [μmol m^{-3}]) by **Eq. S2**.

$$C_z = \frac{C_v * 1000}{22.41} \qquad\qquad \text{[S2]}$$

To correct D_a to in-situ environmental conditions before using it in **Eq. 2** (Johns, 2013), **Eq. S3** is applied:

$$D_a = D_{a0}(\frac{T_a}{T_0})^{1.75}\,(\frac{P_0}{P_a}) \qquad\qquad \text{[S3]}$$

where T_a [K] is the in-situ air temperature, P_a [hPa] is the in-situ air pressure, and D_{a0} [m^2 s^{-1}] is the reference value of D_a at T_0 (293.15 K) P_0 (1013 hPa) and is given as 1.47×10^{-5} m^2 s^{-1}.

Total soil porosity (Φ) equals the sum of the volumetric air content (ε) and the volumetric water content (θ). Soil porosity is calculated using **Eq. S4**.

$$\Phi = 1 - \frac{\rho_b}{\rho_m} = \varepsilon + \theta \qquad\qquad \text{[S4]}$$

where ρ_b [g cm^{-3}] is the bulk density and ρ_m [g cm^{-3}] is the particle density for the mineral soil ($\rho_m = 2.65$ g cm^{-3}).
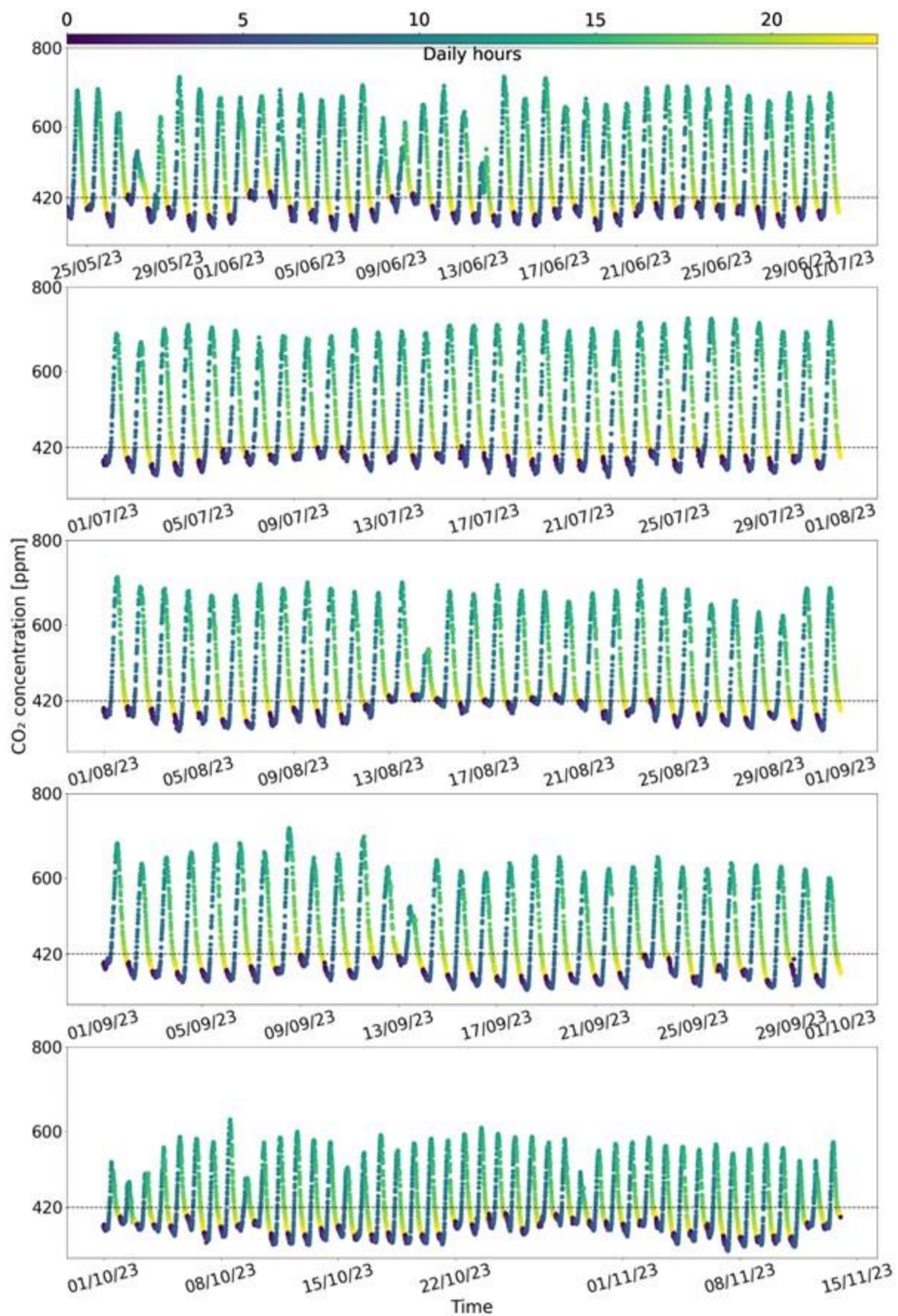
S2. Supplementary results

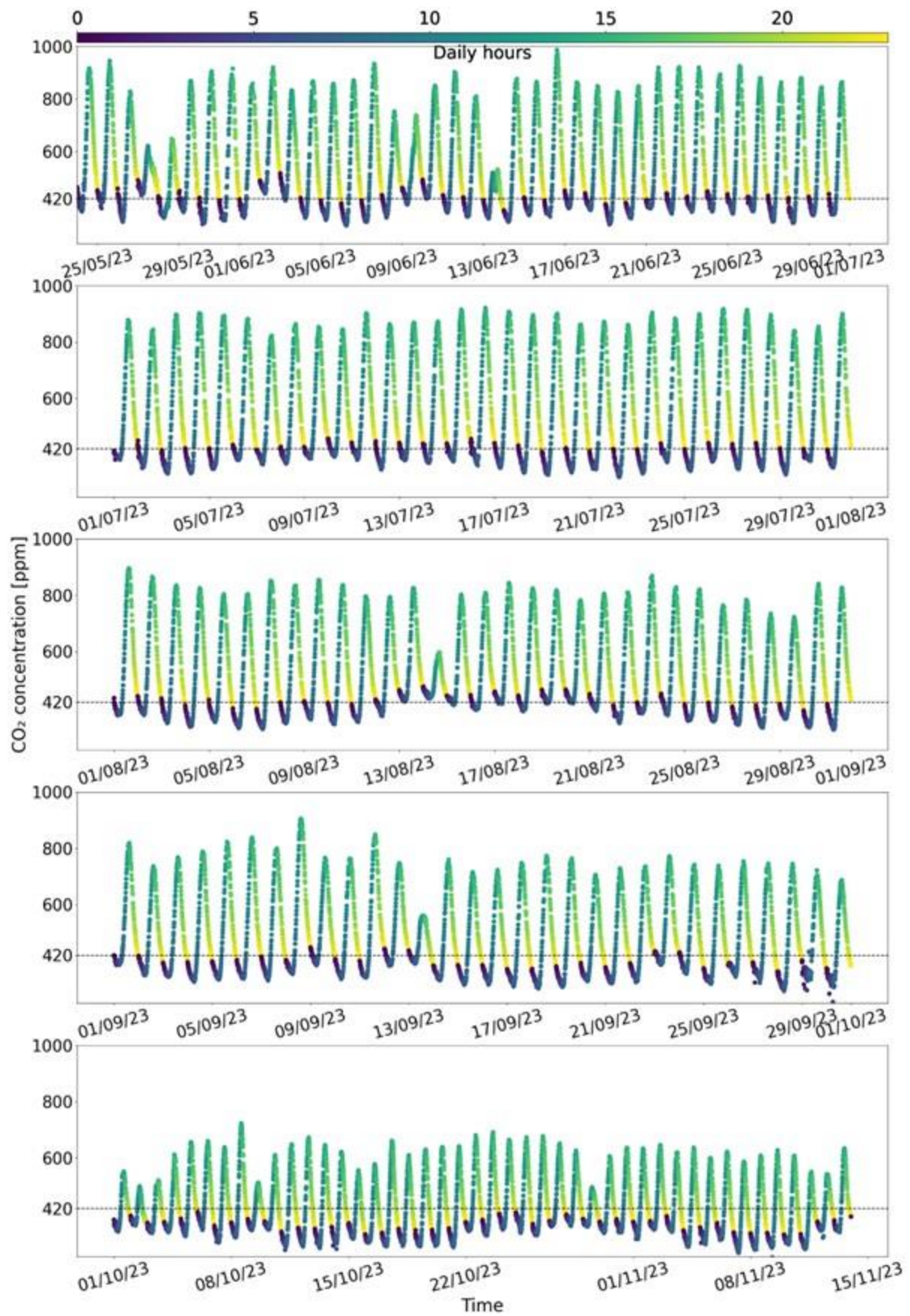**Figure S2.** Soil CO₂ concentrations at 5 cm during the entire study period.

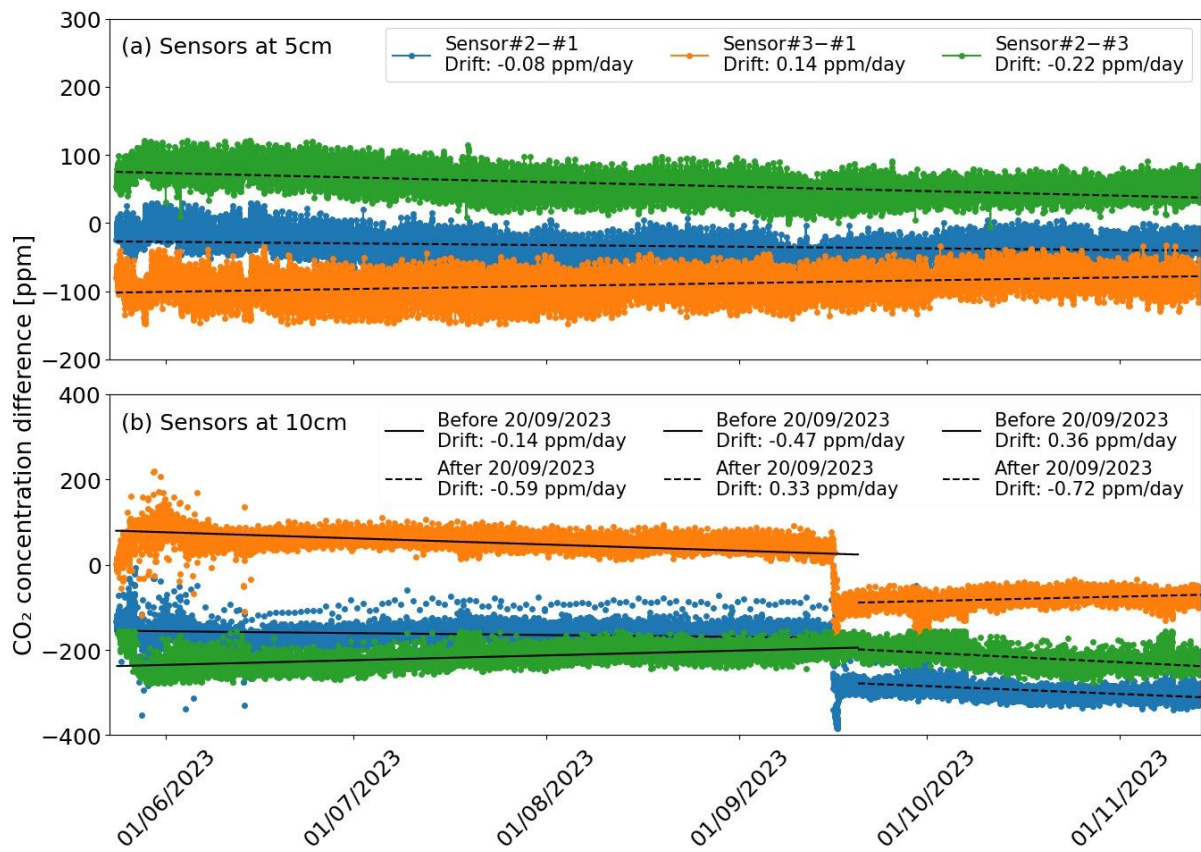**Figure S3.** Soil CO₂ concentrations at 10 cm during the entire study period.

Figure S4. Pair-wise CO_2 concentration differences between three sensors at 5 cm (a) and three sensors at 10 cm (b). The drift rate for sensors at 10 cm was evaluated separately for two periods, before and after 20/09/2023, when the baseline of sensor#1_10cm drifted systematically from ~300 to ~200 ppm.
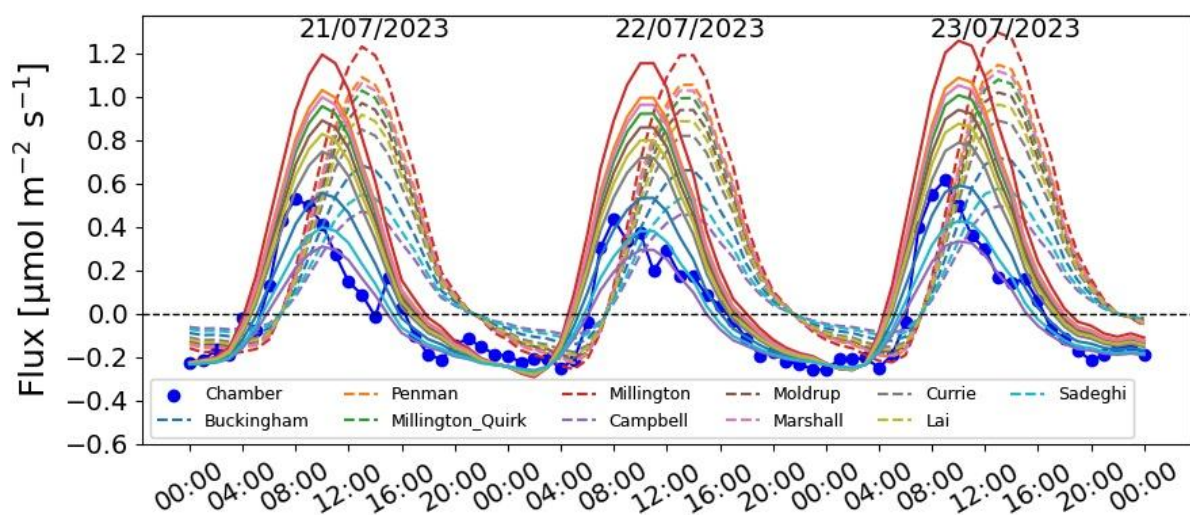

Figure S5. Diurnal cycles of measured chamber flux (blue scatters), calculated gradient fluxes using ten published diffusion models (dashed lines), and gradient flux shifted by 3-hour lag time (solid lines) during three representative days without precipitation 21-23/7/2023.
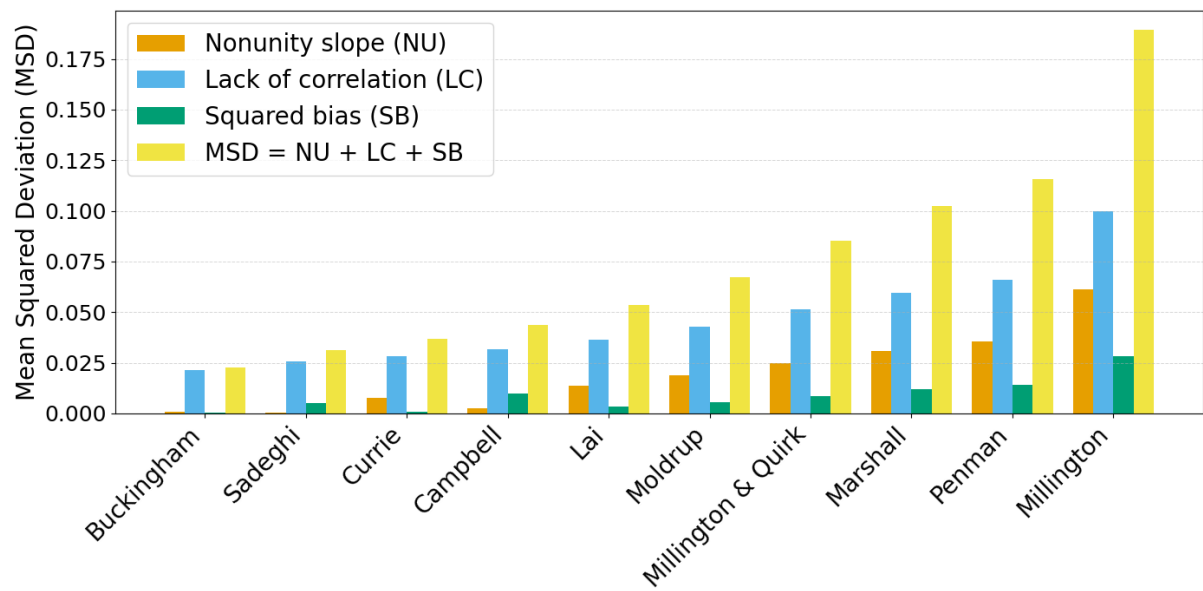
Figure S6. Components of mean squared deviation (MSD) for ten diffusion models. The three components are lack of correlation (LC), non-unity slope (NU), and squared bias (SB). Data for comparison is calculated gradient fluxes (F_{GM}) using ten diffusion coefficient models and chamber flux (F_{CM}) measured by LI-COR chamber and gas analyzer.