

THE IMPORTANCE OF CO₂ VARIATIONS FOR INFORMED CLIMATE ACTION

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The concentration of carbon dioxide (CO₂) in the atmosphere is rising steeply but on top of this trend is an annual variation: CO₂ peaks in spring each year and falls to a minimum every summer. This decrease is caused by high net uptake by the European land ecosystems in spring and summer, which removes CO₂ from the atmosphere. Further, the annual differences in weather cause year-to-year and regional variations in the uptake of CO₂. Fossil fuel emissions also vary in time and space. The ICOS measurements covering Europe detect these changes. To correctly interpret the effects of climate actions taken, we need long-term data showing both the fossil fuel changes and the natural fluxes.

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Over decades, atmospheric observations have shown an accelerating trend of increasing CO₂ concentration, called the "atmospheric growth rate". The aim of the ICOS Atmosphere Network goes far beyond monitoring this long-term trend in greenhouse gas concentrations. Since the atmosphere is mixed well over the globe within a few months to a year, the atmospheric growth rate is a signal that integrates emissions from all over the world.

However, there are seasonal and regional variations in the fluxes that modify the atmospheric greenhouse gas concentration on top of the long-term trend. This information can be analysed on several time scales, mainly revealing daily and seasonal patterns. It is possible to derive information on human-induced emissions as well as on biogenic greenhouse gas

fluxes of land ecosystems and of oceans at regional scale. The following analysis provides examples of information directly drawn from atmospheric observations.

CO₂ is measured in 'parts per million' (ppm) meaning the number of CO₂ molecules in one million air molecules. As shown in Figure 2, all stations show a very similar long-term trend of a 2.3 ppm per year increase over the period 2017–2021. This trend is caused by the global imbalance between CO₂ emissions linked to human activities and carbon dioxide removal by oceans and land ecosystems.

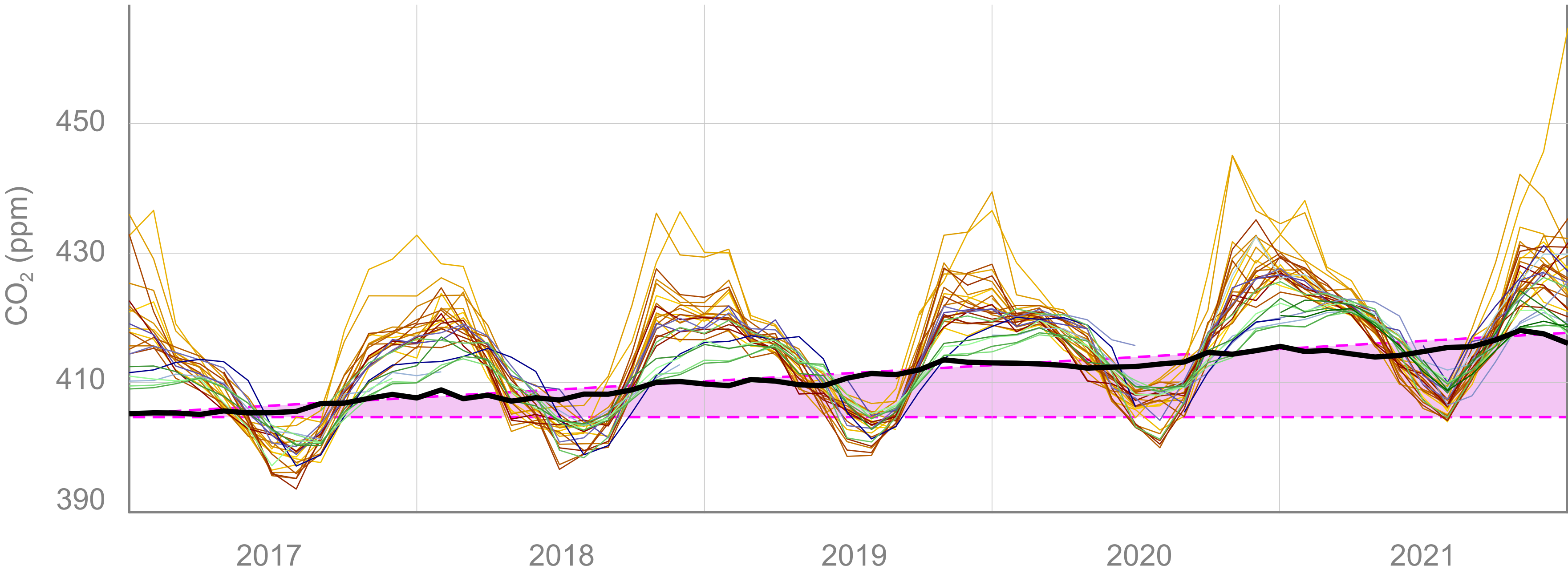
This steady increase shows that all attempts to reduce the risks of ongoing climate change, by mitigating CO₂ emissions on the global scale have failed so far.

HOW DOES ICOS OBSERVE THE ATMOSPHERE?

The European greenhouse gas observations evolved strongly with the establishment of the ICOS research infrastructure. Currently, 36 certified atmosphere stations are continuously recording the carbon dioxide (CO₂) and methane (CH₄) concentrations, as well as a set of meteorological parameters and nitrous oxide (N₂O) at some stations. Many of the stations were established in the ICOS network within the last 10 years, while some have been measuring CO₂ for decades. All stations have adopted standardised measurement, calibration, and quality control protocols to optimise data compatibility, increase traceability, and facilitate the dissemination of measurements. ICOS performs very accurate and precise measurements. The stations are of three types: tall tower stations on the plain land, coastal stations targeting predominantly marine air masses, and mountain stations targeting predominantly free tropospheric air. All stations make continuous hourly measurements. However, to improve the larger spatial representativeness, selective averaging of the data is done: daily averaging of data from continental and coastal stations is done for the daytime hours when the atmosphere is vigorously mixed. Meanwhile, the mountain station data are averaged for the nighttime values to avoid the daytime upwelling of air from the valleys.

Figure 2 Monthly average CO₂ concentrations measured at 36 ICOS stations between 2017 and 2021.

The legend indicates the station's code, and the sampling height in meters above ground. The black line corresponds to the station on the island of Réunion, in the Indian Ocean, the only ICOS site in the southern hemisphere. This station was not exposed either to biogenic nor anthropogenic fluxes, taking place mostly on the northern hemisphere, resulting in a very weak seasonal cycle. Thus, it shows the overall global trend (highlighted by the pink area).



Tower Sites					Mountain Sites			Coastal Sites			Southern Site	
BIR_75.0m	IPR_100.0m	LIN_98.0m	OXK_163.0m	SMR_125.0m	CMN_8.0m	PUY_10.0m	HEL_110.0m	WAO_10.0m	<div>Overall global trend</div>			RUN_6.0m
GAT_216.0m	JUE_120.0m	LUT_60.0m	PUI_84.0m	STE_187.0m	JFJ_5.0m	SSL_12.0m	LMP_8.0m	WES_14.0m				
HPB_131.0m	KIT_200.0m	NOR_100.0m	RGL_90.0m	SVB_150.0m	PAL_12.0m	ZSF_3.0m	SNO_85.0m	ZEP_15.0m				
HTM_150.0m	KRE_250.0m	OPE_120.0m	SAC_100.0m	TOH_147.0m	PRS_10.0m		UTO_57.0m					
				TRN_180.0m								


THE IMPORTANCE OF LONG-TERM OBSERVATIONS

While all ICOS stations show a very similar increase in CO₂ over the last years, the seasonal cycles show notable differences from station to station (Figure 2). The seasonal amplitudes in Europe are different for mountain sites (amplitude of 11.7±1.3 ppm) and continental and marine sites (amplitude 20.3±2.7 ppm) in particular.

The variation results from the difference in exposure of these stations to regional fluxes, and to the seasonal dynamics of atmospheric mixing. The high winter concentrations correspond to the accumulation of CO₂ emitted by anthropogenic and land ecosystem sources, exceeding uptake by ecosystems and oceans.

Conversely, the lowest concentrations observed each year in summer result from the absorption of carbon by terrestrial ecosystems. The seasonal decrease in CO₂ starts each year in spring when the vegetation in the northern hemisphere becomes a net carbon sink.

The case of the Réunion station (RUN in Figure 2) in the Indian Ocean is totally different, since this station is located in the southern hemisphere on an island at more than 2,100 m above the sea level. It is not strongly exposed to natural and anthropogenic fluxes that take place mostly in the northern hemisphere. This explains the very weak seasonal variation (amplitude of 1.5 ppm).



The amount of CO₂ in the atmosphere depends on the year-to-year changes in the weather and the response of natural sinks to climate change.

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The precise continuous measurements from the ICOS network are used to characterise the inter-annual differences in amplitude and phase of the seasonal cycles at each measurement site, as illustrated in Figure 3 for the Torfhaus station located in Germany. Focusing on the period of vegetation growth between April and September, differences can be spotted especially for the years 2018 and 2021 compared to the 5-year average. In 2018 (orange curve), an early drop in CO₂ concentration was observed between April and June, but the summer minimum was 15 % above the average. In 2021 (green curve), an opposite signal was recorded, with a slightly later decrease in atmospheric CO₂ concentrations, but a more pronounced minimum in August.

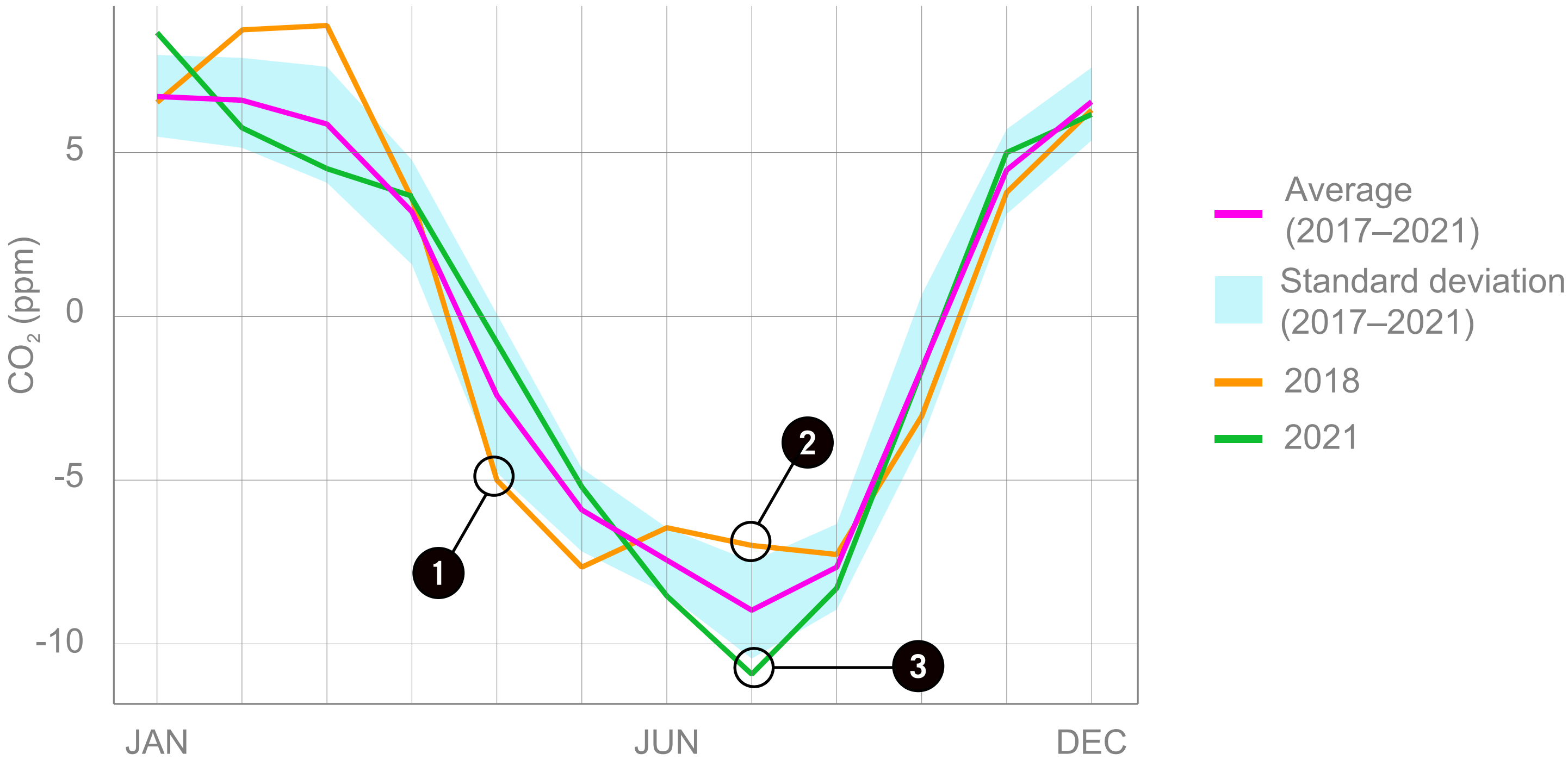


Figure 3 CO₂ seasonal cycles calculated from daytime measurements at the Torfhaus tower station (147 meters above ground level), Germany.

The mean seasonal cycle is represented as a pink line, with the light blue area showing the standard deviation (2017–2021). The cycle is characterized by a drop in concentration during spring and summer and an increase in autumn. Seasonal cycles observed in 2018 and 2021 are represented in orange and green respectively.

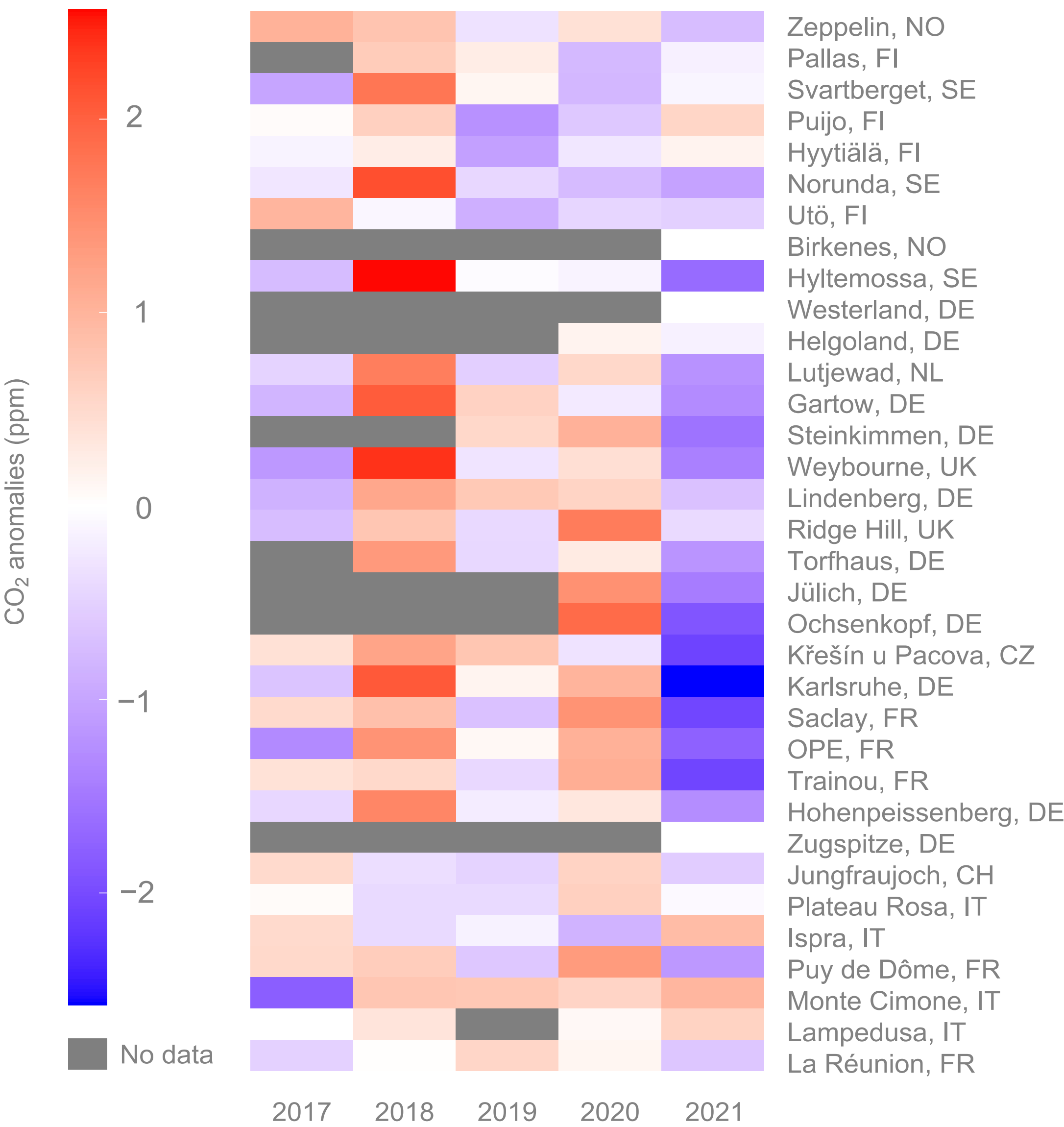
- ❶ 2018 had a warm and sunny spring. Due to the resulting high CO₂ uptake by the vegetation the concentration dropped early.
- ❷ During summer, a drought period dimmed the uptake resulting in a summer minimum smaller than usual.
- ❸ In 2021, the high precipitation supported the CO₂ uptake by the vegetation, resulting in a minimum larger than usual.

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Similar summer anomalies (deviations from the average) have been calculated for all ICOS atmosphere stations by subtracting the mean seasonal concentration in July–August observed in a given year to the same property averaged over the available monitoring period after the long-term trend was removed. In the case of Torfhaus this leads to a summer (July–August) anomaly of +1.3 ppm in 2018, and of -1.2 ppm in 2021. The summer anomalies calculated for all ICOS stations are summarized in Figure 4. It is interesting to note that signals similar to those recorded at the Torfhaus station are found at many stations. The density of the ICOS monitoring network allows for the retrieval of regional patterns regarding the impact of meteorological anomalies on atmospheric CO₂ concentrations over Europe.


Figure 4 CO₂ summertime (July–August) anomalies, 2017–2021.

The stronger the red colour is, the less there has been CO₂ uptake during the period. The stronger the blue, the more the vegetation has taken up CO₂. The picture also shows that most ICOS stations observed small CO₂ uptakes in year 2018; this is most probably due to the drought experienced in Europe in that summer. The stations are listed in order of latitude from north to south.



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The 2018 anomaly observed in western and northern Europe can be explained by increased productivity due to the warm spring, followed by an extreme summer drought and heat wave, resulting in a decrease in the net productivity of terrestrial ecosystems. The pronounced summer depletion in atmospheric CO₂ concentrations during the summer of 2021 resulted most probably from cool and wet conditions over a large part of western Europe, increasing carbon uptake in the ecosystems over this region.

The southern Italian atmospheric sites (IPR, CMN, LMP) showed positive CO₂ anomalies related to the hot and dry summer conditions affecting Italy in the summer of 2021 and already shown in Figure 1B. 

The steep increase of the CO₂ concentration in the atmosphere, primarily driven by fossil fuel emissions, is not linear. Seasonal and regional variations in the fluxes modify the signal. The modified signal can be used to identify larger or smaller than normal variations in natural fluxes or changes in human-induced emissions. However, since these fluxes are mixed in the atmosphere, we need to thoroughly interpret these CO₂ variations: is it perhaps just dry weather, a particularly warm spring, less traffic, or reduced fossil fuel emissions due to increased renewable energy or a pandemic lockdown? In any case, CO₂ variations in the atmosphere contain valuable information for informed, and eventually successful, climate action.