



Drivers of multi-year $\delta^{13}\text{C}$ -CO₂ source signature variability in the Amazon rainforest

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Abstract. The carbon isotopic composition of ecosystem CO₂ exchange provides information on the physiological and environmental controls of land–atmosphere carbon fluxes. Here, we use continuous CO₂ and $\delta^{13}\text{C}$ -CO₂ measurements from five inlet heights at the Amazon Tall Tower Observatory (ATTO) in central Amazonia to derive apparent $\delta^{13}\text{C}_s$ source signatures from vertical-profile Keeling-plot relationships without prescribing an external background. The resulting continuous 2.5-year record from 2022 to 2024 substantially extends previous campaign-based and irregular measurements and provides a unique observational basis for resolving source signature variability in the Amazonia rainforest over time. The observations show pronounced variability on diurnal and seasonal time scales. The diurnal cycle is characterized by more enriched source signatures during the day (−28.5 to −27.5 ‰) and more depleted values during the night (−29.5 to −28.5 ‰). In contrast, the seasonal cycle showed less variability, with an amplitude of approximately 1.5‰. We compare the observed temporal variability of the inferred source signatures with source signatures simulated by the process-based model QUINCY. The observed diurnal cycle is broadly consistent with the sign and timing of the QUINCY response. Although QUINCY is systematically more depleted than the observations, the comparable diurnal amplitude suggests that the model captures the short-term functional response. On seasonal time scales, however, QUINCY simulates substantially stronger variability and much tighter relationships with environmental drivers than observed. These results indicate that the current model representation of isotope discrimination and environmental responses cannot fully explain the observed seasonal behaviour. The weaker observed seasonal response to environmental drivers suggests that Amazonian carbon–water–isotope coupling may be more buffered than represented in QUINCY, for example through canopy microclimate or deep-water access. Overall, the continuous multi-year ATTO record provides a valuable data set for evaluating Amazonian vegetation dynamics and identifies key areas in which process-model representations of isotope discrimination and water-stress responses require improvement.



1 Introduction

Tropical forests are a major component of the global land carbon sink (Pan et al., 2011) and store approximately 230 PgC in above-ground biomass (Brando et al., 2019), but their future response to climatic stress remains one of the key uncertainties in the global carbon cycle (Huntingford et al., 2013; Del Uribe et al., 2023; Meunier et al., 2025; Schimel et al., 2015; Pan et al., 2024). This uncertainty is particularly important in the Amazon basin, which stores a large amount of terrestrial carbon and strongly influences interannual variability in land–atmosphere CO₂ exchange (Feng et al., 2025). Recent studies suggest a long-term decline in carbon accumulation in old-growth forests (Brienen et al., 2015; Hubau et al., 2020), indicating that the Amazon carbon sink is weakening. In some regions, this weakening may be further amplified by the combined effects of climate change, drought, fire, and land-use change (van der Laan–Luijkx et al., 2015; Gatti et al., 2021; Rosan et al., 2024; Botía et al., 2025), but the physiological mechanisms controlling this response remain incompletely understood (Restrepo-Coupe et al., 2017; Chen et al., 2020; Basso et al., 2023; Papastefanou et al., 2024; Botía et al., 2026). Observational constraints that provide information not only on the magnitude of CO₂ exchange but also on the underlying vegetation response to environmental drivers are therefore urgently needed.

The carbon isotopic composition of atmospheric CO₂ provides such a constraint because it contains information on both source contributions and the physiological processes controlling land–atmosphere carbon exchange. Atmospheric $\delta^{13}\text{C}\text{--CO}_2$ has been used to separate carbon-cycle source contributions, including fossil-fuel, oceanic, and biospheric fluxes, often in combination with CO₂, $\Delta^{14}\text{CO}_2$, or CO (Vardag et al., 2016; Graven et al., 2020; Hu et al., 2021). Beyond source attribution, $\delta^{13}\text{C}\text{--CO}_2$ also provides information on biospheric discrimination processes. At the ecosystem scale, the apparent $\delta^{13}\text{C}$ source signature reflects the balance between photosynthetic CO₂ uptake and respiratory CO₂ release, both of which can vary with environmental conditions. In C3 plants photosynthesis preferentially assimilates $^{12}\text{CO}_2$, enriching the remaining atmospheric CO₂ in ^{13}C , while the degree of photosynthetic discrimination depends strongly on the ratio of intercellular to atmospheric CO₂ mole fractions c_i/c_a (Bowling et al., 2008; Cernusak et al., 2013). High atmospheric or soil-water stress promotes stomatal closure, lowers c_i/c_a , and reduces discrimination, leading to less depleted carbon assimilates and, consequently, more enriched ecosystem isotope signatures (Farquhar et al., 1989; Cernusak et al., 2013). Respirated CO₂, in contrast, largely reflects the isotopic composition of the respiratory substrate: autotrophic respiration can carry the signal of recently assimilated carbon, whereas heterotrophic respiration integrates litter and soil-carbon pools with different isotopic histories and turnover times (Bowling et al., 2008; Carbone and Trumbore, 2007; Trumbore, 2006). Accordingly, nighttime signatures are dominated by respiratory CO₂, whereas daytime apparent source signatures are shaped by the increasing contribution of photosynthetic uptake and changes in photosynthetic discrimination. Using this mechanistic link between water stress, stomatal regulation, and carbon-isotope discrimination, Peters et al. (2018) used atmospheric $\delta^{13}\text{C}\text{--CO}_2$ measurements to show that severe droughts over the Northern Hemisphere were associated with spatially coherent increases in water-use efficiency and reductions in net carbon uptake. They further found that the drought response inferred from the isotope observations was stronger than simulated by several state-of-the-art land-surface models, suggesting that models may underestimate drought-induced changes in vegetation gas exchange. Their study demonstrates the potential of atmospheric $\delta^{13}\text{C}\text{--CO}_2$ to provide large-scale information on

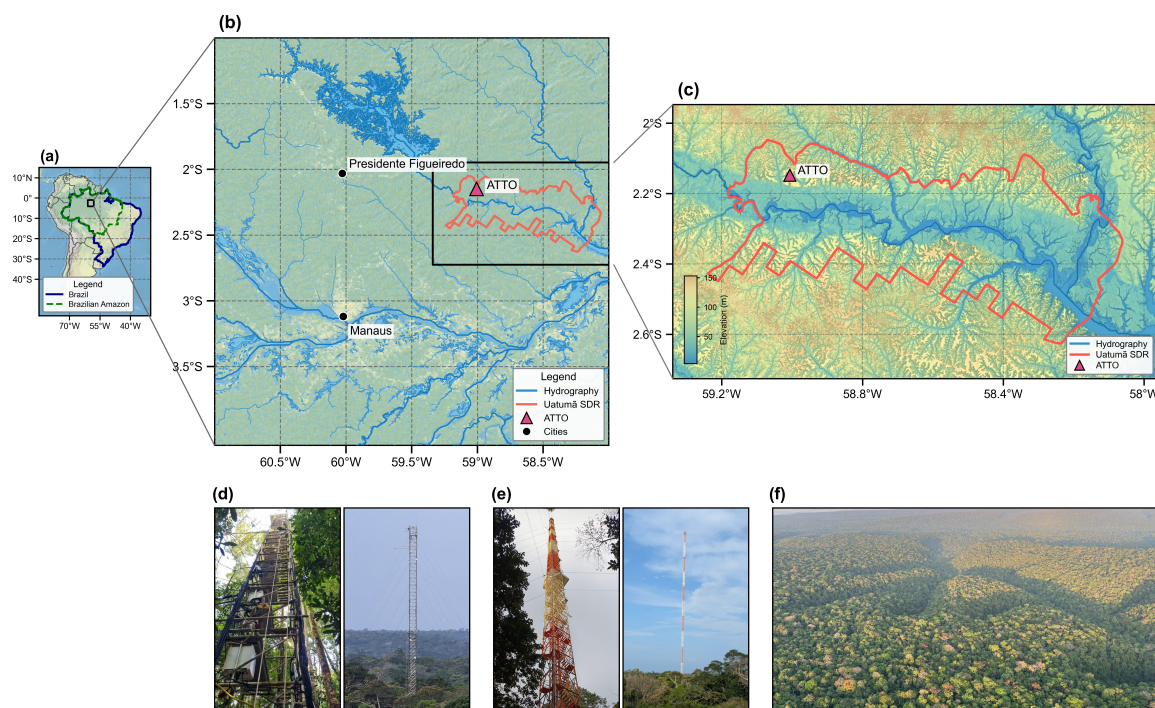


drought-related vegetation responses. However, whether analogous relationships are detectable in humid tropical forests, where radiation, water availability, canopy structure, and atmospheric mixing differ strongly from Northern Hemisphere ecosystems, remains uncertain.

In tropical forests, the relationship between $\delta^{13}\text{C}$ – CO_2 and vegetation water stress may differ from that observed in temperate and boreal ecosystems. Source signature variability can be influenced by several interacting factors, including high atmospheric humidity, seasonal changes in radiation, canopy phenology and structure, deep-root access to water, and the relative contributions of autotrophic and heterotrophic respiration. In addition, atmospheric measurements integrate signals over varying source regions whose isotopic composition may itself shift seasonally as footprint extent and ecosystem functioning covary. Continuous multi-year $\delta^{13}\text{C}$ – CO_2 observations in tropical forests remain scarce, and existing studies are often based on shorter field campaigns or specific meteorological events. For example, van der Merwe and Medina (1989) collected samples during one dry-season month in an Amazonian forest in Venezuela and showed a clear vertical gradient in $\delta^{13}\text{C}$ within the canopy, with more depleted values closer to the soil. Ometto et al. (2002) collected samples during six campaigns spanning 18 months and compared forests in Brazil. They found large seasonal variability, with an amplitude of approximately 3 ‰ in the $\delta^{13}\text{C}$ signature of ecosystem respiration at a forest site near Santarém, whereas the signature remained comparatively constant at the Manaus forest site. Topographic spatial variability in atmospheric $\delta^{13}\text{C}$ was further explored by de Araújo et al. (2008), who compared plateaus with a deep water table and valleys with a shallow water table during two selected dry-season months in 2004 and 2006. Atmospheric $\delta^{13}\text{C}$ was consistently more depleted in valleys than on plateaus during daytime, whereas no consistent spatial pattern was observed at night.

Extending the spatial perspective, Batista et al. (2025) analysed tree-ring $\delta^{13}\text{C}$ records from 21 Amazonian sites and identified a total isotopic range of 7.2 ‰ across the basin, with atmospheric moisture demand emerging as a dominant large-scale control. At the Amazon Tall Tower Observatory (ATTO) site, Chanca et al. (2025) reported source signature estimates from atmospheric measurements during two sampling periods in October 2019 and December 2021, with more depleted values in December (approximately -29 ‰) than in October (approximately -27.8 ‰). Recently, Faassen et al. (2025) analysed the diurnal range of several atmospheric tracers at ATTO, including atmospheric $\delta^{13}\text{C}$ – CO_2 , using continuous observations covering several weeks. They highlighted that atmospheric processes, including entrainment, cloud ventilation, and subsidence, are crucial for interpreting the diurnal amplitudes of atmospheric tracers. Given the campaign-based and often seasonally limited nature of existing studies, the magnitude and detectability of drought- or physiology-related $\delta^{13}\text{C}$ signals in Amazonian forests nevertheless remain uncertain. In this respect, long-term continuous measurements are particularly valuable because they allow source signature variability to be investigated across diurnal cycles, seasonal transitions, wet and dry periods, and changing atmospheric transport regimes. Such data therefore provide a robust basis for testing whether $\delta^{13}\text{C}$ source signature variability can be linked to environmental drivers and whether process-based models reproduce the observed controls.

To investigate these controls using atmospheric observations, the isotopic composition of the CO_2 added to an air mass can be inferred using Keeling plots, which relate $\delta^{13}\text{C}$ – CO_2 to the inverse of the CO_2 mole fraction (Keeling, 1958). The resulting intercept represents the isotopic signature of the CO_2 added to the background air over the sampled concentration range. In continuous tower observations, this approach can be applied repeatedly, for example using a moving Keeling-plot



Map backgrounds: Esri World Physical Map; panel (c): digital elevation model and enhanced local relief; hydrography: HydroRIVERS and HydroLAKES

Figure 1. Location of ATTO relative to the South American continent (a) and to the closest (150 km) city Manaus (b) with the surrounding topography (c) where the main towers are located, the 80-m tower (d) and the tall tower (e). A view of the topographical gradients around the tower are shown in (f), photo taken by the authors. Map backgrounds: Esri World Physical Map; panel (c): digital elevation model and enhanced local relief; hydrography: HydroRIVERS and HydroLAKES.

analysis, to investigate temporal variability in apparent source signatures (Vardag et al., 2016). ATTO provides a rare multi-year data set for investigating the drivers of $\delta^{13}\text{C}$ source signature variability over the Amazon rainforest. Here, we present a 2.5-year $\delta^{13}\text{C}$ -CO₂ record covering 2022–2024 and analyse whether variability in the $\delta^{13}\text{C}$ source signature at ATTO can be explained by local environmental drivers or changing atmospheric footprints. To assess how much information $\delta^{13}\text{C}$ -CO₂ source signatures provide on Amazonian vegetation dynamics and where process understanding must improve before they can be used quantitatively in top-down constraints, we analyse the observed magnitude, timing, and environmental controls of source-signature variability using the state-of-the-art process-based biosphere model QUINCY.

2 Materials and methods

2.1 Study site

The Amazon Tall Tower Observatory (ATTO; 2.14°S, 58.99°W) is located in the Uatuma Sustainable Development Reserve (USDR), approximately 150 km northeast of Manaus in central Amazonia (Fig. 1a), and is described in detail by Andreae



et al. (2015). The main infrastructure is built on a terra firme plateau (130 m a.s.l.) surrounded by a drainage network of valleys and depressions (Fig. 1b–d), forming a small-scale heterogeneous topography with height gradients of up to ~100 m (Fig. 1e). The vegetation of the USDR reflects this topographic heterogeneity. Terra firme dense upland forest dominates the plateaus and slopes, with a canopy height reaching 37 m at the tower location with maximal leaf area index found between 25 and 30 m (Andreae et al., 2015; Gomes Alves et al., 2023), while the valleys have shorter vegetation (canopy height) with different species composition compared to plateaus. Precipitation at ATTO shows a marked seasonality with a dry season of approximately three months (July–October; mean precipitation $<100 \text{ mm month}^{-1}$) and a wet season from February to June (25th percentile consistently above $200 \text{ mm month}^{-1}$). Mean annual precipitation is $\sim 2300 \text{ mm yr}^{-1}$ (Botía et al., 2022; Dias-Júnior et al., 2026).

2.2 CO_2 and $\delta^{13}\text{C}\text{--CO}_2$ measurements

We use in-situ CO_2 and $\delta^{13}\text{C}\text{--CO}_2$ measurements from the Amazon Tall Tower Observatory (see Tab.1). The measurement record covers 2022–2024 and includes five inlet heights at 79 m, 53 m, 38 m, 24 m and 4 m, allowing vertical concentration and isotope gradients to be used for source signature estimation. The inlets, mounted on an 80 m tower, were continuously sampled using a buffer system with a residence time of approximately 20 minutes (Winderlich et al., 2010). Buffers were sequentially sampled for 3 minutes each in a 15 minute cycle. A sub-sample of buffer air was passed through a Nafion dryer (MD-050, Perma Pure LLC, Lakewood, NJ, USA) to reduce water vapour to approximately 1000 ppm, before measurement of CO_2 isotopologue mixing ratios by a cavity ring down spectrometer (G2201-i, Picarro, Santa Clara, CA, USA) installed in an air-conditioned shipping container at the base of the tower. The 15 minute buffer measurement cycle was interrupted every 100 hours to measure 3 calibration cylinders for 10 minutes each and every 30 hours for a 10 minute measurement of a quality control cylinder. Isotopologue mixing ratios from first 115 s and last 5 s of each buffer measurement and the first 535 s and last 5 s of each quality control cylinder measurement were discarded and the remaining 60 s averaged to give a measurement mean for each observation step. Similarly, for the calibration cylinder measurements the first 295 s and last 5 s of each measurement were discarded and the remaining 300 s averaged. Measurement means were excluded where known issues with data quality were present (e.g. during maintenance, detection of leaks, evidence of spectral interference, etc.). Coefficients for the linear regression between measurement mean and known (Gas & Iso Labs, Max Planck for Biogeochemistry, Jena, Thuringia, Germany) isotopologue mixing ratios for the 3 calibration cylinders were determined for each calibration event (Wen et al., 2013). These were linearly interpolated between events providing correction coefficients for each buffer and quality control measurement step. Total CO_2 and $\delta^{13}\text{C}\text{--CO}_2$ were then calculated from corrected isotopologue mixing ratios. For the quality control cylinder, known values for the total CO_2 mixing ratio and $\delta^{13}\text{C}\text{--CO}_2$ were 399.60 (0.05) ppm and -8.46 (0.01) ‰ Vienna Pee Dee Belemnite (VPDB) compared to measured means (1 sd) for the record ($n = 598$) of 399.48 (0.08) ppm and -8.46 (0.23) ‰ VPDB (Fig. A1).



2.3 Derivation of $\delta^{13}\text{C}_s$ source signatures

Hourly source signatures, $\delta^{13}\text{C}_s$, are derived from Keeling-plot regressions using the vertical tower profile (Fig. A2). For each hour, the full available concentration range across the inlet heights is used to fit the relationship between $\delta^{13}\text{C}$ – CO_2 and the inverse CO_2 mole fraction. The intercept is interpreted as an apparent source signature, representing the effective isotopic signature of the CO_2 exchange processes that generated the vertical gradient during that hour. Because the regression is based on simultaneous height differences, this approach reduces sensitivity to slowly varying background concentrations. With this we assume that the CO_2 enhancement measured near the understory at 4 m, where mole fractions are highest, represents a large fraction of the isotopic source being mixed into the air mass whose background composition is captured at 79 m. The inferred $\delta^{13}\text{C}_s$ can therefore be interpreted as an integrated source signature of the footprint-weighted flux, influenced by ecosystem respiration, photosynthetic discrimination and turbulent mixing. Daily source signatures are derived using the same approach as the hourly estimates, with each daily estimate incorporating approximately 24 times more data. The resulting daily estimates agreed well with those obtained by applying a 24 h running mean to the hourly source signatures (mean absolute difference between approaches is 0.3 ‰ for the entire period).

A limitation of the Keeling-plot approach is that it requires that the measurements share a common background and a constant source mix. Changes in atmospheric mixing or source contributions, as well as simultaneously acting sources and sinks, can violate this assumption. Using a synthetic dataset with known source signatures, Vardag et al. (2016) showed that moving Keeling plots can nevertheless provide robust source-signature estimates when regressions that poorly fulfill these assumptions are filtered. Our approach uses approximately simultaneous vertical profiles, reducing sensitivity to temporal changes in background conditions within the regression window. Nevertheless, the vertical profile may not always represent a single connected air mass. During very stable nighttime conditions, the air within or close to the canopy can become partly decoupled from the air above, so that CO_2 accumulating near 4 m may not be efficiently mixed to the upper inlet. At ATTO, however, the comparatively homogeneous regional background reduces the likelihood that weak vertical coupling alone leads to substantially different background compositions across the inlet heights. Slow mixing therefore does not necessarily invalidate the Keeling relationship, provided that the sampled air can still be interpreted as mixtures of a common background and ecosystem exchange. The Keeling intercept may nevertheless become biased if the decoupling is so strong that the different inlet levels no longer represent mixtures of a common background. We therefore exclude regressions with large intercept uncertainties. We use a threshold of 3 ‰, which removes about 23 % of the hourly data and none of the daily data. During daytime, when photosynthetic uptake and respiration occur simultaneously, we therefore interpret the intercept as an apparent ecosystem source signature rather than the isotopic signature of a single source. The interpretation of the apparent signature depends on the combined effects of respiration, photosynthetic uptake and atmospheric mixing, and may additionally be complicated by non-steady-state soil diffusion, which can alter the isotopic signature of soil CO_2 efflux independently of respiratory production signatures (Moyes et al., 2010; van Asperen et al., 2017).

To assess vertical differences, we additionally derived height-specific source signatures by applying the Keeling-plot approach separately to the measurements at each inlet height over the corresponding temporal window. Because these regressions

use only the CO₂ variability observed at a single height, they generally span a smaller concentration range, especially for the higher inlets than the regressions based on the complete vertical profile. Consequently, a larger fraction of the height-specific regressions does not meet the uncertainty criterion. The remaining height-specific estimates follow each other on seasonal time scales (not shown here) and provide an apparent vertical profile of source signatures representative of the air sampled at the different inlet heights.

2.4 Environmental drivers

The source signature time series was compared with local and remotely sensed environmental drivers. From the local measurements we used gross primary production (GPP), vapour-pressure deficit (VPD), air temperature, radiation, soil volumetric water content, soil-water potential and precipitation. Remotely-sensed variables were absorbed photosynthetically active radiation APAR, and SIF/TROPOSIF. Details on these datasets are listed in Table 1. These variables were analysed at diurnal, monthly, and seasonal time scales to separate short-term physiological controls from slower seasonal variability.

2.5 QUINCY simulations

The land surface model QUINCY (as described in detail by Thum et al., 2019) was used to simulate ecosystem carbon, water and energy dynamics at a half-hourly resolution. QUINCY represents vegetation by eight natural plant functional types (PFTs), of which only the moist broadleaved evergreen PFT was applied at this study. QUINCY represents vegetation as an average individual representative of the PFT, characterised by stand density, plant height and leaf area index, which depends on allometric relationships between the simulated plant pools (leaves, coarse and fine roots, sap and heart wood, reproductive organs and fast and long-term nonstructural reserves). Tree canopies are divided into ten layers along the canopy internal light gradient. Within each canopy layer, photosynthesis and stomatal conductance for sunlit and shaded leaves are calculated based on prescribed air temperature, humidity and CO₂, layer-specific leaf characteristics, as well as diffuse and direct light using a coupled photosynthesis-stomatal model (Thum et al., 2019; Medlyn et al., 2011). Photosynthates enter a fast non-structural pool with an average turnover time of a week, from which biosynthesis of new biomass, growth respiration, as well as maintenance respiration are sourced. Growth is allocated to plant pools according to size-dependent allometric relationships, leading to a feedback between net photosynthesis and leaf area index. Turnover of plant pools due to tissue senescence or density and growth-efficiency related mortality produces litter, which is partitioned into three litter pools (metabolic, structural, wood) that in turn decompose into two (fast and slow) soil organic matter pools, which all are vertically explicitly resolved across the 15 soil layers up to a depth of 9.5 m and turn over at pool-specific, temperature and moisture sensitive rates. While QUINCY represents ecosystem nitrogen and phosphorus dynamics, these are not activated in this study, but will not strongly influence the overall outcome of this study.

The water cycle in QUINCY accounts for precipitation inputs, canopy interception loss, water transport and plant water uptake in the vertically resolved soil (again 15 layers, 9.5 m deep in total) as well as surface and deep drainage. Ecosystem latent heat flux, composed of components derived from soil and canopy evaporation as well as plant transpiration, is coupled to the surface energy balance and turbulence calculation of a one-point source model. Plant transpiration herein is derived from



Table 1. Overview of the observational datasets used throughout this study. Temporal resolution refers to the native resolution of the respective dataset. Atmospheric CO₂ and $\delta^{13}\text{C}$ measurements were subsequently aggregated to hourly or daily values depending on the analysis.

Dataset	Symbol	Heights/depths	Resolution	Reference and variable ID
<i>Atmospheric observations</i>				
Atmospheric CO ₂ mole fraction	CO ₂	4, 24, 38, 53, 79 m	15 min	https://www.attodata.org/ddm/data/Showdata/734 (variable ID 2190)
$\delta^{13}\text{C}$ of atmospheric CO ₂	$\delta^{13}\text{C}$	4, 24, 38, 53, 79 m	15 min	https://www.attodata.org/ddm/data/Showdata/734 (variable ID 2192)
<i>Environmental measurements</i>				
Photosynthetically active radiation	PAR	875m	30 min	https://www.attodata.org/ddm/data/Showdata/635 (2022), https://www.attodata.org/ddm/data/Showdata/636 (2023), https://www.attodata.org/ddm/data/Showdata/637 (2024) (variable ID 2465, 2466)
Air temperature	T_{air}	4, 12, 26, 36, 40, 55, 73, 81 m	30 min	same links as for PAR (variable ID 2441-2448)
Relative humidity	RH	4, 12, 26, 36, 40, 55, 73, 81 m	30 min	same links as for PAR (variable ID 2451-2458)
Precipitation	Prec	81m	30 min	same links as for PAR (variable ID 2471)
Soil volumetric water content	VWC	10, 30, 40, 60, 100 cm	30 min	https://www.attodata.org/ddm/data/Showdata/341 for 2021, personal communication Cléo Quaresma for 2022 and 2023
Atmospheric pressure	AP	81 m	30 min	same links as for PAR (variable ID 2469)
Evapotranspiration	ET	81 m	30 min	same links as for PAR (variable ID 3007)
Wind speed	v	26, 36, 55, 81 m	Hourly	same links as for PAR (variable ID 3010)
Short and long wave downward radiation	SWR/LWR	75 m	Hourly	same links as for PAR (variable ID 2461-2464)
TROPOSIF	SIF	total column	Daily	Guanter et al. (2021)
<i>Carbon fluxes</i>				
Net ecosystem exchange	NEE	80 m	30 min	https://www.attodata.org/ddm/data/Showdata/617 (variable ID 2110)
Total ecosystem respiration	R_{eco}	80 m	30 min	https://www.attodata.org/ddm/data/Showdata/617 (variable ID 2113)
Gross primary productivity	GPP	80 m	30 min	https://www.attodata.org/ddm/data/Showdata/617 (variable ID 2114)

the canopy-integrated stomatal conductance and thus coupled to carbon uptake. Plant moisture stress on photosynthesis and growth is represented in response to atmospheric dryness (Medlyn et al., 2011) and soil moisture. The latter is a function of a soil water potential threshold inducing full stomatal closure, a PFT-specific, prescribed rooting profile and layer-specific soil water potential.

A relevant feature of QUINCY that makes it suitable for this study is that it explicitly tracks fluxes and pools of carbon isotopes (¹²C, ¹³C, and ¹⁴C), which means that from all fluxes and pools, isotopic signatures in the form $\delta^{13}\text{C}$ can be derived. Carbon discrimination by stomatal uptake and photosynthesis is simulated following Farquhar et al. (1982). Neither biosynthesis nor respiration processes in plants and soils are assumed to systematically add a process-specific discrimination rate (Brüggemann et al., 2011), but diurnal and longer-term variations in the $\delta^{13}\text{C}$ signal of respiration can derive from the lag time between photosynthetic uptake and respiration processes. Plant respiration is supplied from non-structural carbon reserves,



while heterotrophic respiration draws on litter and soil-carbon pools with pool-specific turnover times, thereby introducing
 210 temporal integration of the assimilated isotope signal.

In this study, QUINCY was applied without any site-specific adjustments apart from using observed soil texture to param-
 eterise soil properties. The model was driven by observed meteorological forcing (shortwave and longwave downward radiation,
 precipitation, air temperature, specific humidity, pressure, atmospheric CO₂, see Tab. 1). QUINCY had previously been shown
 to reproduce ecosystem carbon and energy fluxes to a comparable level than other land surface models (Thum et al., 2019;
 215 Abramowitz et al., 2024) and to reproduce carbon stocks and fluxes in tropical rain forests within observational estimates
 (Fleischer et al., 2026).

2.5.1 Calculation of the modelled $\delta^{13}\text{C}$ source signature

To derive a model quantity comparable to the apparent source signature inferred from the Keeling plots, we calculated the
 isotopic signature of the combined gross ecosystem fluxes following Vardag et al. (2016). All component fluxes were defined
 220 as positive magnitudes. Total ecosystem respiration, F_{TER} , represents CO₂ release to the atmosphere, whereas F_{GPP} represents
 photosynthetic CO₂ uptake.

After aggregation of the required QUINCY variables to hourly resolution, the apparent ecosystem source ratio was calculated
 directly from the isotope-specific fluxes as

$$R_s = \frac{{}^{13}F_{\text{TER}} + {}^{13}F_{\text{GPP}}}{{}^{12}F_{\text{TER}} + {}^{12}F_{\text{GPP}}}. \quad (1)$$

225 Both respiratory release and photosynthetic uptake enter Eq. (1) as positive flux magnitudes because both sources and sinks
 contribute to the apparent source signature inferred from the Keeling-plot relationship. Details on these assumptions can be
 found in Vardag et al. (2016).

Total ecosystem respiration comprises autotrophic and heterotrophic respiration. Because QUINCY provides maintenance
 and growth respiration separately, the isotope-specific total ecosystem respiration fluxes were calculated as

$$230 \quad {}^{12}F_{\text{TER}} = {}^{12}F_m + {}^{12}F_g + {}^{12}F_h, \quad (2)$$

and

$${}^{13}F_{\text{TER}} = {}^{13}F_m + {}^{13}F_g + {}^{13}F_h, \quad (3)$$

where the subscripts m, g, and h denote maintenance respiration, growth respiration, and heterotrophic respiration, respectively.

The modelled apparent ecosystem source signature was subsequently calculated relative to VPDB as

$$235 \quad \delta^{13}\text{C}_s = \left(\frac{R_s}{R_{\text{VPDB}}} - 1 \right) \times 1000. \quad (4)$$

During nighttime, when F_{GPP} is zero, the calculated signature reduces to the isotopic signature of total ecosystem respira-
 tion. During daytime, it represents the combined gross-flux-weighted isotopic signature of respiratory release and photosyn-
 thetic uptake. The resulting hourly $\delta^{13}\text{C}_s$ values were used to analyse the simulated diurnal and seasonal variability and to



compare their temporal evolution and environmental-driver relationships with those inferred from the atmospheric observa-
 240 tions.

Because simultaneously occurring sources and sinks violate the strict two-endmember assumptions of the Keeling-plot approach, both the calculated model quantity and the observational intercept are interpreted as apparent ecosystem source signatures.

3 Results

245 3.1 Multi-height CO₂, $\delta^{13}\text{C}$ -CO₂, and inferred source signatures

The tower record shows pronounced variability in both CO₂ mole fractions and $\delta^{13}\text{C}$ -CO₂ across the five inlet heights (Fig. 2a,b). CO₂ excursions are largest at 4 m, close to the forest floor, and are accompanied by particularly depleted $\delta^{13}\text{C}$ -CO₂ values during high-CO₂ episodes. The mean diurnal cycles show a clear vertical gradient during the night and early morning, with the highest CO₂ concentrations and most depleted $\delta^{13}\text{C}$ -CO₂ values occurring at 4 m (Fig. 2e,f). Between approximately
 250 08:00 and 16:00 local time, the measurements at 24, 38, 53, and 79 m converge to nearly identical values. In contrast, the measurements at 4 m remain distinct, with higher CO₂ and more depleted $\delta^{13}\text{C}$ -CO₂ throughout the day.

The inferred source signatures vary substantially over the 2.5-year period (Fig. 2c). Most values fall within a relatively narrow range of approximately -30 to -27‰ , although shorter episodes with more depleted or more enriched values also occur. Daytime and nighttime estimates show a persistent separation across the record (Fig. 2d). Daytime source signatures are
 255 generally less negative and more variable, whereas nighttime values are more tightly clustered around approximately -30 to -28‰ . The tendency towards more enriched values during parts of the dry season is most apparent in the daytime estimates. The coherent variability over periods of weeks to months indicates that the inferred source signatures contain a temporally structured signal and is not dominated by short-term regression variability.

The mean diurnal cycle of $\delta^{13}\text{C}_s$ differs clearly in shape from the corresponding diurnal cycles of measured CO₂ and
 260 $\delta^{13}\text{C}$ -CO₂ (Fig. 2e–g). Whereas the measured quantities show their strongest vertical differences during the night and largely converge above 4 m during daytime, $\delta^{13}\text{C}_s$ remains relatively stable overnight and becomes progressively more enriched after approximately 06:00–08:00 local time. This morning transition coincides with the onset of GPP shown in Appendix Fig. A3. The source signature reaches its most enriched values of approximately -27.5‰ around midday to early afternoon and subsequently returns towards more depleted nighttime values. The different shapes of the diurnal cycle of the measured $\delta^{13}\text{C}$
 265 and inferred source signature $\delta^{13}\text{C}_s$ suggest that the source signature reflects changes in the relative contributions and isotopic compositions of ecosystem sources and sinks, rather than directly following the diurnal evolution of atmospheric CO₂ accumulation and mixing.

The mean diurnal cycles derived separately for 2022, 2023, and 2024 largely overlap in their timing, shape, and amplitude (Fig. 2g). The diurnal evolution of $\delta^{13}\text{C}_s$ therefore remains comparatively stable across the three years, despite the substantial
 270 variability of the individual estimates. This similarity suggests that the processes controlling the mean within-day evolution operate consistently across years.



In contrast, the monthly mean source signatures show marked differences among years (Fig. 2h). Values are generally close to -29‰ during the first half of the year, but the subsequent seasonal evolution differs in both timing and magnitude. In 2023, the record shows a depleted minimum during the dry season followed by enrichment towards the end of the year. In 2024, $\delta^{13}\text{C}_s$ becomes progressively more enriched during the second half of the year, reaching the least negative monthly values near the end of the record. The available 2022 data show a more moderate and irregular seasonal evolution. Thus, while the mean diurnal cycle is similar among years, the seasonal cycle exhibits substantially greater year-to-year variability. These differences may be associated with interannual variations in the timing and severity of dry-season conditions and in the corresponding ecosystem response.

In addition to the temporal variability, height-specific source signature estimates reveal a systematic vertical structure (Appendix Fig. A4). For these estimates, a separate Keeling regression is calculated for each inlet height using the full 24 hour variability in CO_2 and $\delta^{13}\text{C}\text{--CO}_2$. In both the wet and dry seasons, the apparent $\delta^{13}\text{C}_s$ values are more depleted at the lower measurement levels and become more enriched towards the upper canopy. Despite this systematic vertical offset, the temporal and seasonal evolution is similar across the independently derived height-specific source signatures, indicating that the observed seasonal variability is not specific to the lowest inlet. The direction of the vertical gradient is similar to that of the mean vertical VPD profile, consistent with the distinct microclimatic conditions within the canopy (see Appendix Fig. A4).

Taken together, the observational record spans marked hydrological conditions, from the wet conditions of 2022 to the consecutive drought years of 2023 and 2024. The years diverge most strongly during the dry season. In particular, the pronounced depletion in 2023 contrasts with the more enriched dry-season values in 2022 and 2024. Thus, although moderate dry-season enrichment is evident in parts of the record, the source signature does not respond uniformly to dry-season conditions across years. In Sect. 3.2.2, we therefore examine how $\delta^{13}\text{C}_s$ relates to environmental and ecosystem drivers on diurnal and seasonal time scales.

3.2 Comparison with QUINCY-simulated source signatures

To understand the underlying processes governing the source signature, we first compare the sign, timing, and magnitude of the QUINCY-simulated and observation-derived $\delta^{13}\text{C}_s$ variability on diurnal and seasonal time scales. Agreement in these characteristics would suggest that the model captures the dominant processes controlling the source signature variability and their relative strength. In the following, we first examine the mean diurnal cycle and its relationships with short-term environmental drivers, before assessing the seasonal cycle and its longer-term environmental controls. The complete monthly diurnal cycle of the observed and simulated source signatures is shown in Appendix Fig. A5.

3.2.1 Mean diurnal cycle and wet–dry season contrast

The mean diurnal cycles separated into wet- and dry-season conditions show that the observations and QUINCY agree in the overall sign and timing of the diurnal source signature variability, but differ substantially in the absolute value and shift between wet- and dry-season conditions (Fig. 3). In both observations and QUINCY, $\delta^{13}\text{C}_s$ is more depleted during the night and early morning and becomes more enriched from morning to midday or early afternoon. The subsequent return to more depleted

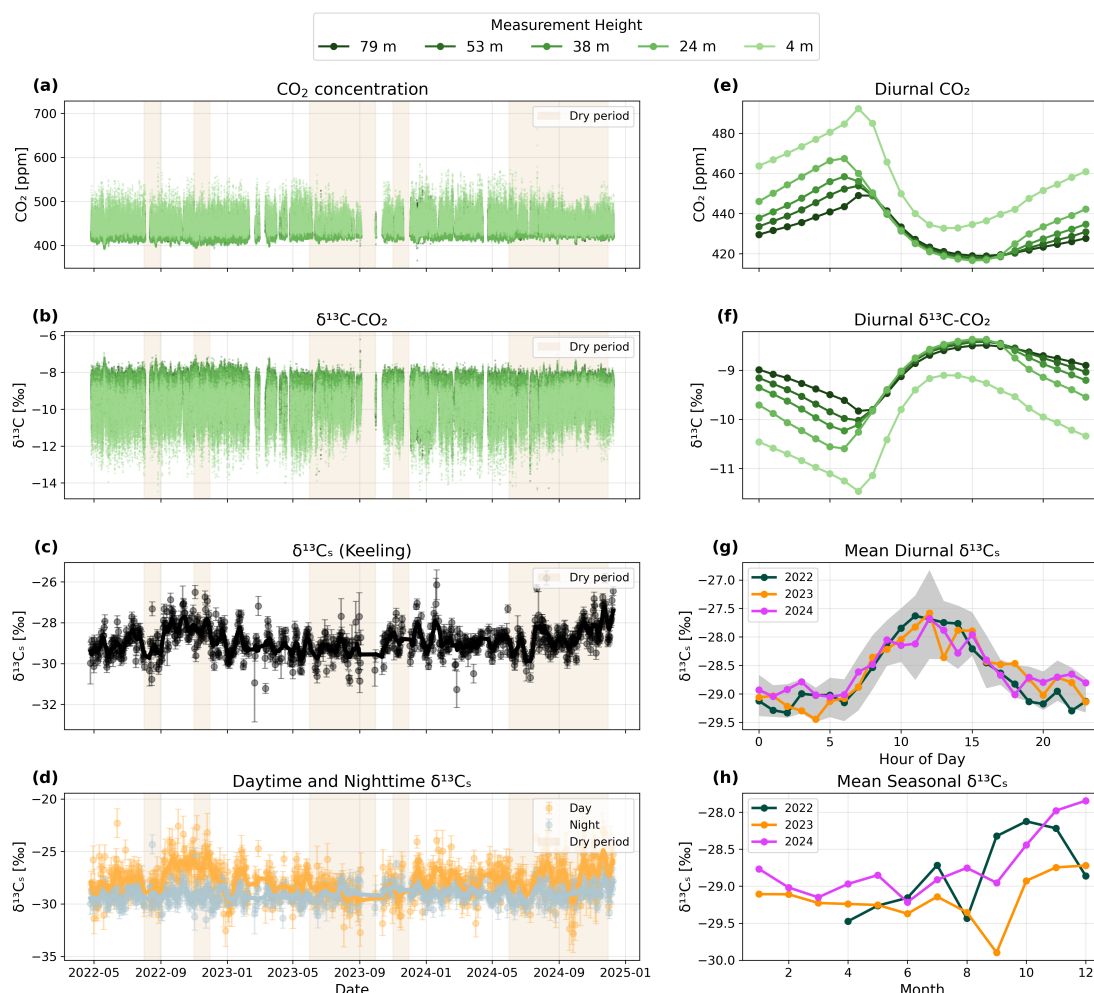


Figure 2. Multi-height CO_2 mole fraction, $\delta^{13}\text{C}\text{-CO}_2$, inferred $\delta^{13}\text{C}$ source signature and day and night inferred $\delta^{13}\text{C}$ source signature at ATTO. The upper two panels show the full in-situ measurement record at the available tower heights; the lower panels show the daily source signatures derived from vertical-profile Keeling-plot regressions. Daytime and nighttime data were filtered for 10:00-16:00 LT and 20:00-04:00 LT, respectively. Error bars for panel c and d indicate the regression uncertainty where available. The diurnal cycles of the source signature are shown for each year on the right side with the standard deviation of the hourly source signature for the entire period.

values in the afternoon and evening is also broadly reproduced. In QUINCY, a distinct short-lived minimum occurs around 06:00–07:00 local time before the subsequent daytime enrichment. This feature is much less pronounced in the observations. In QUINCY, this daytime enrichment arises as photosynthetic uptake increasingly contributes to the gross-flux-weighted apparent



source signature and as photosynthetic discrimination changes over the course of the day, whereas at night, when GPP is zero, the simulated signature reduces to that of total ecosystem respiration. In the observations, the wet- and dry-season cycles overlap largely during the night and early morning and diverge mainly during daytime, when the dry-season source signatures are moderately more enriched. The overall wet-to-dry-season shift in the observations is therefore small. In QUINCY, by contrast, the entire dry-season diurnal cycle is shifted towards more enriched values relative to the wet-season cycle. This separation persists throughout most of the day and night and is substantially larger than observed.

The observations and QUINCY agree closely in both the magnitude and the seasonal change of the diurnal amplitude. The difference between the maximum and minimum mean diurnal source signature is 1.9‰ during the dry season and 1.5‰ during the wet season in the observations, compared with 2.0 and 1.6‰, respectively, in QUINCY. Thus, both data sets show a moderately larger diurnal cycle during the dry season, while reproducing similar wet- and dry-season amplitudes despite the systematic difference in their absolute isotopic levels. The stronger seasonal variability in QUINCY is therefore expressed primarily as a large shift in the isotopic baseline between the wet and dry seasons.

The most obvious difference in the absolute source signature values is that QUINCY is systematically more depleted than the observations. Nevertheless, the model broadly reproduces the direction, timing, and magnitude of the observed within-day variation. The much stronger wet-to-dry-season shift in QUINCY indicates that the magnitude of the modelled seasonal response differs from that inferred from the observations. To assess whether the short-term functional response is represented consistently, we next examine how diurnal changes in $\delta^{13}\text{C}_s$ relate to concurrent changes in environmental drivers.

3.2.2 Diurnal relationships with environmental drivers

The diurnal relationships with environmental drivers provide a functional comparison of observed and modelled source signature variability. GPP, radiation, air temperature, and VPD share pronounced and partly phase-shifted diurnal cycles and are therefore strongly correlated with one another (Appendix Fig. A3). Nevertheless, we show all driver variables to compare the timing and shape of their relationships with $\delta^{13}\text{C}_s$ in the observations and QUINCY (Fig. 4).

In the observations, $\delta^{13}\text{C}_s$ becomes more enriched during daytime as GPP increases and radiation, VPD, and air temperature rise. The most enriched source signatures occur around midday, when GPP, radiation, temperature, and VPD are close to the daytime maxima. Relationships with soil-water variables are less direct on this time scale because soil volumetric water content and root-zone soil-water potential are buffered and vary slower.

QUINCY shows the same overall direction of change with GPP, radiation, VPD, and temperature, but remains shifted towards more depleted $\delta^{13}\text{C}_s$ values, as described in Sect. 3.2.1. The model therefore reproduces the broad timing and sign of the observed diurnal response, despite the difference in the absolute isotopic baseline.

The colour-coded hysteresis-like hourly progression further shows that the relationships are time-dependent. In the observations, a clear morning–afternoon separation occurs particularly in the relationship with VPD: similar VPD values are associated with different $\delta^{13}\text{C}_s$ values on the rising morning and declining afternoon branches. A weaker separation is also visible for GPP. In QUINCY, the relationship with VPD is reproduced, but a stronger hysteresis-like structure occurs in the relationship

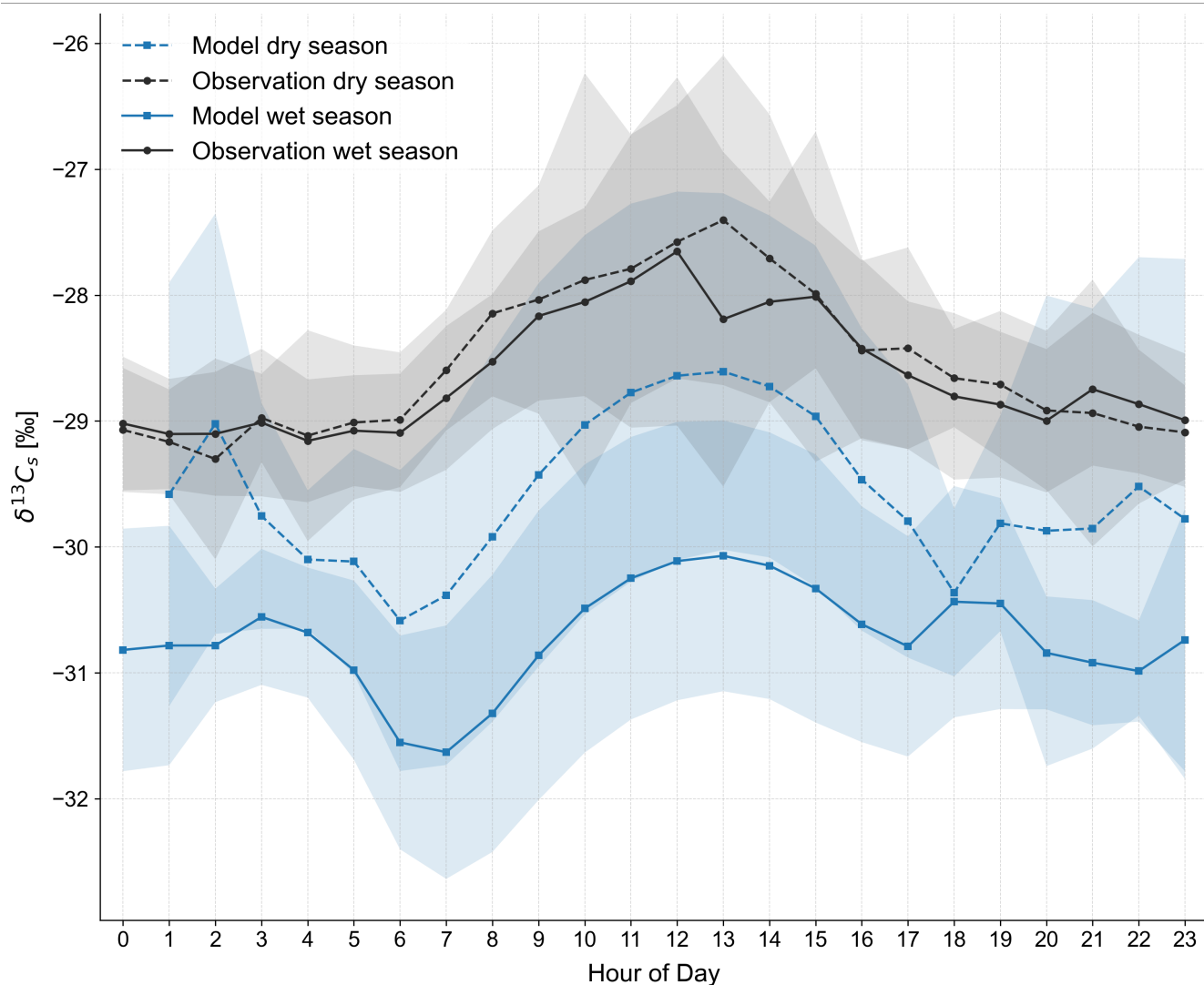


Figure 3. Mean diurnal cycles of $\delta^{13}\text{C}$ source signatures during the wet and dry seasons in the observations and QUINCY. Circles show observations, and squares show QUINCY. Blue and red lines indicate wet- and dry-season conditions, respectively. Hours are shown in local time (UTC−4). The observations show moderate dry-season enrichment, predominantly during daytime, whereas QUINCY shows a larger separation between the wet- and dry-season cycles throughout most of the day and night.

with GPP. Because the environmental variables covary strongly, the relationships shown in Fig. 4 describe the combined diurnal evolution and should not be interpreted as independent causal effects.

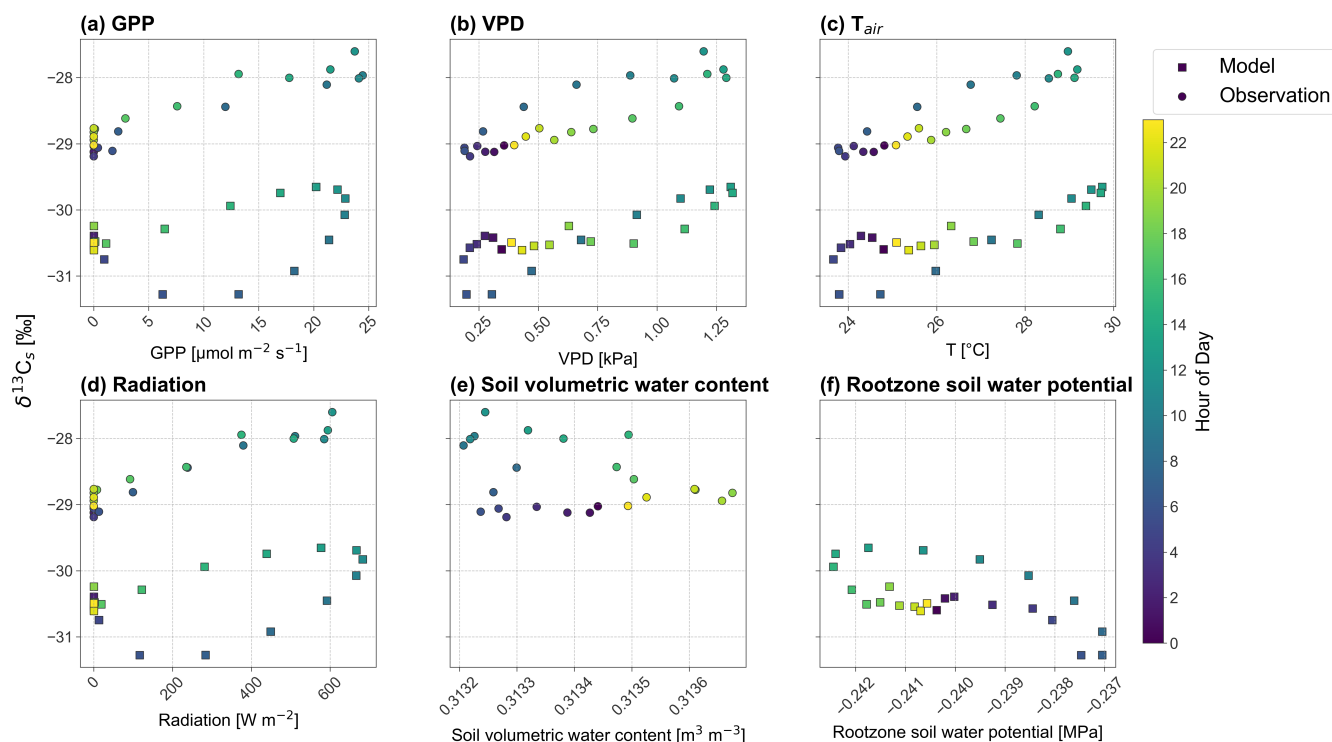


Figure 4. Diurnal relationships between $\delta^{13}\text{C}$ source signatures and environmental drivers. Circles show observations and squares show QUINCY; colours indicate hour of day. Because GPP, radiation, VPD, and temperature co-vary strongly over the diurnal cycle, the panels are interpreted as functional relationships along the combined diurnal trajectory. Soil moisture is given at 1m depth.

3.2.3 Seasonal cycle and footprint sensitivity

The seasonal comparison reveals a much stronger model–observation mismatch than the diurnal comparison (Fig. 5). The observed seasonal cycle is relatively muted: source signatures remain close to approximately -29% for much of the year, with only moderate enrichment during parts of the dry season at the end of the year. By contrast, QUINCY simulates a pronounced seasonal cycle, especially in 2023, with very depleted values during the early wet-season months and a strong enrichment from August to October.

Because the current QUINCY source signatures represent a site level run using local forcing, whereas the atmospheric source signatures integrate exchange over the larger and temporally varying tower footprint, differences in spatial sampling could contribute to the seasonal variability in the observations. We therefore first tested whether changing atmospheric transport and source-region sensitivity could explain the observed seasonal signal. To do so, we performed an additional Bayesian inversion of spatially varying $\delta^{13}\text{C}$ source signatures using the time-varying transport footprints and a temporally fixed isotopic source signature field (see Appendix A6, Fig. A6 and Fig. A7). The posterior footprint-based reconstruction of source signature

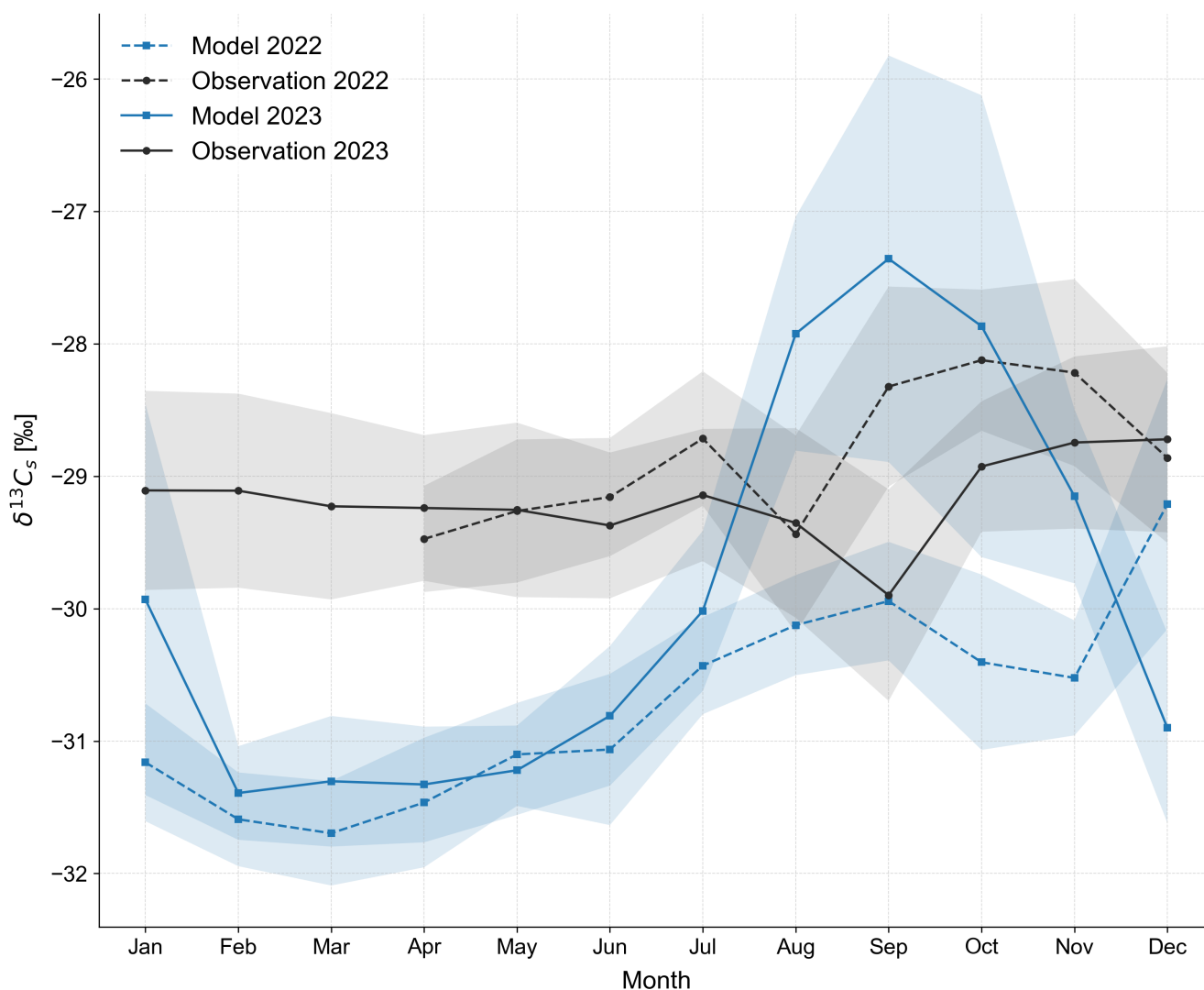


Figure 5. Seasonal cycle of $\delta^{13}\text{C}$ source signatures in QUINCY and observations. Monthly mean values are shown separately for 2022 and 2023. The model shows a substantially larger seasonal amplitude than the observations, particularly during the 2023 dry-season period.

355 reproduced only weak temporal variability and remained close to the prior source signature. Under the assumptions of this analysis, changing source-region sensitivity alone explains only a small fraction of the observed seasonal variability.

Having ruled out changing transport footprints as the dominant explanation, we next assess whether the model–observation mismatch is associated with differences in the response of $\delta^{13}\text{C}_s$ to environmental conditions. We therefore analyse the relationships between $\delta^{13}\text{C}_s$ and environmental drivers and subsequently use a multilinear fit to quantify how much of the observed
 360 and modelled variability can be explained by local environmental conditions.

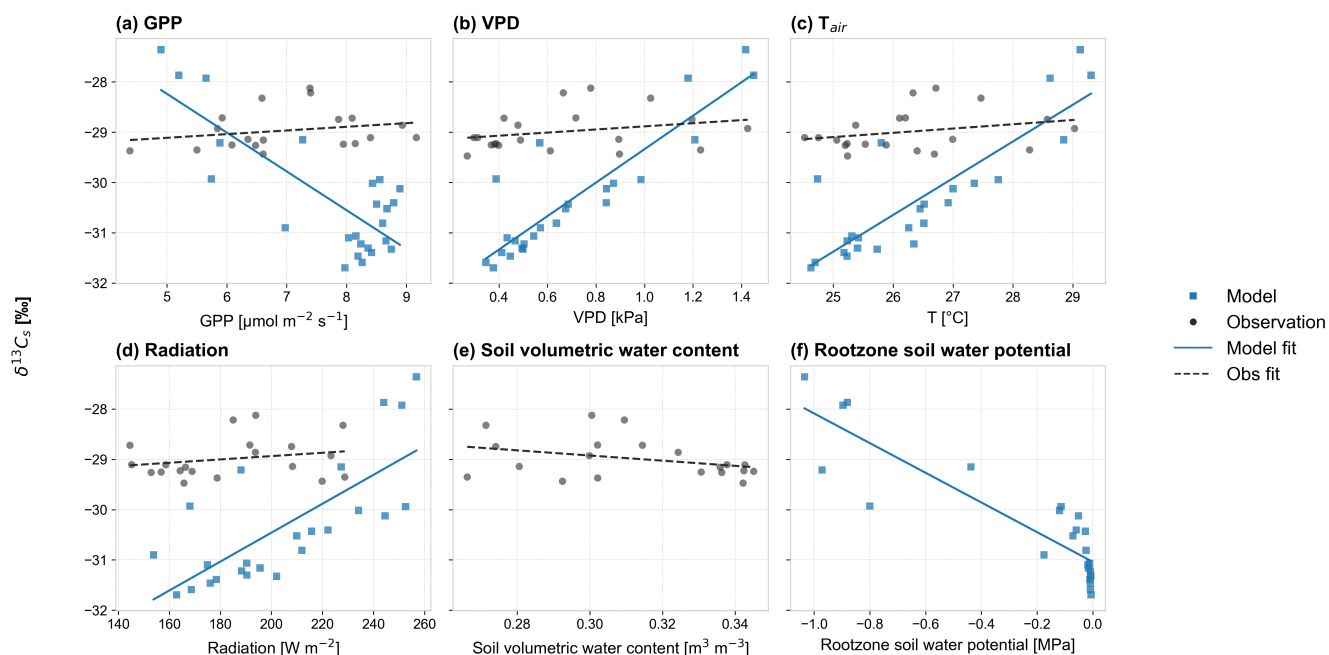


Figure 6. Seasonal relationships between $\delta^{13}\text{C}_s$ source signatures and raw monthly environmental drivers. Blue squares and solid lines show QUINCY, and grey circles and dashed lines show observations. Relationships with the analysed environmental drivers are substantially stronger in QUINCY than in the atmospheric source signature observations. September 2023 was excluded from the observations because it contained only five daily values due to data gaps and is therefore not representative.

3.2.4 Seasonal relationships with environmental drivers

Figure 6 shows that the relationships between $\delta^{13}\text{C}_s$ and individual raw monthly environmental drivers are considerably stronger in QUINCY than in the observations. The modelled source signatures span a substantially wider isotopic range than the observations and show clear linear relationships with most of the analysed variables. In QUINCY, $\delta^{13}\text{C}_s$ becomes more enriched with increasing VPD, air temperature, and radiation, whereas increasing GPP is associated with more depleted source signatures. The relationship with root-zone soil-water potential is also pronounced: more negative soil-water potentials, corresponding to drier root-zone conditions, are associated with more enriched modelled source signatures. VPD shows the tightest individual relationship with the modelled source signatures ($R^2 = 0.80$), followed by air temperature and root-zone soil-water potential ($R^2 = 0.72$ and $R^2 = 0.78$, respectively). While radiation and GPP show a moderate correlation ($R^2 = 0.54$ and $R^2 = 0.63$, respectively, see Fig. A9).

In the observations, relationships with individual raw monthly drivers are much weaker. The observed source signatures remain clustered around approximately -29‰ across most of the observed environmental range, and the fitted relationships are generally weak. TROPISIF shows the highest individual explanatory power ($R^2 = 0.20$), followed by Soil volumetric water content at 100cm depth ($R^2 = 0.11$), whereas the remaining drivers explain little of the observed variability (Fig. A9).



375 Note that the hydrological relationships in Fig. 6 e and f are not a direct observation–model comparison of the same variable. Panel (e) shows observed soil volumetric water content at 1m depth, whereas panel (f) shows root-zone soil-water potential from QUINCY. These variables characterize similar, but different aspects of soil-water availability and are therefore interpreted separately. Because the environmental variables covary seasonally, the individual relationships represent associations with the combined seasonal progression and do not isolate independent effects of the respective drivers.

380 Combining environmental predictors to explain the observed variability in both data sets improves the correlation. To identify predictor combinations that improve the fit without introducing unnecessary model complexity, we compared alternative multilinear models using the Akaike information criterion (AIC). The AIC-selected models contained two predictors in each case. For QUINCY, the selected combination of VPD and GPP explains 93 % of the modelled $\delta^{13}\text{C}_s$ variability ($R^2 = 0.93$). For the observations, the selected combination of soil volumetric water content at 100 cm depth and TROPOSIF explains 47 % of the
 385 variability ($R^2 = 0.47$). Thus, the inclusion of two complementary predictors captures substantially more variability than the individual driver relationships, while the AIC selection avoids adding further predictors that do not sufficiently improve model performance. Nevertheless, the selected environmental predictors explain substantially less variability in the observations than in QUINCY. The corresponding multilinear fits are shown in Fig. A10.

We additionally tested whether $\delta^{13}\text{C}_s$ is related more strongly to month-to-month changes in environmental conditions than
 390 to their absolute monthly values. In QUINCY, monthly changes explain considerably less variability than the raw monthly values, with R^2 values ranging from 0.00 to 0.15 across the analysed drivers (see Fig. A9 and Fig. A11). In the observations, several driver changes show greater explanatory power than their corresponding absolute values, particularly changes in TROPOSIF ($R^2 = 0.41$), APAR ($R^2 = 0.30$), VPD ($R^2 = 0.22$), and air temperature ($R^2 = 0.16$; Fig. A9). QUINCY variability is therefore more closely associated with the absolute seasonal environmental state, whereas the observed source signatures
 395 show comparatively stronger relationships with transitions between monthly conditions.

To further examine how the strong seasonal response to environmental conditions in QUINCY is expressed in the underlying carbon fluxes, we used the model’s explicit representation of the isotopic composition of individual fluxes to separate the simulated apparent source signature into its photosynthetic and respiratory components. We additionally examined the partitioning of total ecosystem respiration into autotrophic and heterotrophic respiration and their respective $\delta^{13}\text{C}$ signatures (Appendix
 400 Fig. A8). Autotrophic and heterotrophic respiration contribute on average approximately 72% and 28% of total respiration, respectively, although their relative contributions vary substantially over time. The isotopic signature of heterotrophic respiration remains comparatively stable, whereas that of autotrophic respiration varies more strongly over time and broadly follows the photosynthetic isotope signal. During the pronounced dry-season enrichment in 2023, the relative contribution of autotrophic respiration increases, while that of heterotrophic respiration decreases (Appendix Fig. A8).



405 4 Discussion

4.1 Observational value of the ATTO $\delta^{13}\text{C}$ source signature record

The ATTO record provides an unprecedented opportunity to investigate $\delta^{13}\text{C}$ source signature variability over a remote Amazonian rainforest using 2.5 years of continuous, height-resolved atmospheric observations. We inferred source signatures from vertical CO_2 and $\delta^{13}\text{C}$ gradients, so that hourly and daily Keeling-plot estimates can be derived without prescribing an external
 410 background. The resulting dataset captures apparent source signature variability across a wide range of diurnal, seasonal, and meteorological conditions.

This makes it possible to analyse $\delta^{13}\text{C}_s$ as a temporally resolved diagnostic of the coupled biosphere–atmosphere isotope signal. In the following, we first discuss the observational information contained in the ATTO source signature and examine what the comparison with QUINCY reveals about the representation of carbon–water coupling and isotope discrimination in
 415 tropical forests, before discussing the implications for using $\delta^{13}\text{C}\text{--CO}_2$ as a tracer in future top-down and model-evaluation studies.

4.2 Observed source signature and its temporal variability

The absolute level of the observed source signature of approximately -29‰ represents a clearly ^{13}C -depleted C_3 -vegetation signal relative to background atmospheric CO_2 and falls within the range of previously reported Amazonian ecosystem-respiration and canopy-air source signatures (Ometto et al., 2002, 2006; Buchmann et al., 1997; Guehl et al., 1998; Batista et al., 2025). Within that range, our mean value is closer to the depleted end, consistent with a strongly forest-dominated source signature and only limited influence from more ^{13}C -enriched components. The tendency to be rather depleted with respect to earlier studies may also reflect the long-term decline in atmospheric $\delta^{13}\text{C}\text{--CO}_2$, as carbon assimilated during earlier studies originated from a more ^{13}C -enriched atmosphere than carbon assimilated today (Graven et al., 2020). The value
 425 also agrees well with the campaign-based estimates of Chanca et al. (2025), who derived ecosystem-respiration source signatures of approximately -27.8 to -29.0‰ from two sampling periods at ATTO. Our continuous record therefore extends these earlier snapshot-based constraints and shows that similar source signature values persist across a much broader range of meteorological conditions.

The day–night differences and the mean diurnal cycle show that the apparent source signature is sensitive to diurnal ecosystem dynamics (Fig. 2). Source signatures become more enriched during the day and more depleted during the night and early morning. The increase of source signature is in parallel to the onset of GPP. This pattern may be driven by the interplay between GPP and respiration, but also stomatal regulation during the day. Reduced discrimination, associated with a lower ratio of intercellular to ambient CO_2 , leads to less depleted assimilated carbon (Farquhar et al., 1982).
 430

The relationships with environmental drivers provide a more detailed view of this diurnal response (Fig. 4). Observed $\delta^{13}\text{C}_s$ becomes more enriched as GPP, radiation, VPD, and air temperature increase during the day. However, these variables covary strongly over the diurnal cycle: radiation drives photosynthetic activity and contributes to the evolution of temperature and VPD. The individual relationships therefore represent different projections of the same combined diurnal trajectory.
 435



However, a morning–afternoon separation is visible in several of the relationships. Similar VPD values occur in the morning and afternoon but are associated with different $\delta^{13}\text{C}_s$ values. Hysteresis-like trajectories are also visible for GPP and radiation. Radiation and GPP generally peak earlier in the day, whereas VPD remains elevated further into the afternoon. The apparent source signature is therefore not uniquely determined by the instantaneous value of any single driver.

On seasonal time scales, the observed $\delta^{13}\text{C}_s$ variability is only weakly related to the absolute monthly values of the analysed hydroclimatic and photosynthetic drivers (Figs. A9 and Fig. 6). No single local driver explains a large fraction of the observed variability, indicating that the seasonal isotope signal is not tightly coupled to the absolute monthly environmental state. Instead, it may reflect interacting and potentially lagged responses to multiple drivers, together with integration across ecosystem components and timescales.

Previous studies nevertheless indicate that Amazonian carbon-isotope signals can vary with hydroclimatic conditions. Such evidence has largely been derived from spatial gradients, comparisons among sampling periods, or syntheses across ecosystems (Ometto et al., 2002; Pataki et al., 2003; Chanca et al., 2025). At ATTO, Chanca et al. (2025) found a more depleted ecosystem-respiration signature during a wetter sampling period in December 2021 than during a drier period in October 2019. In our continuous record, the dry-season enrichment is consistent with a hydroclimatic influence. However, the pronounced depletion during the 2023 dry season, in contrast to the more enriched dry-season values in 2022 and 2024, shows that dry conditions alone do not determine the observed $\delta^{13}\text{C}_s$ response. Consistent with this, individual hydroclimatic drivers explain little of the month-to-month variability. The seasonal isotope signal therefore likely reflects combined and potentially lagged responses involving atmospheric demand, soil-water availability, photosynthetic activity, and respiratory source contributions.

Under the assumptions of our footprint sensitivity analysis, changing source-region sensitivity appears unlikely to be the dominant cause of the muted seasonal variability. The posterior reconstruction remains close to the prior and shows only weak temporal variability, suggesting that transport-driven changes in footprint weighting contribute only marginally to the observed seasonal signal.

The strong relationships with monthly changes in drivers, rather than with the absolute values, suggest that transitions in ecosystem state may contain additional information beyond the absolute seasonal mean state. One possible explanation is that ecosystem-level buffering or acclimation to slowly varying seasonal conditions reduces sensitivity to the absolute environmental state, while transitions between states lead to a stronger isotope response.

Atmospheric decoupling during stable nighttime conditions remains a source of uncertainty in the inferred signatures (Sect. 2). Within-canopy stratification and the release of accumulated CO_2 during the morning transition can complicate their interpretation (Faassen et al., 2025). As stated in Sect. 2, we therefore interpret the intercept as an apparent ecosystem source signature rather than the isotopic signature of a single source.

4.3 Model–observation comparison of $\delta^{13}\text{C}_s$ variability

The comparison with QUINCY provides a direct test of whether the model reproduces the observed magnitude, timing, and environmental controls of $\delta^{13}\text{C}_s$ variability. The strongest agreement occurs on diurnal time scales. Both the observed and modelled source signatures become more enriched during the day and more depleted during the night and early morning. This



agreement in sign and timing suggests that QUINCY captures part of the short-term physiological response associated with photosynthetic discrimination, stomatal regulation, GPP, VPD, and canopy-atmosphere coupling. One distinct feature of the simulated diurnal cycle is a short-lived minimum in $\delta^{13}\text{C}_s$ around 06:00–07:00 local time, which is much less pronounced in the observations. This minimum occurs as photosynthetic uptake begins to increase and may reflect a transient phase in which photosynthesis already contributes to the apparent source signature while photosynthetic discrimination remains relatively strong, before the subsequent daytime enrichment. The weaker expression of this feature in the observations may therefore indicate a difference in the timing or magnitude of the early-morning isotope response. However, this period also coincides with the transition from the stable nocturnal boundary layer to daytime mixing, making the observational Keeling-plot estimates particularly difficult to interpret.

The systematic offset between QUINCY and the observations can arise from a bias in the mean isotopic discrimination, for example through the parameterization of (c_i/c_a) , stomatal conductance, intrinsic water-use efficiency, mesophyll conductance, or respiratory substrate signatures. A shift in the baseline discrimination could move the simulated $\delta^{13}\text{C}_s$ values without fundamentally altering the modelled response to diurnal environmental forcing.

Turning to the driver relationships, the morning–afternoon separation with respect to VPD is broadly similar in the observations and QUINCY, indicating that both show a dependence of $\delta^{13}\text{C}_s$ on the phase of the diurnal cycle rather than on instantaneous VPD alone. At similar VPD, differences between morning and afternoon may reflect changes in canopy hydraulic state over the course of the day. The fact that QUINCY reproduces this separation suggests that it captures this aspect of the diurnal coupling reasonably well. A clearer model–observation difference occurs for GPP, for which QUINCY shows a substantially more pronounced loop-like relationship. This largely reflects the strongly depleted simulated $\delta^{13}\text{C}_s$ during the morning increase in GPP, suggesting that QUINCY might not fully reproduce the isotope response during this time period.

The seasonal comparison reveals a much stronger model–observation mismatch. The observed seasonal cycle remains relatively muted, with source signatures close to approximately -29‰ for much of the year and only moderate seasonal enrichment. QUINCY, in contrast, simulates a substantially larger seasonal cycle, especially during the 2023 dry-season period.

QUINCY links $\delta^{13}\text{C}_s$ strongly to raw monthly environmental state variables such as VPD, air temperature, radiation, GPP, and root-zone soil-water potential, which is expected from the model dynamics (Sect. 2.5). The observations show much weaker relationships with the same raw drivers and appear more sensitive to changes in drivers than to their absolute monthly values. This suggests that the atmospheric isotope signal integrates a more complex and temporally damped ecosystem response than represented by the direct model relationships.

The contrasting behavior of QUINCY and observations is particularly during the 2023 drought. QUINCY shows a strong dry-season enrichment of $\delta^{13}\text{C}_s$, whereas the observations exhibit a much weaker and non-uniform response, including a pronounced depletion during part of the dry season.

Several mechanisms could explain why QUINCY simulates a stronger seasonal isotope response than is observed. The model–observation mismatch may arise from differences in how water limitation on canopy carbon exchange are represented. One possibility is that the model overestimates the effective water stress experienced by the canopy during the dry season.



Excessive stomatal limitation lowers c_i/c_a , reduces photosynthetic discrimination, and thereby shifts simulated source signature towards more enriched values.

Two aspects of the representation of canopy water stress may be particularly relevant. First, above-canopy VPD may not represent the effective atmospheric demand experienced by leaves throughout the canopy. The mean vertical profiles at ATTO show substantially lower VPD in the lower canopy than at upper-canopy and above-canopy levels in both seasons, with a particularly pronounced gradient during the dry season (Fig. A4). Thus, leaves in the lower canopy experience a more humid and less atmospherically demanding microclimate than would be inferred from above-canopy meteorological conditions alone. The vertical VPD gradient may therefore reflect both a direct physiological forcing and, more generally, the strongly stratified microclimate within the canopy. Consistent with this interpretation, pronounced vertical gradients in humidity and a persistent within-canopy temperature inversion, have been shown to restrict mixing between the lower canopy and the top crown at ATTO (González-Armas et al., 2025). These observations suggest that a model driven by, or responding predominantly to, above-canopy meteorological conditions may overestimate the effective VPD experienced by parts of the canopy and may not capture its temporal evolution within the canopy (Evans et al., 2025).

The vertical gradient in leaf-tissue $\delta^{13}\text{C}$ reported by Ometto et al. (2002), with more negative $\delta^{13}\text{C}_{\text{leaf}}$ values closer to the ground, is further consistent with persistent vertical differences in canopy microclimate and physiological conditions. This is supported by the recent findings of González-Armas et al. (2025), who observed a 3.75 ‰ increase in leaf $\delta^{13}\text{C}$ from the understory to the top-crown canopy at the ATTO site. Our height-specific apparent source signatures show a corresponding vertical gradient, with more depleted $\delta^{13}\text{C}_s$ values at the lower measurement levels and progressively more enriched values towards the upper canopy in both seasons (Fig. A4b). VPD, radiation, temperature, humidity, hydraulic path length, and leaf characteristics all vary with canopy height and may jointly influence photosynthetic discrimination. In addition, increasing hydraulic path length towards the upper canopy may increase hydraulic limitation of transpiration and stomatal conductance, thereby lowering c_i/c_a and reducing photosynthetic discrimination.

The height-specific apparent source signatures may also reflect differences in source contributions, with more depleted signatures at lower levels potentially influenced by a larger contribution from soil and understory respiration (Ometto et al., 2002; Buchmann et al., 1997). The co-occurring VPD gradient is therefore consistent with increasingly dry and potentially more physiologically limiting conditions towards the upper canopy, but may also serve as an indicator of broader vertical differences in canopy microclimate.

Second, deep-root water access may allow Amazonian trees to maintain transpiration and photosynthesis even when upper soil layers dry. A possible contribution to the excessive simulated water stress is therefore that effective plant water availability declines too rapidly in QUINCY during progressive surface drying. This could occur, for example, if water uptake does not shift sufficiently towards deeper soil layers or if the prescribed static rooting distribution provides less access to deep plant-available water than occurs in the real forest. Under such conditions, the model would impose water stress while the observed ecosystem remains comparatively resistant. Elevated VPD could therefore coincide with sufficient plant-available water to buffer the seasonal isotope response.



540 Finally, the seasonal isotope response may additionally reflect differential responses of photosynthesis and ecosystem respiration to progressive drying. If GPP and respiration decline at different rates during the wet-to-dry-season transition, their changing relative contributions alter the apparent ecosystem source signature independently of changes in photosynthetic discrimination itself. Thus, the seasonal $\delta^{13}\text{C}_s$ response in QUINCY could result from a combination of the simulated c_i/c_a response and differences in how GPP and respiratory fluxes respond to increasing water stress.

545 The partitioning of ecosystem respiration between autotrophic and heterotrophic components could additionally affect the absolute source signature and its seasonal variability. As shown in Fig. A8, heterotrophic respiration in QUINCY has a comparatively stable isotopic signature, whereas autotrophic respiration varies more strongly and broadly follows the photosynthetic isotope signal. The mean partitioning is well with independent estimates for tropical forests (Trumbore and Barbosa De Camargo, 2009; Sierra et al., 2021; Chanca et al., 2025), while the relative contributions vary substantially over time (Appendix
 550 Fig. A8) Consequently, in the model the changing respiration partitioning reduces the buffering contribution of heterotrophic respiration during periods when the autotrophic component is most enriched and thereby amplifies the simulated seasonal $\delta^{13}\text{C}_s$ cycle.

QUINCY also shows a substantially larger year-to-year contrast in $\delta^{13}\text{C}_s$ between 2022 and 2023 than the observations. If this discrepancy reflects excessive sensitivity to water stress, the same process bias could also affect the simulated interannual
 555 variability of carbon fluxes. If stomatal conductance and photosynthesis respond too strongly to hydroclimatic anomalies, year-to-year variations in GPP, respiration, and net carbon exchange may likewise be overestimated. This possibility is particularly important because Amazonian and other tropical ecosystems contribute strongly to year-to-year changes in the global land carbon sink (Feng et al., 2025). However, because the present comparison covers only 2022 and 2023 and does not directly evaluate carbon-flux variability, this broader implication remains to be tested against longer isotope records and independent
 560 observations of GPP and net carbon exchange.

5 Conclusions

In this study, we used continuous, height-resolved CO_2 and $\delta^{13}\text{C}\text{-CO}_2$ measurements from ATTO to infer apparent $\delta^{13}\text{C}$ source signatures over a 2.5 year period from 2022 to 2024. The vertical-profile Keeling-plot approach provides a temporally resolved record of source signature variability over a remote Amazonian rainforest without prescribing an external background.
 565 The inferred $\delta^{13}\text{C}_s$ values remain centred near -29‰ across the 2.5-year record, with a robust diurnal cycle but comparatively muted and non-uniform seasonal variability. This shows that the atmospheric source signature contains temporally resolved, but integrative information on ecosystem–atmosphere carbon-isotope dynamics.

On diurnal time scales, the observations and QUINCY agree qualitatively in the sign and timing of the $\delta^{13}\text{C}_s$ cycle. Both show more enriched source signatures during the day and more depleted values during the night and early morning. This
 570 indicates that QUINCY captures the direction of short-term physiological controls, consistent with the expected influence of photosynthetic discrimination, stomatal regulation, GPP, VPD, and canopy–atmosphere coupling. The systematic offset



between observed and modelled $\delta^{13}\text{C}_s$ values points to a bias in the absolute isotope baseline, but the broadly comparable diurnal timing and amplitude indicate that the underlying short-term response is nevertheless partly represented by the model.

On seasonal time scales, the model–observation mismatch is much larger. QUINCY simulates a substantially stronger and
 575 more coherent environmentally driven $\delta^{13}\text{C}_s$ response than observed. Although combinations of variables related to photosynthetic activity and water availability explain variability in both data sets, they explain substantially more of the variability in QUINCY, and the observed relationships with individual monthly drivers remain weak. A footprint-based test shows that changing atmospheric source regions alone cannot explain the muted observed seasonal variability.

One plausible explanation is that QUINCY overestimates the effective water stress experienced by the canopy. If above-
 580 canopy VPD or upper-soil drying impose too strong a stomatal limitation in the model, QUINCY would simulate too large a reduction in c_i/c_a , too weak a photosynthetic discrimination, and therefore an exaggerated dry-season enrichment of $\delta^{13}\text{C}_s$. In the real forest, canopy microclimate, high humidity within the canopy, deep-root water access, ecosystem heterogeneity, and temporal lags may mute this response. The muted seasonal isotope response is consistent with recent findings that the ecosystem around ATTO maintains soil-moisture availability and buffers the VPD and temperature anomalies during the 2023 drought
 585 more strongly than simulated by DGVMs (Botía et al., 2026). More generally, several mechanisms may buffer the physiological response of Amazon forests to seasonal drying, including within-canopy microclimates (González-Armas et al., 2025), access to deep soil water (Nepstad et al., 1994), and hydraulic regulation across Amazonian forests (Tavares et al., 2023; Langan et al., 2025). The tendency of land-surface models to overestimate the effect of VPD on tropical-forest canopy conductance has also been demonstrated (Fang et al., 2021). Our results therefore suggest that models may translate meteorological drought
 590 too directly into plant water stress when these buffering processes and their heterogeneity are insufficiently represented.

Overall, the ATTO $\delta^{13}\text{C}_s$ record provides a valuable diagnostic data set for evaluating Amazonian carbon–water–isotope coupling. Our results show that $\delta^{13}\text{C}$ source signatures contain physiological information, particularly on diurnal time scales, and can reveal whether process models capture the sign, timing, and relative strength of isotope responses to environmental forcing. They also demonstrate that isotope observations can identify both insufficient and excessive model sensitivity to water
 595 stress.

At the same time, $\delta^{13}\text{C}_s$ should currently be viewed as a diagnostic tracer of Amazonian vegetation dynamics. Its use in inversions or attribution studies requires models that correctly represent both the mean isotope baseline and the sensitivity of discrimination and respiratory source signatures to environmental drivers. The ATTO comparison therefore provides a first step towards using atmospheric $\delta^{13}\text{C}$ – CO_2 more systematically for model evaluation, by identifying which aspects of the observed
 600 isotope variability are already captured by QUINCY and where improved representations of isotope discrimination, stomatal regulation, canopy water stress, respiratory-substrate dynamics, and lagged ecosystem responses are still needed.

Data availability. All data sets are listed in Tab. 1.

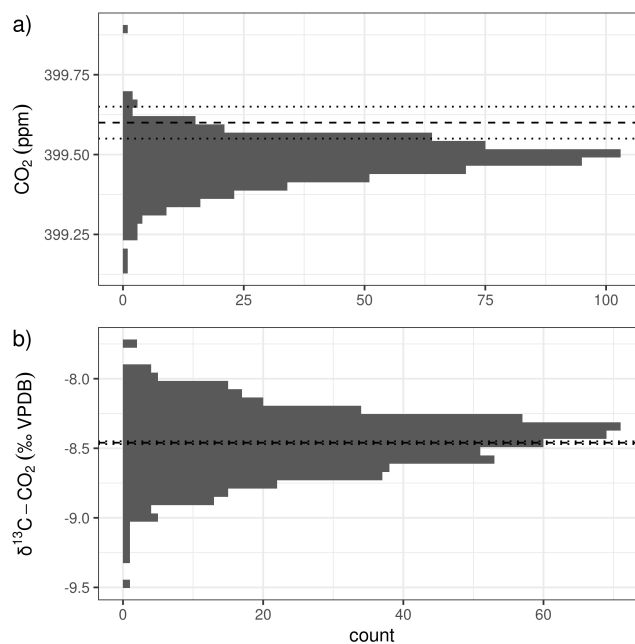


Figure A1. Distribution of corrected quality-control cylinder measurements for the record period ($n = 598$): (a) measured total CO_2 , with a mean (1 standard deviation) of 399.48 (0.08) ppm, and (b) measured $\delta^{13}\text{C}\text{--CO}_2$, with a mean of -8.46 (0.23) ‰. Horizontal dashed and dotted lines indicate the externally assigned values for total CO_2 and $\delta^{13}\text{C}\text{--CO}_2$ of 399.60 (0.05) ppm and -8.46 (0.01) ‰, respectively.

Appendix A

A1 Quality control of CO_2 and $\delta^{13}\text{C}\text{--CO}_2$ measurements



605 A2 Keeling-plot analysis

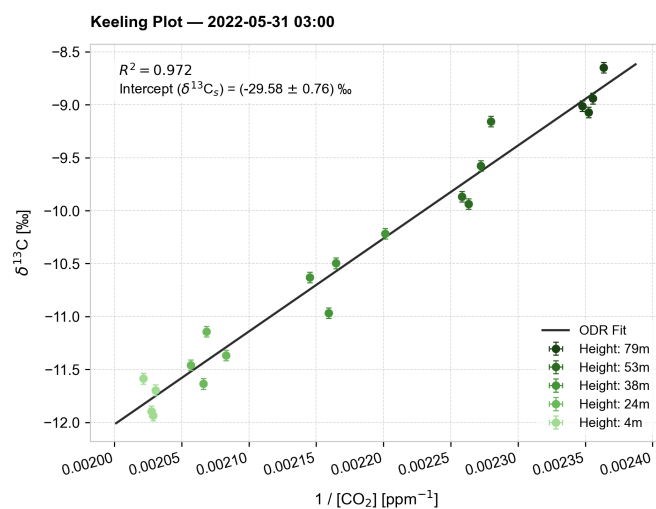


Figure A2. Example for Keeling-plot approach using the entire vertical profile for a selected hour. We apply an orthogonal regression that accounts for uncertainty in both x and y .

A3 Diurnal cycle of environmental variables and $\delta^{13}\text{C}_s$

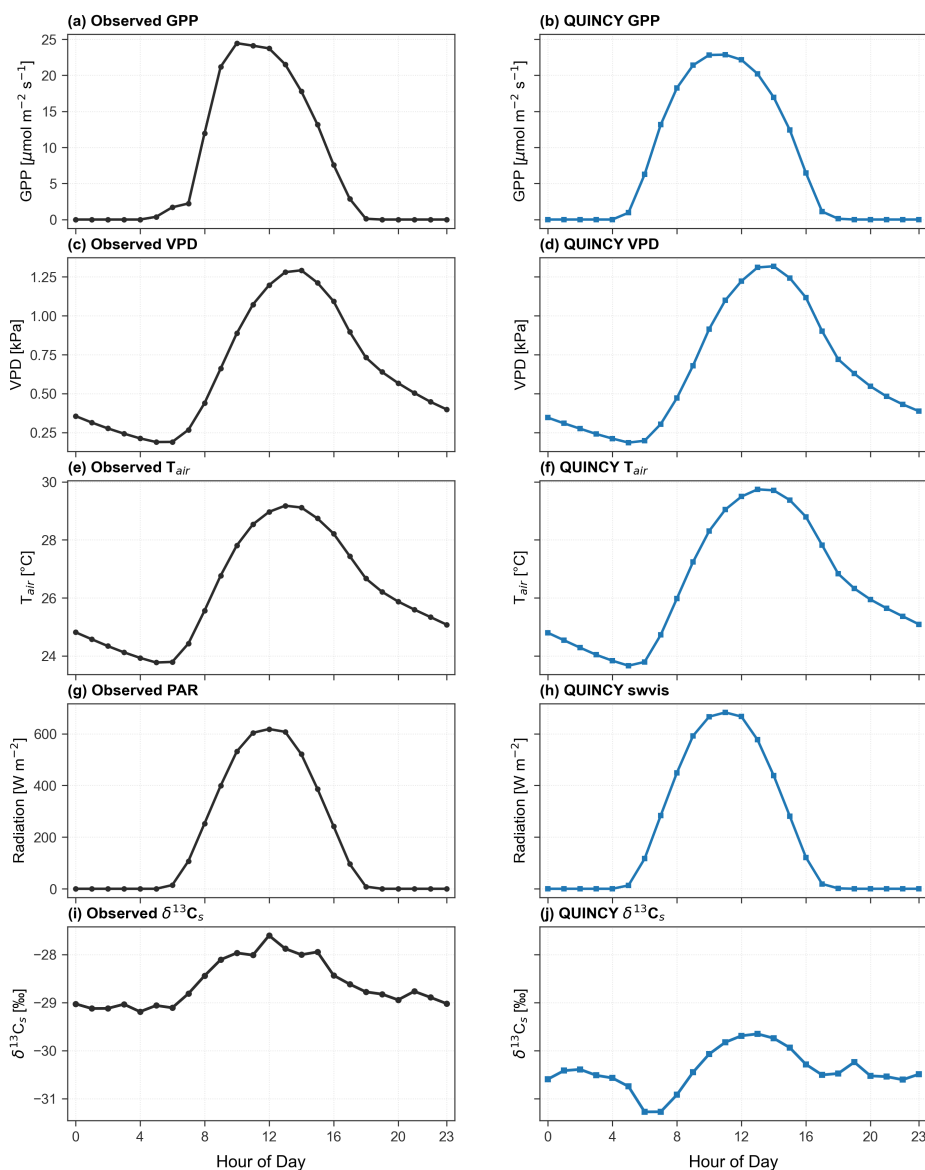


Figure A3. Mean diurnal cycles of environmental variables and $\delta^{13}\text{C}_s$ in the observations (left column; black) and QUINCY (right column; blue). Shown are GPP (a, b), vapour-pressure deficit (VPD; c, d), air temperature (T_{air} ; e, f), observed photosynthetically active radiation (PAR) and simulated incoming shortwave radiation (swvis; g, h), and the inferred or simulated $\delta^{13}\text{C}_s$ (i, j). Values are averaged by hour of day over the respective study periods and are shown in local time (UTC−4). The figure illustrates the relative timing of the environmental variables and source signature response used to interpret the diurnal driver relationships.



A4 VPD profile at ATTO

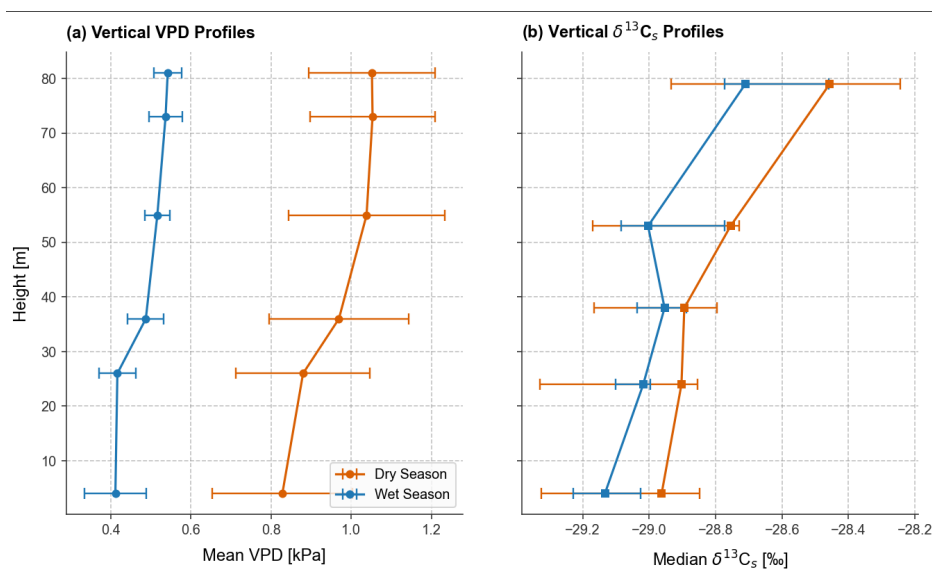


Figure A4. (a) Mean vertical profiles of vapour-pressure deficit (VPD) during the wet and dry seasons at ATTO. Points show mean VPD at the respective measurement heights, and horizontal error bars indicate the standard deviation. (b) Mean vertical profile of source signature during dry and wet season.



A5 Monthly mean diurnal cycles of source signature

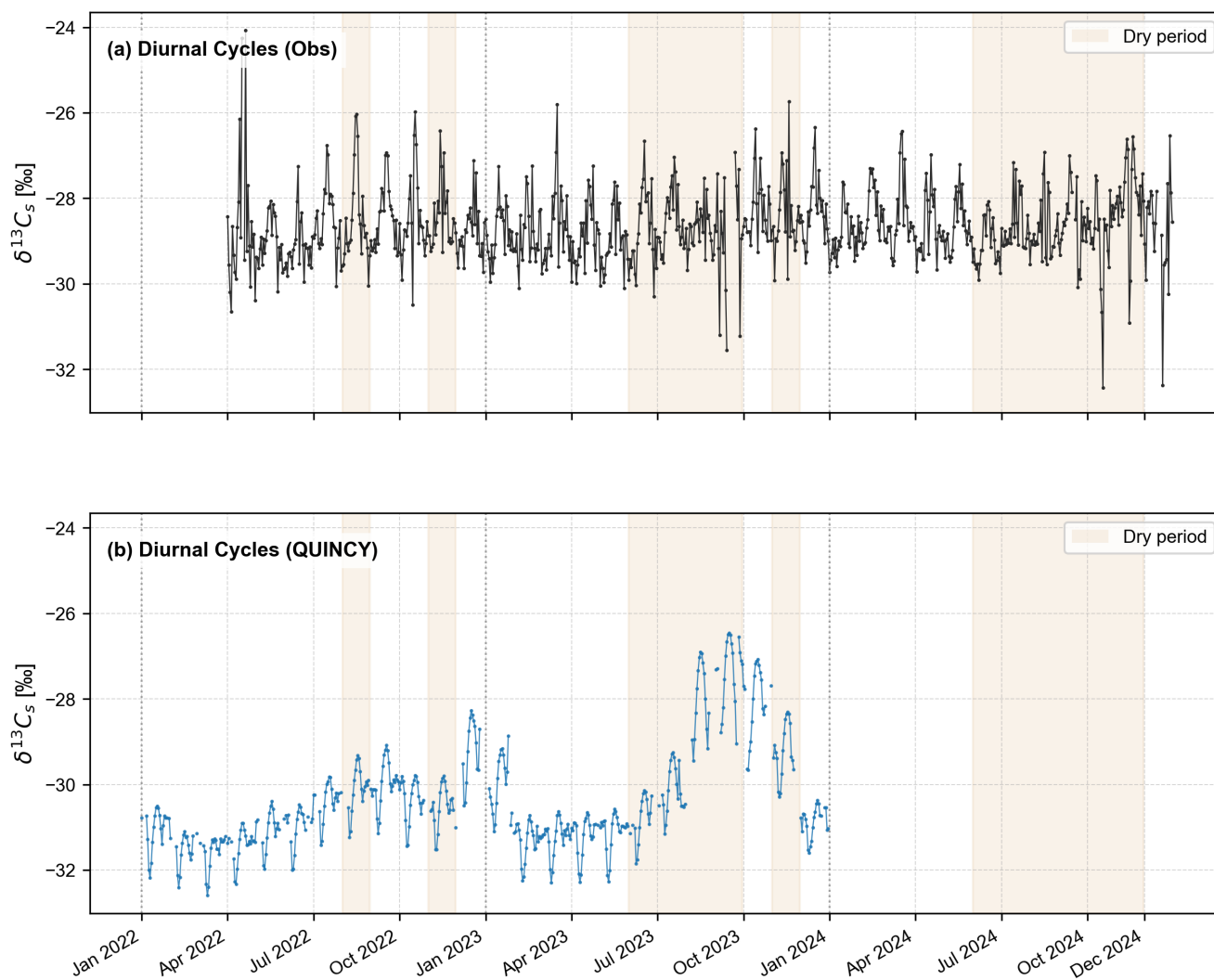


Figure A5. The upper panel shows ATTO source signature estimates averaged by month and hour; the lower panel shows the corresponding QUINCY source signatures for the available simulation period. We use a dry season threshold of 100 mm of monthly precipitation.



A6 Bayesian inversion of spatial $\delta^{13}\text{C}$ source signatures

610 To test whether temporal variability in the inferred $\delta^{13}\text{C}$ source signature could result from changing atmospheric transport footprints, we performed a Bayesian inversion of spatially varying source signatures. The analysis was not intended to estimate spatial CO_2 fluxes, but to determine whether changing sensitivity to different source regions could reproduce the observed variability in $\delta^{13}\text{C}_s$.

Transport sensitivities were calculated from STILT footprints driven by ECMWF-IFS meteorological fields after the setup
 615 of (Botía et al., 2022) but with a coarser spatial resolution of 0.25×0.25 degree. The state vector contained the $\delta^{13}\text{C}_s$ value assigned to each grid cell in the footprint domain. The Bayesian update was calculated as

$$\mathbf{x}_{\text{post}} = \mathbf{x}_{\text{prior}} + \mathbf{S}_{\text{prior}} \mathbf{H}^T (\mathbf{H} \mathbf{S}_{\text{prior}} \mathbf{H}^T + \mathbf{S}_{\text{obs}})^{-1} (\mathbf{y} - \mathbf{H} \mathbf{x}_{\text{prior}}). \quad (\text{A1})$$

Here, $\mathbf{x}_{\text{prior}}$ and $\mathbf{x}_{\text{post}}$ are the prior and posterior spatial $\delta^{13}\text{C}_s$ fields, $\mathbf{y}$ contains the source signatures inferred from the Keeling plots, $\mathbf{H}$ is the footprint-based observation operator, $\mathbf{S}_{\text{prior}}$ is the prior error covariance matrix, and $\mathbf{S}_{\text{obs}}$ is the model–
 620 data mismatch covariance matrix.

Assuming an equal CO_2 flux from every grid cell, each footprint was normalized by its total sensitivity. The modelled source signature for observation k was therefore

$$\hat{y}_k = \sum_{i=1}^n H_{ki} x_i, \quad \sum_{i=1}^n H_{ki} = 1, \quad (\text{A2})$$

where H_{ki} is the normalized sensitivity of observation k to grid cell i , and x_i is the source signature in that grid cell.

625 The prior field was spatially uniform at -29‰ . Its covariance matrix was defined as

$$(\mathbf{S}_{\text{prior}})_{ij} = \sigma_{\text{prior}}^2 \exp\left(-\frac{d_{ij}}{L}\right), \quad (\text{A3})$$

where $\sigma_{\text{prior}} = 3 \text{‰}$ is the prior uncertainty, d_{ij} is the distance between grid cells i and j , and $L = 2^\circ$ is the spatial correlation length.

Model–data mismatch errors were assumed to be uncorrelated, such that $\mathbf{S}_{\text{obs}}$ was diagonal:

$$630 (\mathbf{S}_{\text{obs}})_{kk} = \sigma_{\text{obs},k}^2, \quad (\text{A4})$$

where $\sigma_{\text{obs},k}$ where an uncertainty of 1‰ was added to the uncertainty of the respective Keeling-plot estimate to represent both the model uncertainty, as well as the uncertainty of the signature. A mean value of the total uncertainty was about 1.5‰ .

The posterior $\delta^{13}\text{C}_s$ field showed moderate spatial deviations from the prior. However, sampling this field with the time-varying footprints produced a reconstructed time series that remained close to -29‰ and varied substantially less than the
 635 observed Keeling-plot source signatures. Changing footprint sensitivity therefore explains only a small fraction of the observed $\delta^{13}\text{C}_s$ variability.

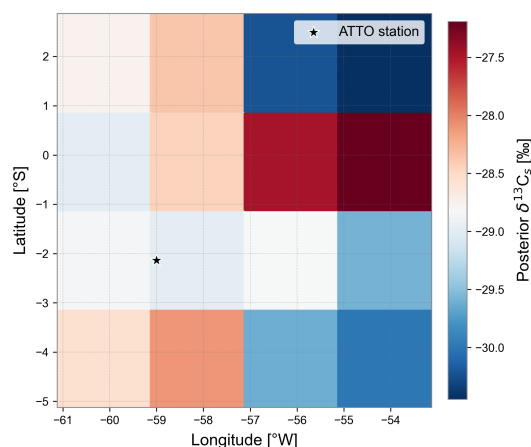


Figure A6. Posterior spatial $\delta^{13}\text{C}_s$ source signature field. Posterior $\delta^{13}\text{C}_s$ values show moderate spatial deviations from the prior, reflecting the spatial information inferred from the time-varying footprint sensitivity. Because CO_2 fluxes are prescribed as spatially uniform, the posterior field should be interpreted as an effective source signature pattern conditional on the transport footprints, not as an estimate of spatially varying CO_2 fluxes.

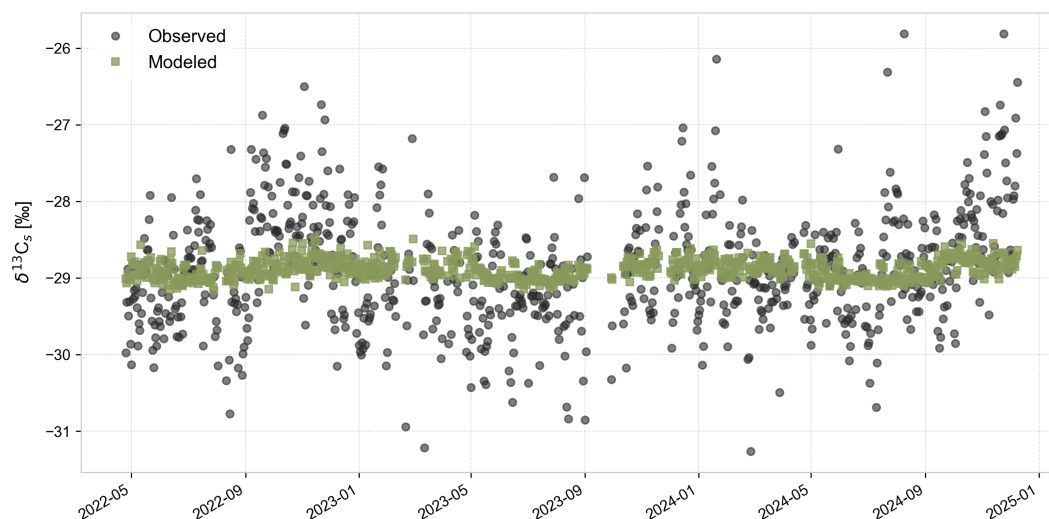


Figure A7. Comparison of observed and footprint-based posterior $\delta^{13}\text{C}_s$ time series. The posterior modelled source signatures remain close to the prior value and show substantially weaker temporal variability than the observed Keeling-plot source signatures. This indicates that changing footprint sensitivity explains only a small part of the observed variability, supporting the interpretation that most of the $\delta^{13}\text{C}_s$ variability reflects temporal changes in biospheric exchange processes.

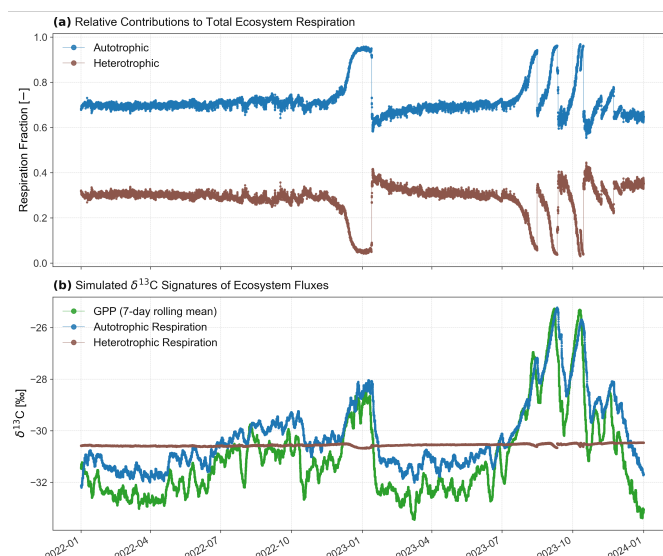


Figure A8. Temporal variability in the simulated partitioning and isotopic composition of ecosystem carbon fluxes in QUINCY. (a) Relative contributions of autotrophic and heterotrophic respiration to total ecosystem respiration. (b) Simulated $\delta^{13}\text{C}$ signatures of GPP, autotrophic respiration, and heterotrophic respiration; the GPP signature is shown as a 7-day rolling mean.

A7 Partitioning of gross fluxes in QUINCY

A8 Correlation to environmental drivers

To quantify which environmental variables explain the variability in the inferred $\delta^{13}\text{C}$ source signature, we analyse the correlation to environmental drivers and fit multilinear regression models to the observed and modelled $\delta^{13}\text{C}_s$ time series. Candidate predictors included proxies for photosynthetic activity, atmospheric dryness (VPD), radiation, temperature, precipitation, and soil-water availability as described in Sect. 2.4. All predictors were aggregated to the same temporal resolution as the $\delta^{13}\text{C}_s$ estimates before fitting. Because several environmental drivers covary seasonally, the regression results are interpreted as an empirical measure of explanatory power.

In addition to regressions using the absolute values of the environmental drivers, we also tested regressions based on temporal changes in the drivers. These change-based predictors were used to assess whether $\delta^{13}\text{C}_s$ variability is more closely related to transitions in ecosystem state than to the absolute monthly mean state (see Fig. A11 and Fig. A9).

To compare alternative predictor combinations, we used the Akaike information criterion (AIC; Akaike, 1974). The AIC provides a measure of relative model quality by balancing goodness of fit against model complexity. Models with more predictors can achieve lower residual errors simply because they contain more degrees of freedom; the AIC penalizes this additional complexity and therefore helps identify predictor combinations that improve the fit without overfitting the data. For each set of candidate models, we select the model with the lowest AIC as the preferred empirical model. We report the selected pre-

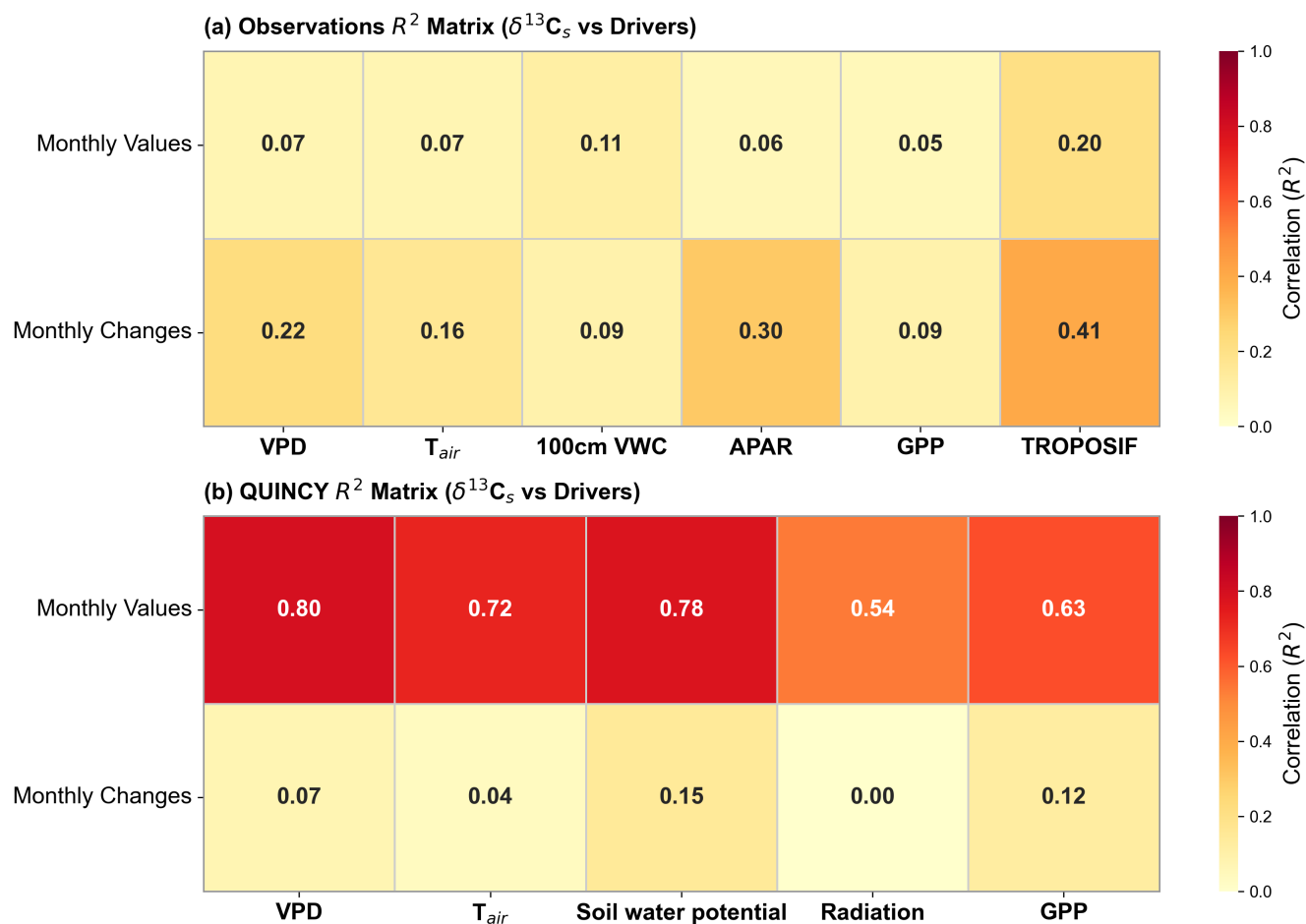


Figure A9. R^2 of $\delta^{13}\text{C}$ source signatures over environmental drivers for the years 2022 and 2023. Heat maps show R^2 values for raw monthly drivers and monthly driver changes. QUINCY is best explained by raw drivers, whereas the observations show higher R^2 values for several driver-change relationships.

dictors together with the explained variance to compare how well environmental drivers account for $\delta^{13}\text{C}_s$ variability in the observations and in QUINCY (see Fig. A10).

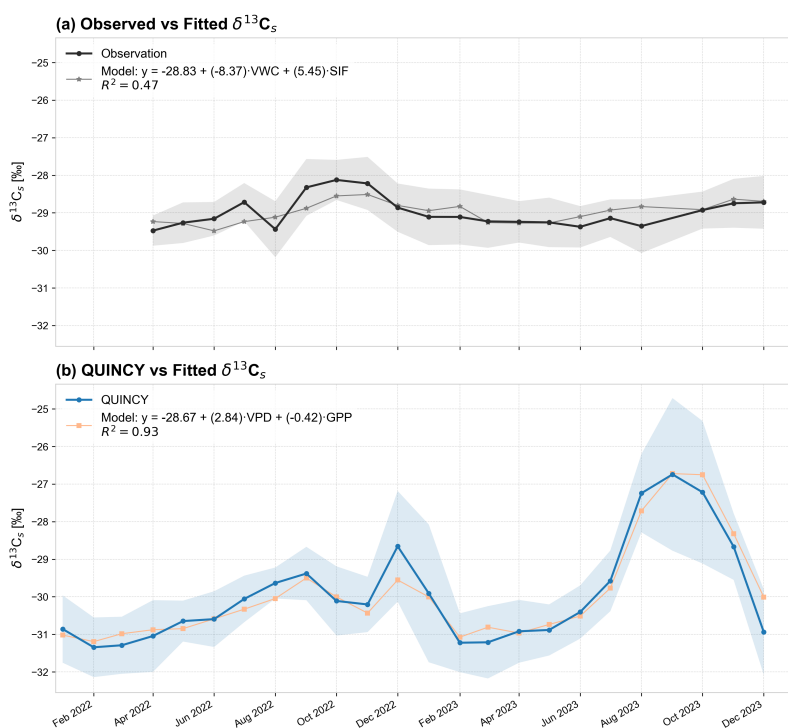


Figure A10. Observed and modelled monthly $\delta^{13}\text{C}_s$ compared with the predictions of the AIC-selected multilinear regression models. Panel (a) shows the observations and the model based on soil volumetric water content at 100 cm depth and TROPISIF. Panel (b) shows QUINCY and the model based on VPD and GPP.

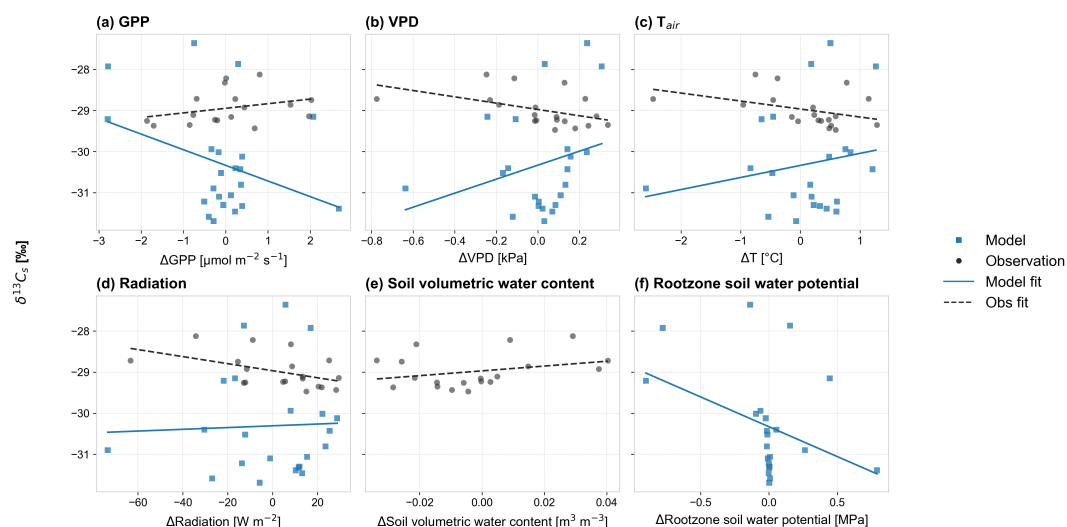


Figure A11. Correlations between monthly $\delta^{13}\text{C}_s$ and month-to-month changes in selected drivers for the ATTO observations and QUINCY simulations. The figure shows the driver analysis based on absolute monthly driver values and illustrates the contrasting behaviour between observations and model: observed $\delta^{13}\text{C}_s$ shows stronger relationships with changes in several drivers, including VPD, TROPOMI-SIF, air temperature, and APAR, whereas QUINCY $\delta^{13}\text{C}_s$ is more strongly structured by the absolute seasonal driver state. The relationships are empirical and are used to assess whether changes in ecosystem and atmospheric conditions contain additional information on $\delta^{13}\text{C}_s$ variability beyond the monthly mean environmental state.



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