FLUXES

The European Greenhouse Gas Bulletin

Volume #1-2022

ARE CARBON SINKS AT RISK?

http://fluxes.science

A publication by ICOS Integrated Carbon Observation System

EDITORIAL

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Imagine the atmosphere as a reservoir containing a powerful greenhouse gas, carbon dioxide (CO_2), the level of which has a serious impact on our climate. What determines this level? Fluxes! Fluxes of CO_2 from various sources into the atmosphere and fluxes from the atmosphere into other reservoirs, the so-called carbon sinks, like the ecosystems on land and in the ocean. These fluxes give the European Greenhouse Gas Bulletin, FLUXES its name.

To understand what drives the concentration of CO_2 in the atmosphere, it is crucial to understand the complexity of the underlying CO_2 fluxes, and this first volume of FLUXES will inform you about this. FLUXES is a new publication designed to inform the interested audience of key scientific aspects regarding the European greenhouse gas budget. FLUXES will be published every summer to support the European Union in their preparation for the upcoming UNFCCC Conference of Parties and to guide European climate action in general. As researchers, we are convinced that scientific knowledge based on systematic observations is the foundation of climate action. All fluxes, whether natural or created by humans, whether related to ocean or land, ultimately produce changes in greenhouse gas concentrations in the atmosphere. The monitoring of these concentrations is consequently the ultimate proof that climate action has succeeded – or failed.

Greenhouse gas fluxes vary from year to year, that's natural. However, Europe and the world are currently facing multiple hazards (heatwaves, droughts, fires, floods…) that are driven by climate change and – among many other damages – are altering greenhouse gas fluxes. These feedbacks put particularly natural CO_2 sinks at risk but it requires monitoring over long times to clearly identify and understand them.

FLUXES, the European Greenhouse Gas Bulletin aims to transfer most recent scientific findings in order to distinguish occasional phenomena from long-term trends. It will focus

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on observations as the basis of a scientific value chain towards climate services and policy support. The Integrated Carbon Observation System (ICOS), as part of global observing networks, makes these observations in its rapidly expanding network of measuring stations across the European continent. The ICOS high-precision data are available for the scientific community within 24 hours. They are then further interpreted using statistical analyses and used in advanced models. Eventually, the generated scientific knowledge is thoroughly assessed, e.g. by the Intergovernmental Panel on Climate Change (IPCC) and taken up by decision-makers to design climate action.

Just from the initial data, it is already possible to have a reliable estimate of the recent developments of the carbon cycle of Europe. This information is very useful for preparing a science-based European position in policy negotiations. Observations can already answer questions like 'Has there been an acceleration of the increase of greenhouse gases in the atmosphere?', or 'Has extreme weather in Europe influenced the carbon cycle of ecosystems and, consequently, changed their ability to store carbon?'.
We hope that FLUXES will help to provide some of these answers and that it will be a valuable contribution for the organisations in charge of finding our common way into a sustainable future.

"With natural sinks at risk and technological solutions to remove carbon dioxide from the atmosphere being still highly uncertain, policy-makers need to drastically reduce fossil fuel emissions to keep the 1.5°C target of the Paris Agreement."

SUMMARY

FLUXES by ICOS

ICOS, the Integrated Carbon Observation System, is a European-wide greenhouse gas research infrastructure: ICOS produces standardised data on greenhouse gas concentrations in the atmosphere, as well as on carbon fluxes between the atmosphere, the ecosystems, and the oceans. This ICOS-based knowledge supports policy- and decision-making to combat climate change and its impacts.

The high-quality ICOS data is based on the measurements from over 150 observation stations – funded by top universities and research institutions across 15 European countries – and produced by the roughly 500 scientists in the community. The ICOS Carbon Portal offers unlimited access to thousands of datasets and other advanced digital products.

ICOS has the status of an ERIC, European Research Infrastructure Consortium, with a legal capacity recognised in all countries within the European Union. The inter-governmental organisation is financed by its member countries: Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom, (Ireland as of Jan 1st 2023).
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UNDERSTANDING GREENHOUSE GASES TO SUPPORT CLIMATE ACTION

Photo: nblxer / Adobe Stock

The climate crisis with increasing global temperatures is a consequence of increasing greenhouse gas concentrations in the atmosphere. The concentration of carbon dioxide, the most important greenhouse gas in the atmosphere, is driven by three major fluxes:

1. Release and uptake by land ecosystems.
2. Release and uptake by the ocean.
3. CO_2 emissions from fossil fuel burning.

The land ecosystems and oceans are 'natural sinks' as they have taken up half of the fossil fuel emissions to date. Whether this remains the case in the near and distant future is far from certain.

by **Dr Philippe Ciais** & **Dr Werner L. Kutsch**

Disentangling the three drivers of the atmospheric CO_2 concentration and understanding each of them is crucial to support climate action.

On the next page each of the three fluxes over Europe in 2021 is shown in a separate map. The maps show annual results. Blue areas symbolise net carbon uptake during the year, reducing the CO_2 load of the atmosphere. Red areas symbolise net carbon loss adding additional CO_2 to the atmosphere.

Land ecosystem fluxes over Europe show a complex pattern of net CO_2 uptake or release. In regions with net uptake (blue), the uptake by photosynthesis over the year was higher than the release by respiration. In red regions it was vice versa: the carbon stored in the ground was released to the atmosphere.

The ocean fluxes are small compared to land fluxes and emissions but it has to be taken into account that oceans cover about 70% of the Earth's surface. That makes oceans an important sink compensating for about one quarter of the global anthropogenic emissions.

The map of fossil fuel emissions shows only red areas. Highest emissions are located in industrial and highly populated areas (cities). Emissions from marine transport can be seen on the major shipping routes. These maps are highly-integrated products based on observations, inventory data and models.

They reveal that we produce more emissions than the natural sinks can take up, meaning that European efforts towards carbon neutrality have not been very successful in 2021. The natural carbon sinks have become more vulnerable; land and oceans sinks are impacted by climate change. We need to radically reduce fossil fuel emissions, rather than rely on natural sinks.

> *"The natural carbon sinks have become more vulnerable; land and oceans sinks are impacted by climate change. We need to radically reduce fossil fuel emissions, rather than rely on natural sinks.*

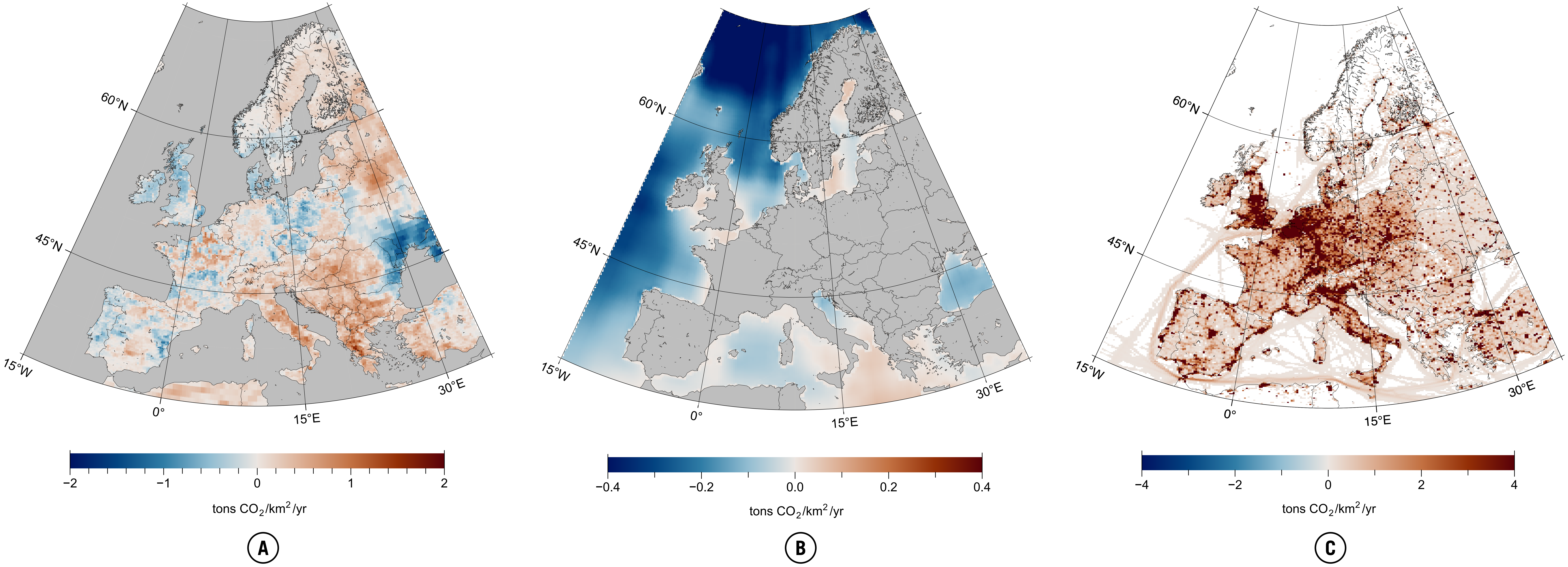


Figure 1 The three major CO_2 fluxes for Europe and adjacent ocean areas in 2021: (A) Biogenic fluxes of land ecosystems, (B) Ocean fluxes, (C) Human emissions of fossil fuels.

(A) Biogenic fluxes of land ecosystems. This map shows the complex pattern of land ecosystem fluxes over Europe. Blue areas symbolise net carbon uptake during the year, reducing the CO_2 load of the atmosphere. Red areas symbolise net carbon loss adding additional CO_2 to the atmosphere. Italy, most of the Balkan States, Scandinavia and the Baltic countries showed carbon losses mainly due to hot and dry summer conditions. (B) Ocean fluxes. This map shows a strong carbon sink in the open ocean while coastal areas as well as the Baltic and the Mediterranean seas show a more complex pattern of both sources and sinks. (C) Human emissions of fossil fuels. This map shows the spatial distribution of fossil fuel emissions. Highest emissions are located in industrial and highly populated areas (cities). Emissions from marine transport can be seen on the major shipping routes.

These maps are highly-integrated products based on observations, inventory data and models. Note that the flux scales of the maps are different: the same colour is twice as high in fossil fuel emissions than land ecosystem fluxes, and ten times higher than ocean fluxes.

THE IMPORTANCE OF CO_2 VARIATIONS FOR INFORMED CLIMATE ACTION

Photo: Adam Radosavljevic / Adobe Stock

The concentration of carbon dioxide (CO_2) in the atmosphere is rising steeply but on top of this trend is an annual variation: CO_2 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 CO_2 from the atmosphere. Further, the annual differences in weather cause year-to-year and regional variations in the uptake of CO_2. 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.

by **Dr Michel Ramonet** (lead writer), **Dr Paolo Cristofanelli, Dr Marc Delmotte, Dr Dagmar Kubistin, Dr Martin Steinbacher**

Over decades, atmospheric observations have shown an accelerating trend of increasing CO_2 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.

CO_2 is measured in 'parts per million' (ppm) meaning the number of CO_2 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 CO_2 emissions linked to human activities and carbon dioxide removal by oceans and land ecosystems.

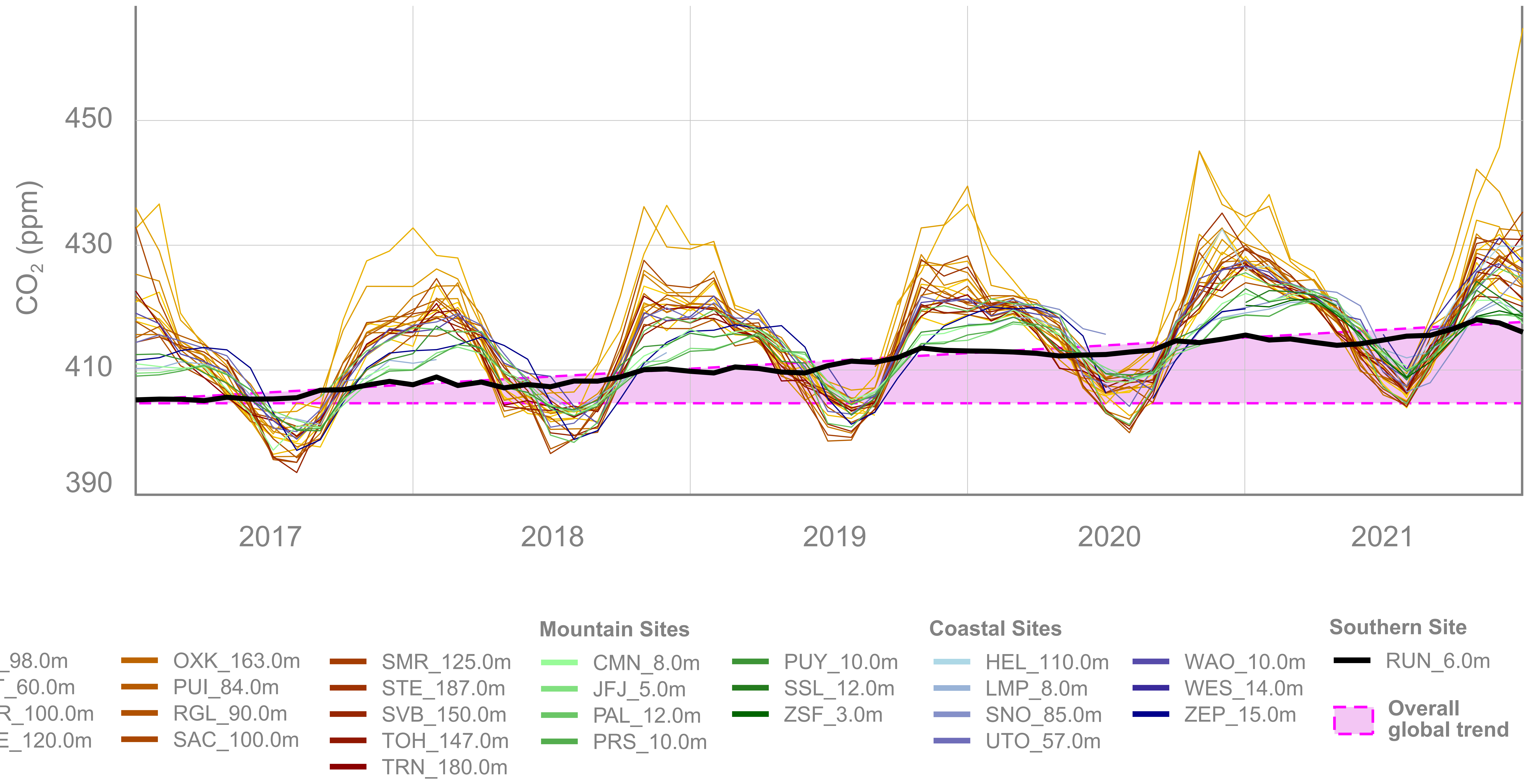
This steady increase shows that all attempts to reduce the risks of ongoing climate change, by mitigating CO_2 emissions on the global scale have failed so far.

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 (CO_2) and methane (CH_4) concentrations, as well as a set of meteorological parameters and nitrous oxide (N_2O) at some stations. Many of the stations were established in the ICOS network within the last 10 years, while some have been measuring CO_2 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 CO_2 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).



THE IMPORTANCE OF LONG-TERM OBSERVATIONS

While all ICOS stations show a very similar increase in CO_2 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 CO_2 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 CO_2 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 is the northern hemisphere. This explains the very weak seasonal variation (amplitude of 1.5 ppm).

> *The amount of CO_2 in the atmosphere depends on the year-to year changes in the weather and the response of natural sinks to climate change.*

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 CO_2 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 CO_2 concentrations, but a more pronounced minimum in August.

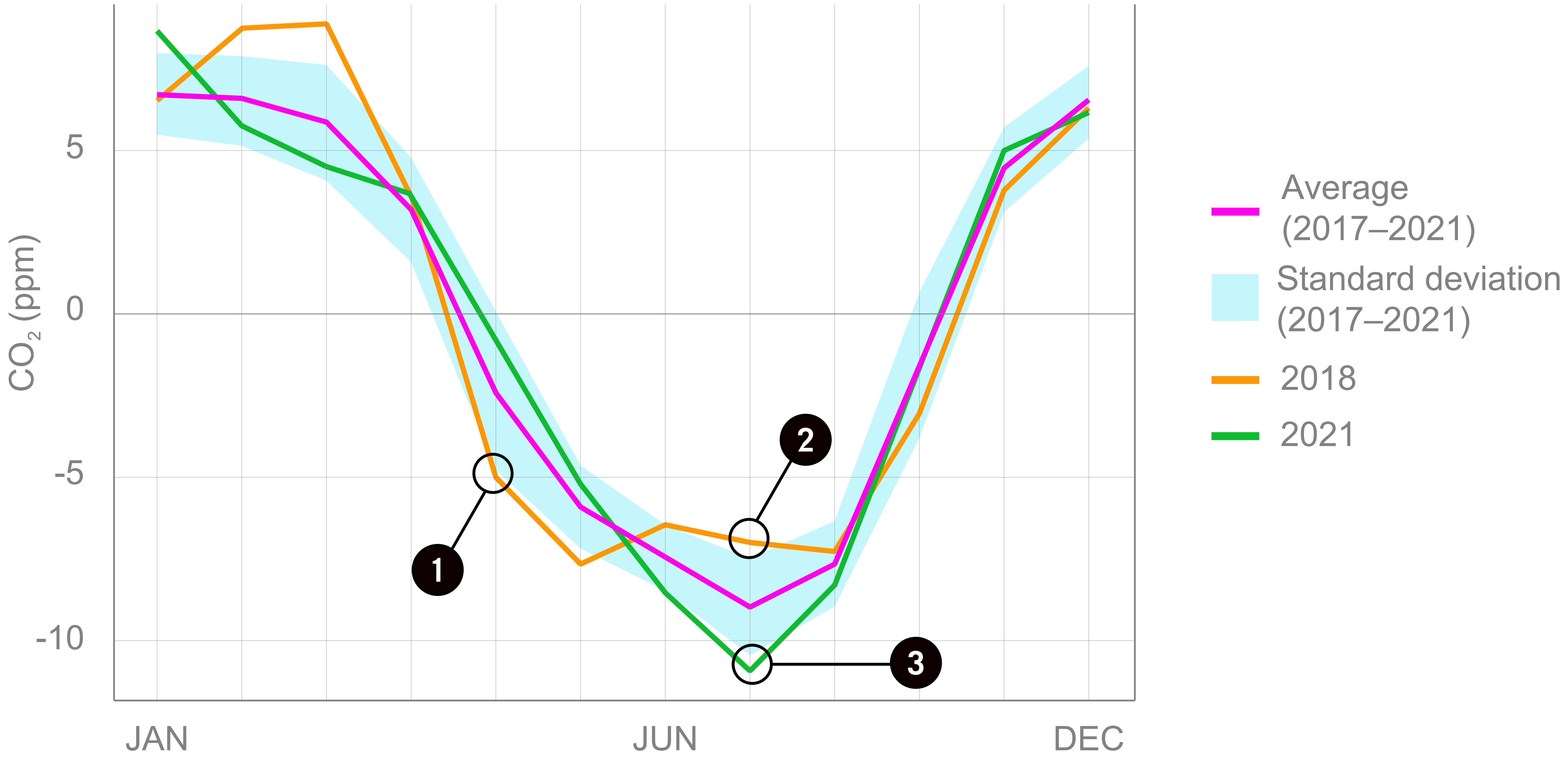


Figure 3 **CO_2 seasonal cycles calculated from daytime measurements at the Torfhaus tower station (147 meters above ground level), Germany.**

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.

1. 2018 had a warm and sunny spring. Due to the resulting high CO_2 uptake by the vegetation the concentration dropped early.
2. During summer, a drought period dimmed the uptake resulting in a summer minimum smaller than usual.
3. In 2021, the high precipitation supported the CO_2 uptake by the vegetation, resulting in a minimum larger than usual.

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 CO_2 concentrations over Europe.

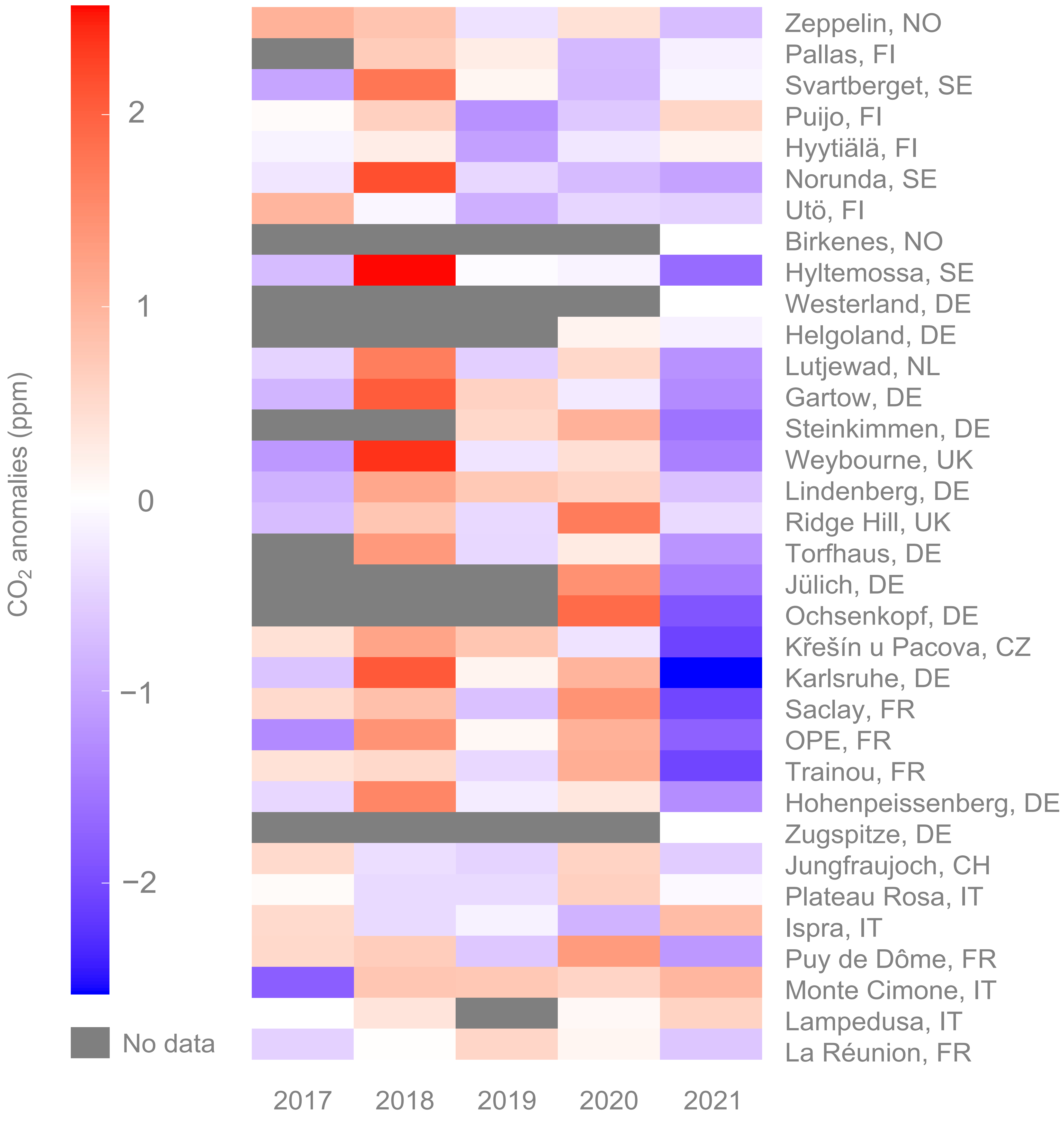


Figure 4 **CO_2 summertime (July—August) anomalies, 2017—2021.**

The stronger the red colour is, the less there has been CO_2 uptake during the period. The stronger the blue, the more the vegetation has taken up CO_2. The picture also shows that most ICOS stations observed small CO_2 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.

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 CO_2 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 CO_2 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 CO_2 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 CO_2 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, CO_2 variations in the atmosphere contain valuable information for informed, and eventually successful, climate action.

THE DELICATE BALANCE OF LAND CARBON SINKS

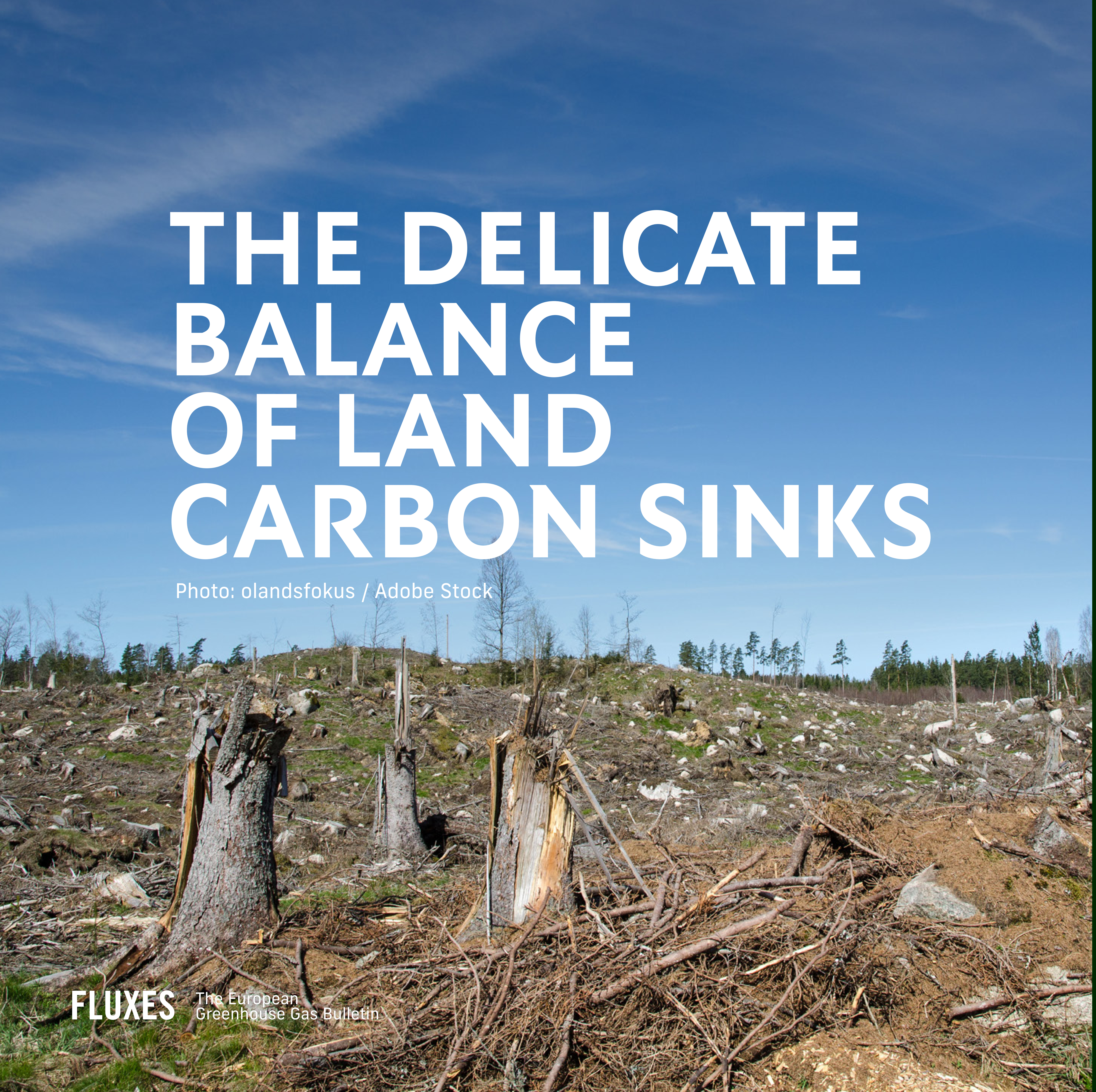


Photo: olandsfokus / Adobe Stock

Ecosystems capture carbon dioxide (CO_2) from the atmosphere and store it in vegetation and soil. They also release CO_2 via plant and soil respiration or fires. If the CO_2 uptake is larger than the release, an ecosystem acts as a net sink. This delicate balance can be easily disturbed by human actions such as cutting forests, clearing green areas for housing or roads, or by agricultural practices depleting carbon from the soil. The balance is also very sensitive to climate change. ICOS data show how the ecosystems respond to changes in climate and land use. Land sinks weakening or turning into sources can seriously hamper societal efforts to reach carbon neutrality.

by **Dr Jutta Holst** & **Dr Bert Gielen** (lead writers), **Prof. Giacomo Gerosa**

Europe is covered by a complex mosaic landscape of ecosystems differently influenced by human management: forests, grasslands, wetlands but also managed areas such as croplands, settlements, urban and industrial areas or roads. Each ecosystem has its own carbon cycle and exchange pattern of the main greenhouse gases (carbon dioxide CO_2, methane, CH_4 and nitrous oxide, N_2O) with the atmosphere.

The fluxes of greenhouse gases between land ecosystems and the air above cause concentration changes in the atmosphere as shown in the previous chapter. The dense ICOS network of ecosystem observations should be able to confirm the atmospheric observations and provide deeper insights into the response of ecosystems to regional weather conditions. Terrestrial ecosystems have a major influence on the CO_2 concentration in the atmosphere (Figures 2 and 3). The decreasing concentrations during the European spring and summer show how efficiently photosynthesis can remove CO_2 from the atmosphere. However, its counterpart, the process of respiration, emits CO_2 and brings balance in autumn by mineralising most of the organic material that has been built. Only few ecosystems are strong net sinks, among them forests where carbon fixed by photosynthesis is stored in the wood of the growing trees and in the soil.

The balance between photosynthesis and respiration is called NEE (net ecosystem exchange). A negative NEE indicates a CO_2 flux from the atmosphere into the ecosystem or an uptake by the ecosystem.
NEE is usually calculated on a half-hourly or daily time step and accumulated through the year (ΣNEE).

HOW DOES ICOS OBSERVE THE ECOSYSTEMS?

The ICOS ecosystem network consists of flux towers monitoring the CO_2 exchange between the vegetation and the atmosphere. The technology uses fast measurements of vertical wind speed and CO_2 concentration in the air, and can distinguish between air particles transported from the atmosphere downwards into the ecosystem, and air parcels moving upwards from the ecosystem into the atmosphere. The difference in CO_2 concentration between up and down flowing air parcels allows to calculate whether the ecosystem takes CO_2 up or releases CO_2 to the atmosphere.

The driver of uptake is photosynthesis and growth of plants; the driver of CO_2 release is respiration by plants, animals and microorganisms. In many ecosystems the uptake by photosynthesis is higher than the release by respiration. The ecosystem then stores carbon (e.g. as wood) and is, thus, a sink for atmospheric CO_2. The ICOS ecosystem network currently counts 85 stations covering the most prevalent ecosystem types on the European continent and most European climate zones.

The value of ΣNEE by the end of the year shows the annual carbon balance of the ecosystem. The more negative ΣNEE of a certain area is at the end of the year, the larger the annual sink is. The forest of Tharandt in Germany is an example for an ecosystem carbon sink. Figure 5 shows its daily net ecosystem exchange (NEE, green bars) and the cumulative flux (ΣNEE) over the year.

Like all terrestrial ecosystems, the Tharandt forest is influenced by the weather. The drought in 2018 reduced the CO_2 uptake severely while the more favorable conditions in 2021 resulted in higher uptake than usual. Both years deviate from the long-term average.

A view of the Tharandt old spruce forest with the 40 m tower for meteorological and flux measurements.
Photo: Christian Brümmer / ICOS Germany

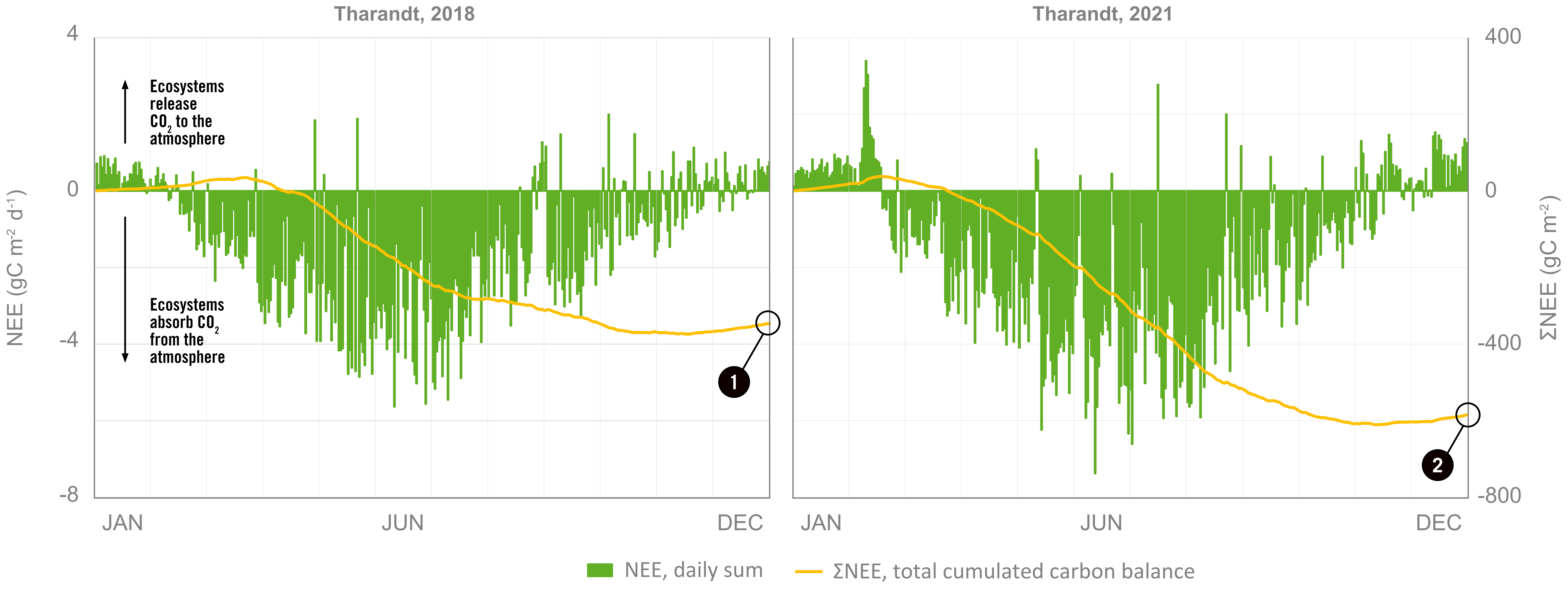


Figure 5 **Net ecosystem exchange (NEE) between a forest ecosystem and the atmosphere (Tharandt, Germany).**

Here, CO_2 fluxes are described from the perspective of the atmosphere: fluxes e.g. from trees to the atmosphere are positive, fluxes from the atmosphere to the vegetation are negative. In the beginning of the year, NEE is positive: the photosynthesis of the trees is hampered by low temperature and the lack of light, while respiration, even during winter, is active (net release of CO_2 to the atmosphere – positive value). During spring and summer, photosynthesis overtakes respiration (net uptake of CO_2 from the atmosphere – negative value). Each green bar describes the daily exchange of carbon. The yellow line symbolises the account balance during the year (ΣNEE, total cumulated carbon balance). Its value by the end of the year shows the annual carbon balance of the forest. The lower the yellow curve ends, the bigger the annual uptake. In both years there was a net uptake of CO_2 by the forest. However, the drought in 2018 reduced the accumulated uptake severely ❶ compared to 2021 ❷.

Figure 6 shows anomalies (deviations) in the summertime uptake (July-August) of forest and wetland ecosystems over a period of five years, expressed as a percent deviation from the long-term average. Red colors mean a lower uptake, blue colors a higher uptake than normal. The stations are sorted along latitudes with the northernmost station on top. The drought in 2018 affected many ecosystems in northern and central Europe and reduced their carbon uptake. Higher rainfall in Central Europe during the summer of 2021 resulted in higher CO_2 uptake by forest ecosystems.

The similar pattern observed by the ICOS ecosystem and atmosphere station networks confirms that we need systematic and integrated observations covering different compartments of the carbon cycle.

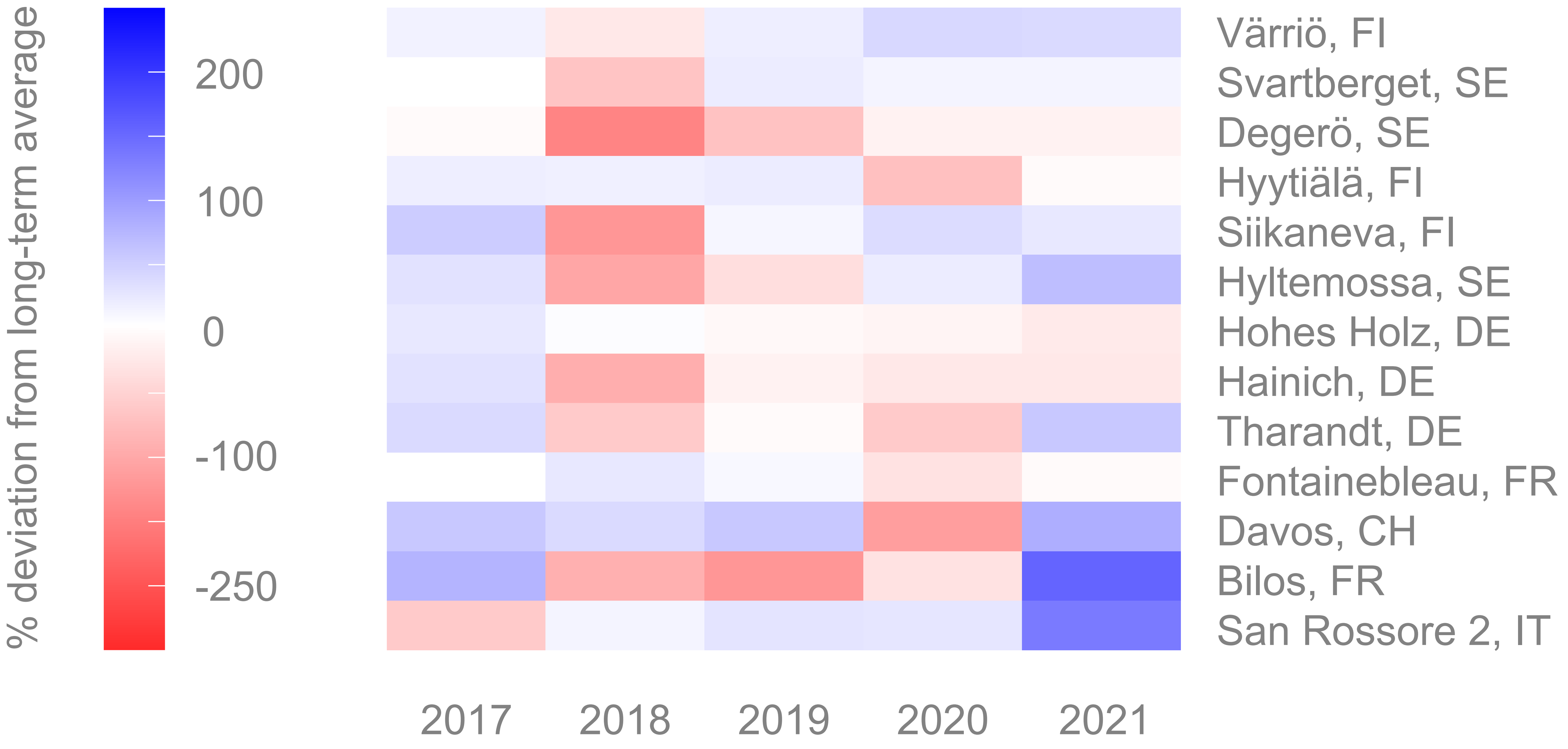


Figure 6 Summertime (July-August) anomalies (deviations from the average) in the uptake of ecosystems over a period of five years (2017-2021).

Only wetland (Degerö, Siikaneva) and forest (all others) stations are shown in this figure in order to minimise human management influences. Stations are shown in order of latitude from north to south. Red colours indicate lower than normal and blue colours higher than normal uptake of CO_2 by the ecosystem.

The year-to-year changes in CO_2 exchange from forest ecosystems are not only driven by weather patterns, but also by natural and human-related disturbances such as insect attacks, storm damage or forest management practices. As an example of the latter, the impact of thinning was observed at the 60-year old Scots pine forest at the forest station of Hyytiälä (Finland).

Thinning during the winter of 2019—2020 reduced the standing biomass by 30 % and resulted in a reduction of the photosynthesis. It turned the forest from a CO_2 sink of 220 g carbon per square meter per year in 2019 into a source of 90 g of carbon. In 2021, the forest had partly recovered, and absorbed again 170 g of carbon from the atmosphere (Figure 7).

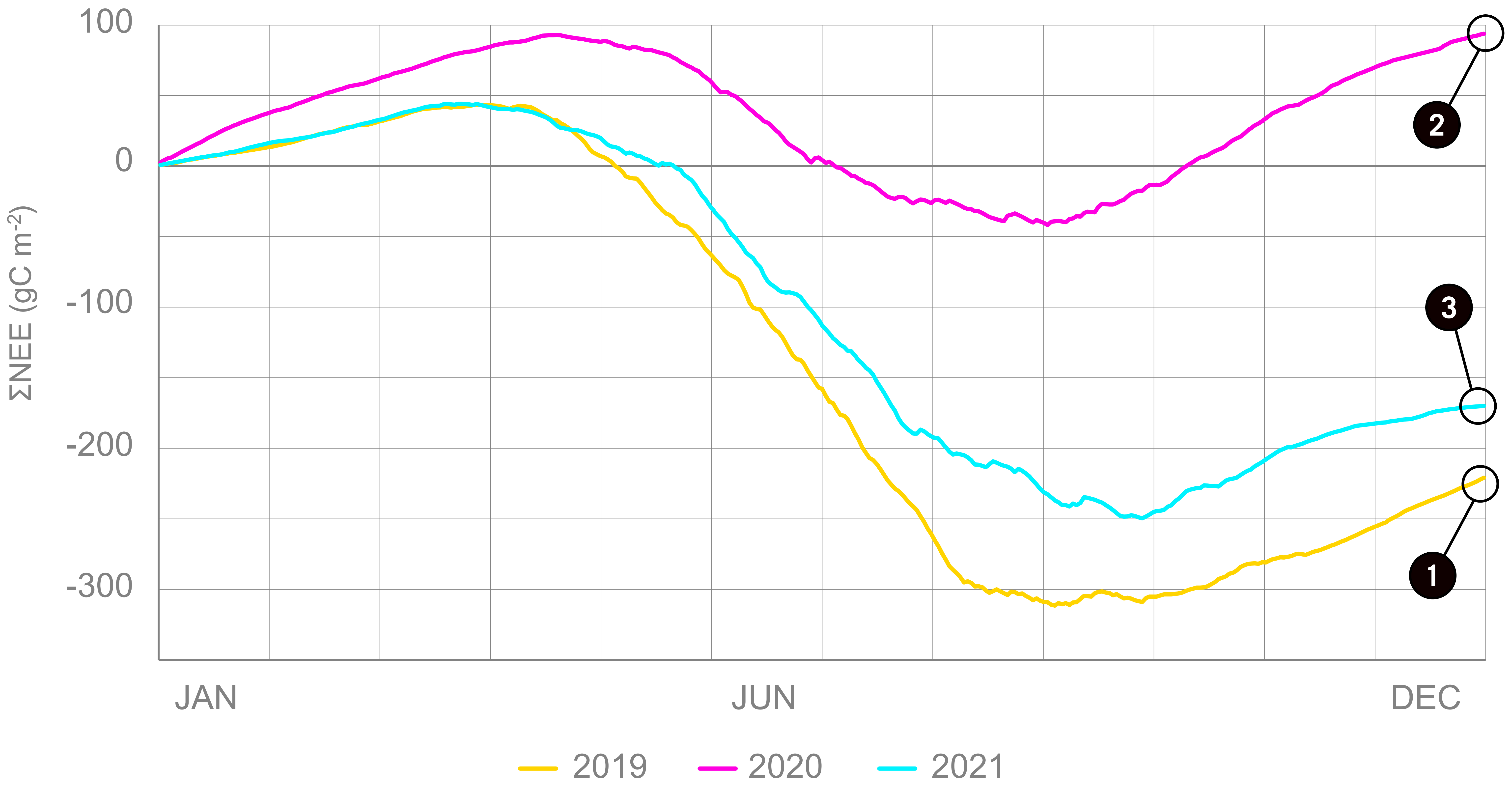


Figure 7 Net ecosystem exchange CO_2 fluxes (ΣNEE) measured over the 60-year old Scots pine forest in Hyytiälä (Finland) for three consecutive years (2019-2021).

Management can severely influence carbon fluxes and the forest's ability to remove carbon dioxide from the atmosphere: the year 2019 represents the typical behaviour over a longer period resulting in an annual uptake of carbon ❶. Thinning during winter 2019—2020 resulted in a reduction of the photosynthesis in 2020 and turned the forest from a sink into a source of carbon ❷. In 2021, the forest had partly recovered and became a sink again ❸.

While this example may show fast resilience after a disturbance, many observations have shown that management decisions can durably change the pattern of carbon uptake and storage.
This, again, increases uncertainties and puts severe risks on using forest carbon sinks in national inventories, or selling them on the carbon market.

To be able to understand the response of ecosystems to management and meteorological conditions, and to verify that intended sinks have indeed been achieved, standardised long-term time series of systematic observations are indispensable.

The carbon cycle of croplands is even more driven by management. Together with weather, the management greatly influences the year-to-year variations in CO_2 exchange (NEE) and the net biome production. NBP also includes management-related carbon fluxes into and out of the ecosystem such as harvest and the spread of manure.

This can be clearly seen in the NEE fluxes from the cropland site in Lonzée, Belgium (Figure 8). In 2020, sugar beet was sown in April, resulting in a clear CO_2 uptake until the crop was harvested in October (1). The field was plowed in November at which point it is turned into a CO_2 source until the end of the year.

The cumulative NEE is now shown as NBP: in addition to summing up NEE throughout the year, the carbon transport out of the ecosystem, causing a sudden increase, is accounted for. Fertilising the field with organic manure, on the other hand, adds carbon into the ecosystem, causing a sudden decrease in the carbon balance.

> *Management decisions can severely change the pattern of carbon uptake and storage. This puts severe risks on using forest carbon sinks in national inventories, or selling them on the carbon market.*

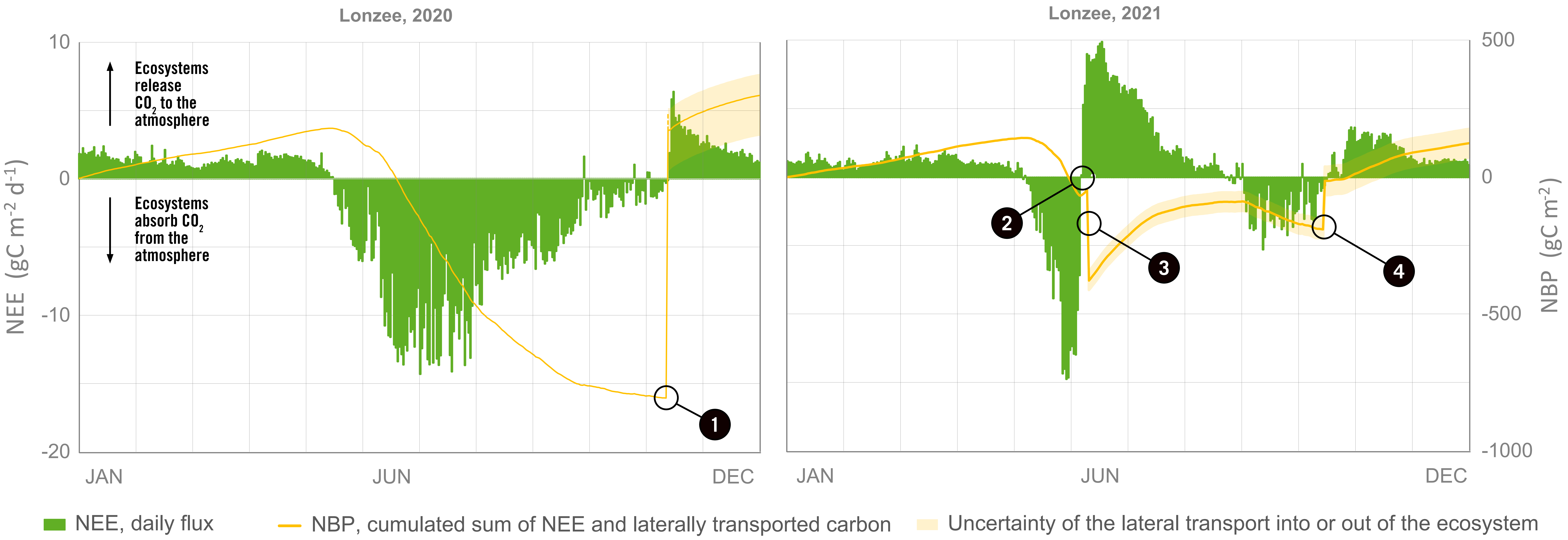


Figure 8 Daily Net Ecosystem Exchange (NEE, green bars) and cumulative Net Biome Production (NBP, orange line) from the ICOS cropland station in Lonzée (Belgium) for 2020 and 2021.

NBP (Net Biome Production) is the cumulative flux throughout the year (ΣNEE) plus the carbon transport out of the ecosystem (harvest), causing a sudden increase, or into the ecosystem (organic manure), causing a sudden decrease. The following management events can be seen in the figures: ❶ Harvest of sugar beet in autumn 2020 causes a sudden increase of the NBP line. The yellow area around the line reflects the uncertainty related to the transfer of carbon out of the ecosystem. ❷ Crushing of the spinach plants in summer 2021 turned the field from CO_2 uptake (negative green bars) to CO_2 release (positive green bars). ❸ Organic manure brought carbon into the field and caused a sudden decrease of the NBP line. ❹ Harvest of beans in autumn 2020 cause a sudden increase of the NBP line.

In April 2021, the farmer sowed spinach, which was harvested in June, but it was crushed and left on site due to oversupply on the market (2). The loss of the green leaves resulted in a halt of photosynthesis and the remaining high respiration turned the NEE into high positive values.

Thereafter, manure was spread (3), which accounted for an addition of carbon to the field and a sudden decrease of the NBP curve, and the field was plowed. In summer, beans were sown after which a new period of net CO_2 uptake started, until the crop was harvested in October (4, sudden increase in the NBP curve). This practice caused the site to switch again from a sink to a source after removal of the vegetation. The example shows that cropland management underlies many influences including market-driven factors that may overrule the target to use croplands as carbon sinks. In fact, in both years shown here the NPB curve ends with a positive value, meaning that the cropland loses carbon to the atmosphere from its soil.

Most strategies toward carbon neutrality are largely based on the assumption that current natural carbon sinks are constant. However, long-term observations show that land ecosystems as carbon sinks are fragile: extreme weather events that are predicted to occur more often, as well as some human actions in forestry or agriculture, are just a few examples of putting the land ecosystem sinks to risk.

Decreasing land sinks will seriously compromise the goal to limit temperature increase to 1,5°C - even more so if carbon dioxide removal technologies do not develop as hoped. Therefore, the best strategy for carbon neutrality is to significantly reduce fossil fuel emissions.

THE OCEAN, OUR ALMOST UNKNOWN HELPER

Photo: Marina Boyarkina/ Adobe Stock

The ocean is a natural sink that takes up about a quarter of fossil fuel emissions each year. However, the ocean's ability to absorb carbon changes from year to year, season to season, and between locations. Generally, the CO_2 exchange between the ocean and the atmosphere varies much more in the coastal areas than in the open ocean. Some areas can even release CO_2. Yet we know too little about the ocean: There are simply not enough observations to fully understand the reasons for the variations in the ocean's ability to absorb carbon, especially when it comes to its future response to climate change.

by **Dr Meike Becker** (lead writer),
Dr Carolina Cantoni, Dr Thanos Gkritzalis,
Dr Anna Luchetta, Prof. Dr Gregor Rehder,
Prof. Anna Rutgersson

The uptake of CO_2 by the oceans is not homogeneously distributed and some ocean areas are even a source of CO_2 (Figure 1). CO_2 fluxes vary from one location to another based on different ecosystems and climatic conditions. The sink also changes during a year with the length of daylight, with temperature and nutrient concentration. These factors determine the growth of algae and thus primary production throughout the year. Additionally, CO_2 fluxes between the ocean and the atmosphere vary from year to year.

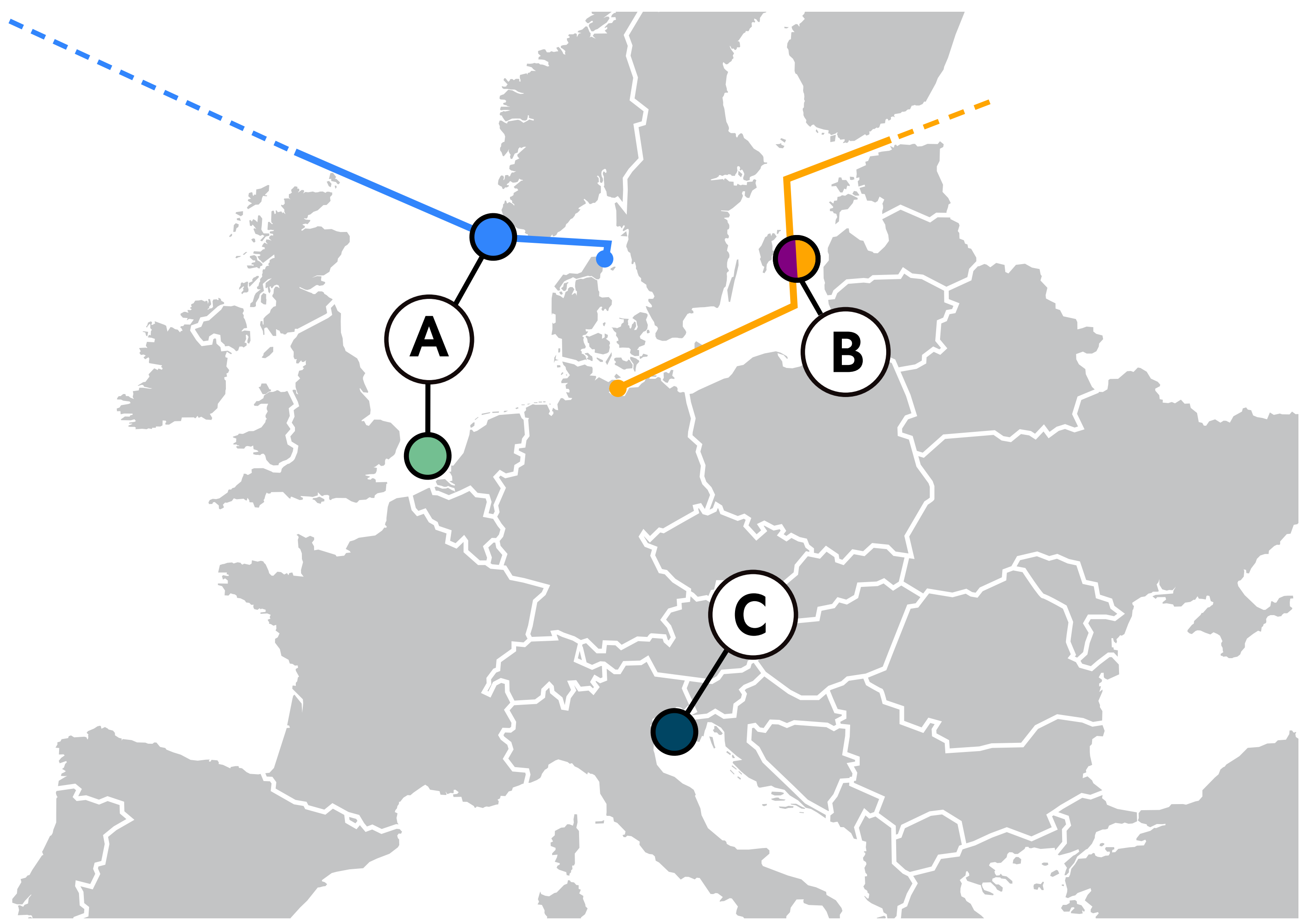
This variability tends to be larger in coastal regions than in the open waters. One reason for this is the stronger influence of rivers transporting carbon and nutrients to the coasts. Organic carbon deposited by rivers in coastal areas may be mineralised by bacteria, forming CO_2 that finds its way to the atmosphere. On the other hand, nutrient inputs result in increased algae growth, which increases photosynthesis, which in turn increases the uptake of CO_2 by surface waters. On top of these biogeochemical patterns, temperature is a very important driver, since colder water can store more CO_2.

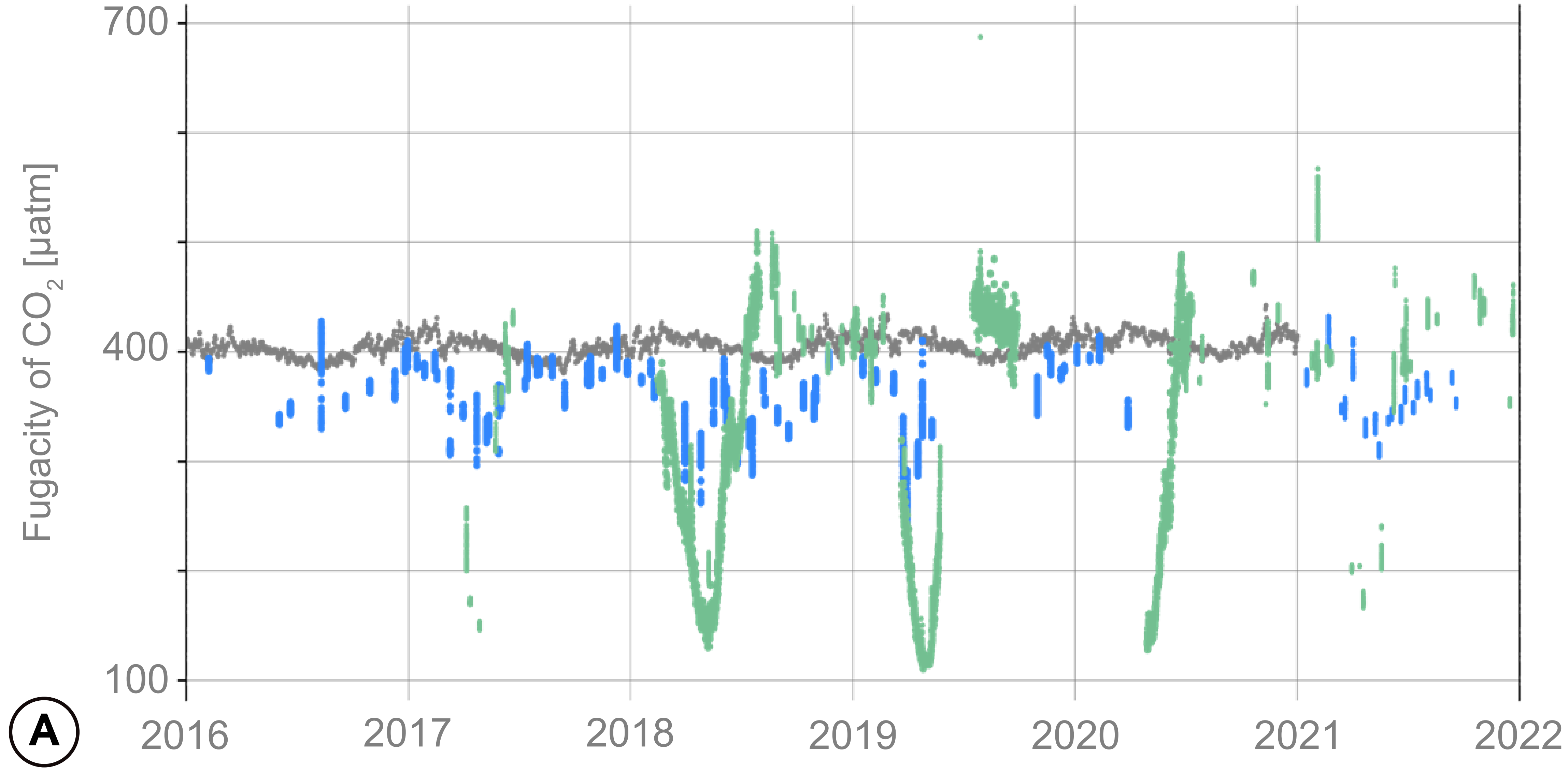
Data from different measurement stations across European coastal or inland seas show the variability in fugacity around Europe (Figure 9): in the northern North Sea (NO-SOOP-Nuka Arctica and NO-SOOP Tukuma Arctica), the southern North Sea (BE-SOOP-Simon Stevin, BE-FOS-Thornton Buoy), the Baltic Sea (DE-SOOP-Finnmaid, SE-FOS-Östergarnsholm) and the Mediterranean Sea (IT-FOS-PALOMA).

HOW DOES ICOS OBSERVE THE OCEAN?

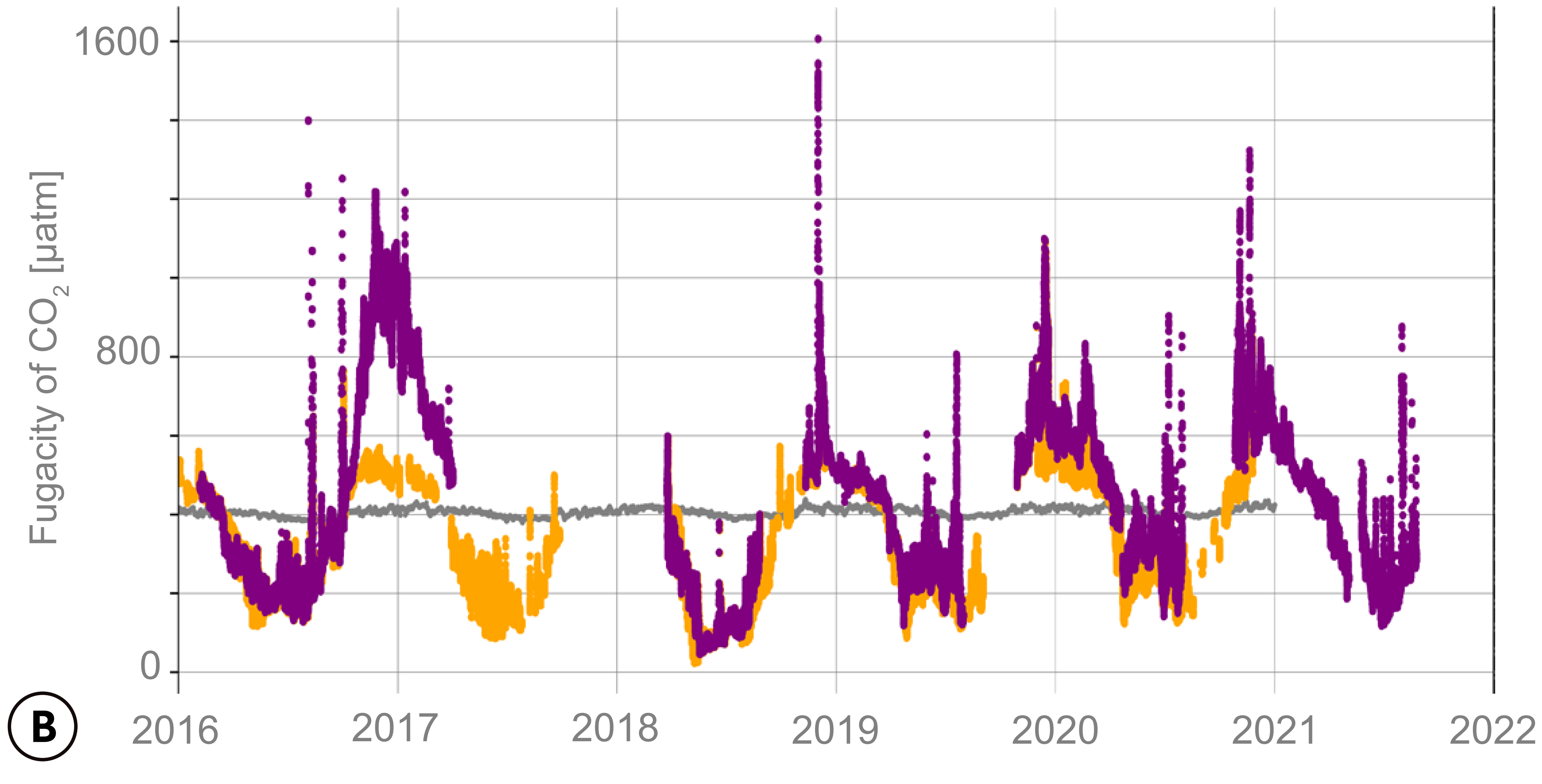
The ICOS Ocean observation network provides CO_2 flux data between the surface ocean and the atmosphere from fixed marine monitoring stations or from ships – either research vessels or 'Ships of Opportunity' (SOOPs): commercial ships that allow scientists to install their equipment on board. CO_2 fluxes between the ocean and the atmosphere are driven by the CO_2 gradient and the physical conditions at the sea surface. The respective scientific parameter that defines the flux is the difference in fugacity of CO_2 (fCO_2) between ocean and atmosphere. The fugacity describes the effective partial pressure and is calculated for the air above the ocean and for the seawater. The difference between fCO_2 in the air and in the water determines whether the seawater is releasing CO_2 or taking it up from the atmosphere. The ability of water to dissolve CO_2 and the fugacity are strongly dependent on temperature. Fixed stations and SOOPs cover only a small part of the ocean surface. The gaps between stations and SOOPs are filled in with statistical approaches ranging from simple multilinear regressions to more elaborated machine learning techniques such as neural networks and inverse modelling. The results are intermediate maps of fCO_2. The flux of CO_2 between the ocean and the atmosphere is calculated based on these maps and additional data on wind strength.

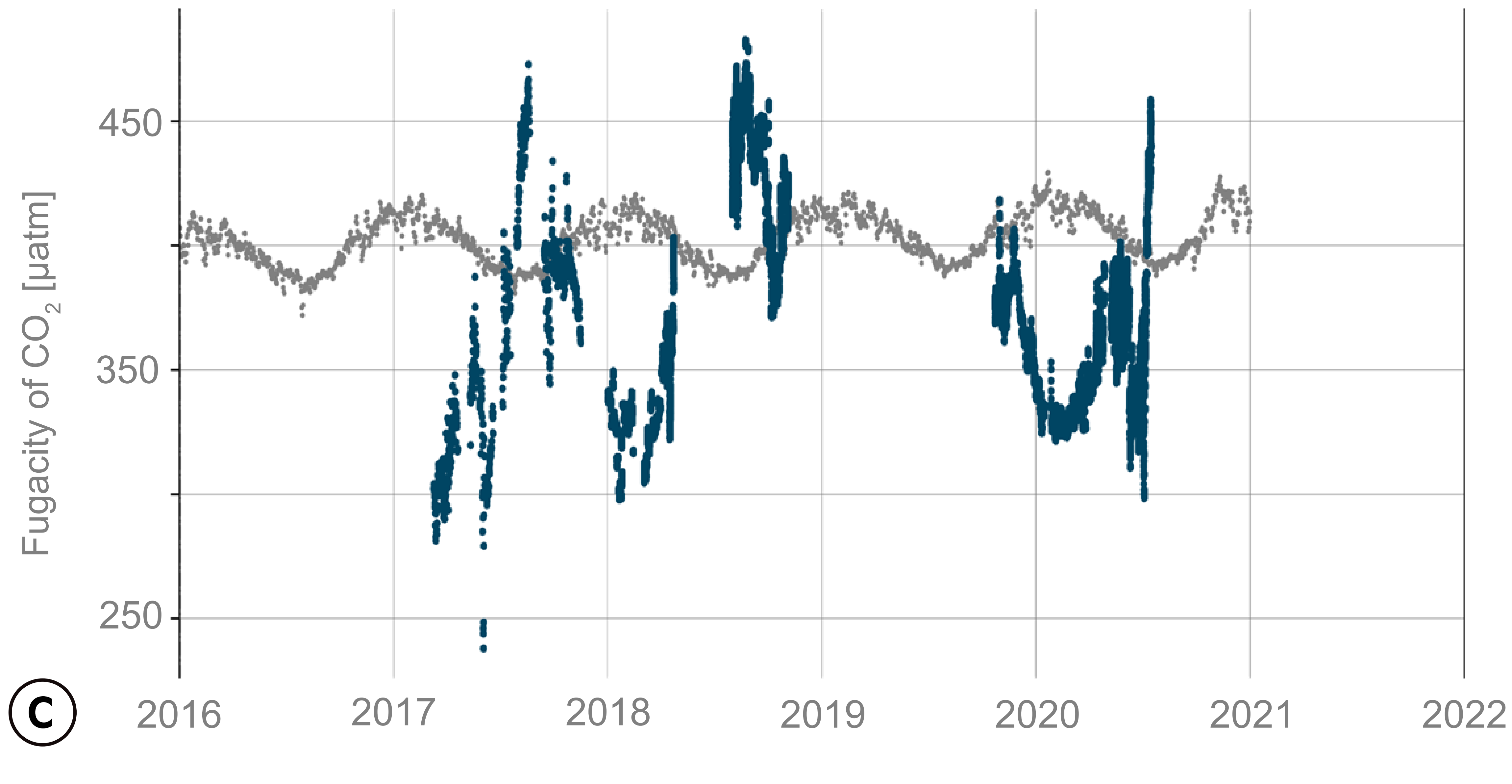
Figures 9A, 9B, 9C
Time series of CO_2 concentrations from seven ICOS stations in three zones: North Sea (A), Baltic Sea (B) and Mediterranean Sea (C).





A NO-SOOP-Nuka Arctica
NO-SOOP-Tukuma Arctica
A BE-SOOP-Simon Stevin
BE-FOS-Thornton Buoy
B DE-SOOP-Finnmaid
B SE-FOS-Östergarnsholm
C IT-FOS-PALOMA
Atmosphere





Oceanic observations from all stations highlight the variability of fCO_2 in these areas, and show that large differences between seasons and years can be found in the very same region.

The general pattern in fCO_2 is similar for most areas, i.e. a sharp decrease during the phytoplankton bloom in spring and a maximum during winter. The further south, the earlier the spring bloom starts and more common is a high fCO_2 during summer caused by seasonal heating of the surface ocean.

The fugacity of CO_2 in the atmosphere is shown as well. When fCO_2 in seawater is lower than in the atmosphere, the ocean absorbs CO_2. When it is higher, the ocean releases CO_2. In the North Sea, we see the difference between the coastal stations in the south (Thornton buoy, Simon Stevin) and open ocean stations in the north (Nuka Arctica, Tukuma Arctica). Both ocean regions are net sinks of carbon, but the variability in the coastal area is much larger, both on seasonal and inter-annual timescales.

The data from two stations in the Baltic Sea come from the same region but from two different types of station: one is a mooring (SE-FOS-Östergarnsholm) and the other one a ship that is passing by the mooring regularly (DE-SOOP-Finnmaid). Their data match nicely during spring and summer while the fCO_2 is low but can diverge largely during winter. The mooring station closer to the shore is more affected by local upwelling events where carbon-rich water is mixed to the surface, which leads to high fugacity.

> ***"The Earth's ocean is a natural sink that takes up about a quarter of human-induced carbon dioxide emissions each year.***

While the stations in the North Sea and Baltic Sea show a seasonal cycle with a minimum of fugacity during spring and summer, the station in the Mediterranean sea, IT-FOS-PALOMA, has its lowest fugacity during the winter season. In the south, the seasonal cycle is dominated by the temperature: when the water is warming, its ability to dissolve CO_2 decreases, while primary production and respiration, i.e. phytoplankton growth, is the main driver of seasonality further North.

Compared to other regions, at the Mediterranean station, inter-annual variability is driven by meteorological conditions and the changes in riverine inputs: mild and rainy winters lead to high fugacity while cold dry winters result in rather low fugacity.

The ocean is a huge carbon sink: it absorbs a quarter of fossil fuel emissions, thus keeping the world cooler. How long the ocean continues this uptake with the warming climate, we do not know. We have a blurry picture of the current ocean CO_2 exchanges, but not how global warming affects them. The marine ecosystems will react differently to changes in river runoff, nutrient availability, and temperature. Rising temperatures and changing climate also challenge the ocean's ability to dissolve CO_2. If we want to have any chance to understand the upcoming changes in the ocean carbon cycle, we need a stronger observation system, which also covers vulnerable ocean ecosystems.

THE UNPREDICTABLE BEHAVIOUR OF HUMAN EMISSIONS

Photo: Andrey Solovev / Adobe Stock

The excess CO_2 emissions driving climate change are caused by humans burning fossil fuels for electricity, industry, transport, and heating. In recent years, European fossil fuel emission levels have been declining due to the increasing use of renewable energies and due to increased efficiency. However, to correctly interpret the results of particularly local or regional emission-curbing actions, we must consider all the causes for the changes in the CO_2 levels: in addition to the variation of natural sinks discussed previously, the weather also affects the need for fuels for heating (or cooling). Unexpected events may occur as well, such as the lockdown in 2019, which reduced traffic emissions.

by **Dr Hugo Denier van der Gon** (lead writer), **Dr Ingrid Super, Dr Arjan Droste**

The steadily-increasing concentration of carbon dioxide in the atmosphere as shown in this bulletin is the result of continuous CO_2 emissions from fossil fuel burning and land use change on a global scale. The variations between different years in the natural fluxes on land and in the ocean have been shown in previous chapters. What is often less known is the variability in anthropogenic emissions, which also influence the inter-annual variability of CO_2 concentration in the atmosphere.

This variability takes different forms. For example, a power plant in the vicinity of an observation station may be closed for maintenance from weeks up to several months, thereby influencing the anthropogenic signal. Such individual cases are erratic, but from other sources the variability can be more structural.

The following examples will illustrate that. Some human-induced emission sources, such as the use of fuels or electricity in housing, are partly affected by changes in the annual weather. The difference between cold and warm years can be substantial. It results in a variability in CO_2 emissions from gas, oil, coal and wood use in households, offices and commercial buildings for heating in winter and electricity use for air-conditioning in summer, especially in southern European countries.

The CO_2 emissions from fossil fuels and solid biomass in small scale combustion are shown for selected countries in Figure 10A and 10B. The countries represent different sizes and vary in infrastructure with more or less fossil fuels being used.

> ***Some human-induced emissions sources, such as the use of fuels or electricity in housing, are partly affected by changes in the annual weather.***
>
> ***The difference between cold and warm years can be substantial. In certain years with cold winters, emissions are 10-20% higher across Europe.***

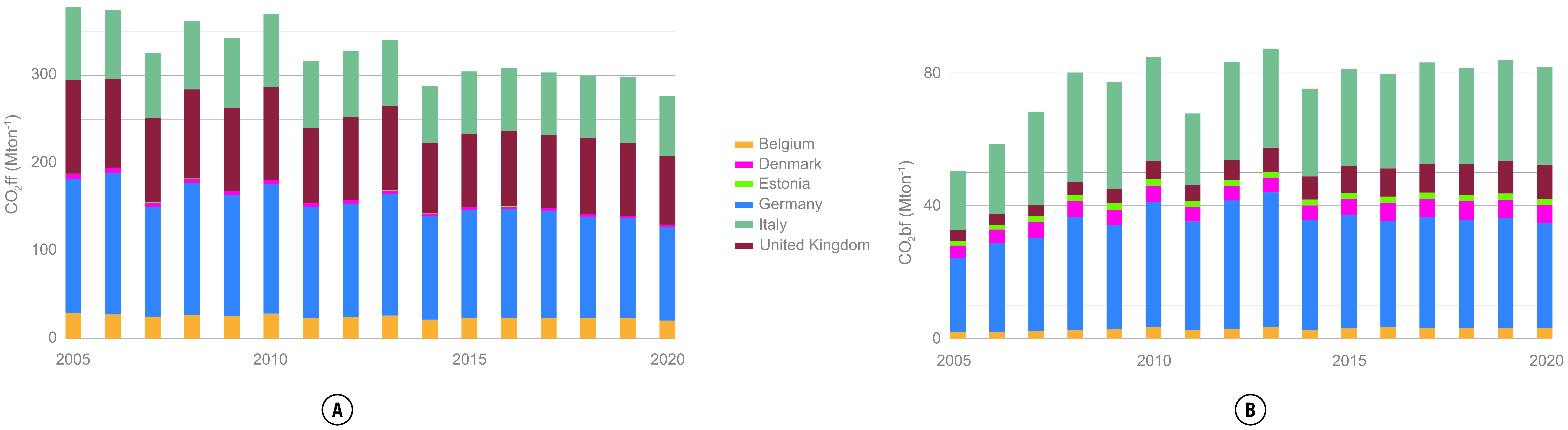


Figure 10 (A) Total Anthropogenic fossil (ff) and (B) non-fossil (bf) CO_2 emissions from residential and small scale combustion (heating of buidings) for the period 2005-2020 for Belgium, Denmark, Estonia, Germany, Italy and United Kingdom. Note that A+B provide the total CO_2 emission from the residential sector. Please note the scale of Figures A and B are different.

In certain years with cold winters, emissions are 10-20% higher across Europe (see e.g. Germany, Belgium, UK in 2010). These climate patterns do not always influence all of Europe in the same way. For example, higher emissions during 2010 are much less pronounced in other countries during the same year than in Germany. It can also be seen that 2020 had less emissions due to a much milder winter and spring, which reduced emissions from heating in this year.

When looking at total emissions (all sectors) this can be misinterpreted as an impact of COVID-19 because 2020 is known to have experienced reduced emissions due to COVID-19 lockdowns compared to 2019. However, the emissions from heating shown in Figure 10A & 10B were expected to increase due to more people staying at home. This increase clearly did not happen because of the warmer weather during that year. Another interesting feature from Figure 11 is the large difference in the ratio between biomass and fossil fuel CO_2 emissions from heating and small-scale combustion between countries.

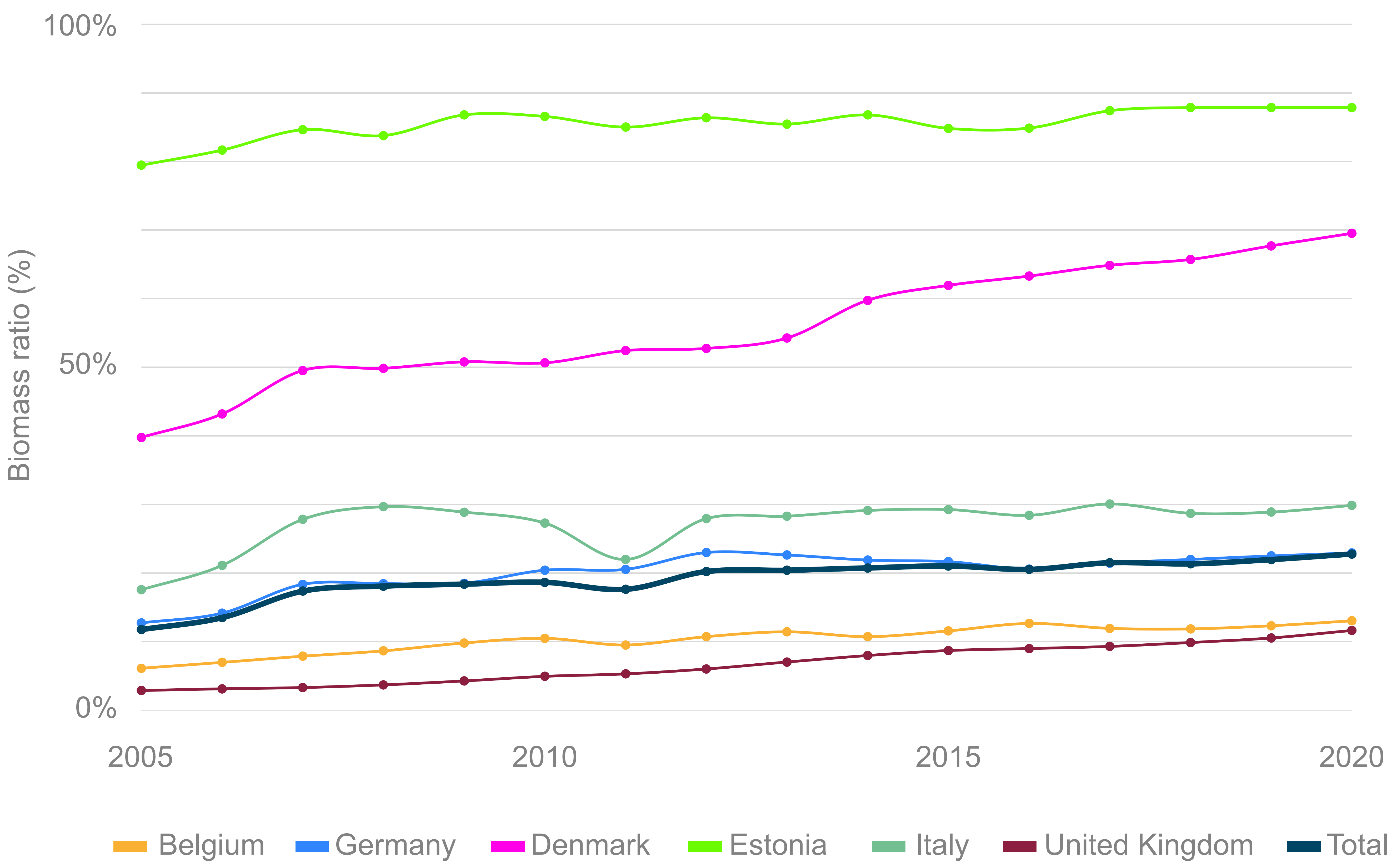


Figure 11 Percentage of biomass combustion of total fuel use in the residential sector in seven countries in Europe.

The share of solid biomass (wood) steadily increases (Belgium, Denmark) and is dominant in some countries (Denmark, Estonia) while in others it is marginal (UK).

In addition to climatic variations, large disruptions in society, like the COVID-19 pandemic or the Russian war against Ukraine, can result in inter-annual variations of CO_2 emissions from fossil and biofuel combustion. The impact on the aviation and road transport sectors in Germany due to the COVID pandemic is shown in Figure 12. There is, however, for 2020 and 2021, also important seasonal variability that differs from previous years. These patterns differ by country.

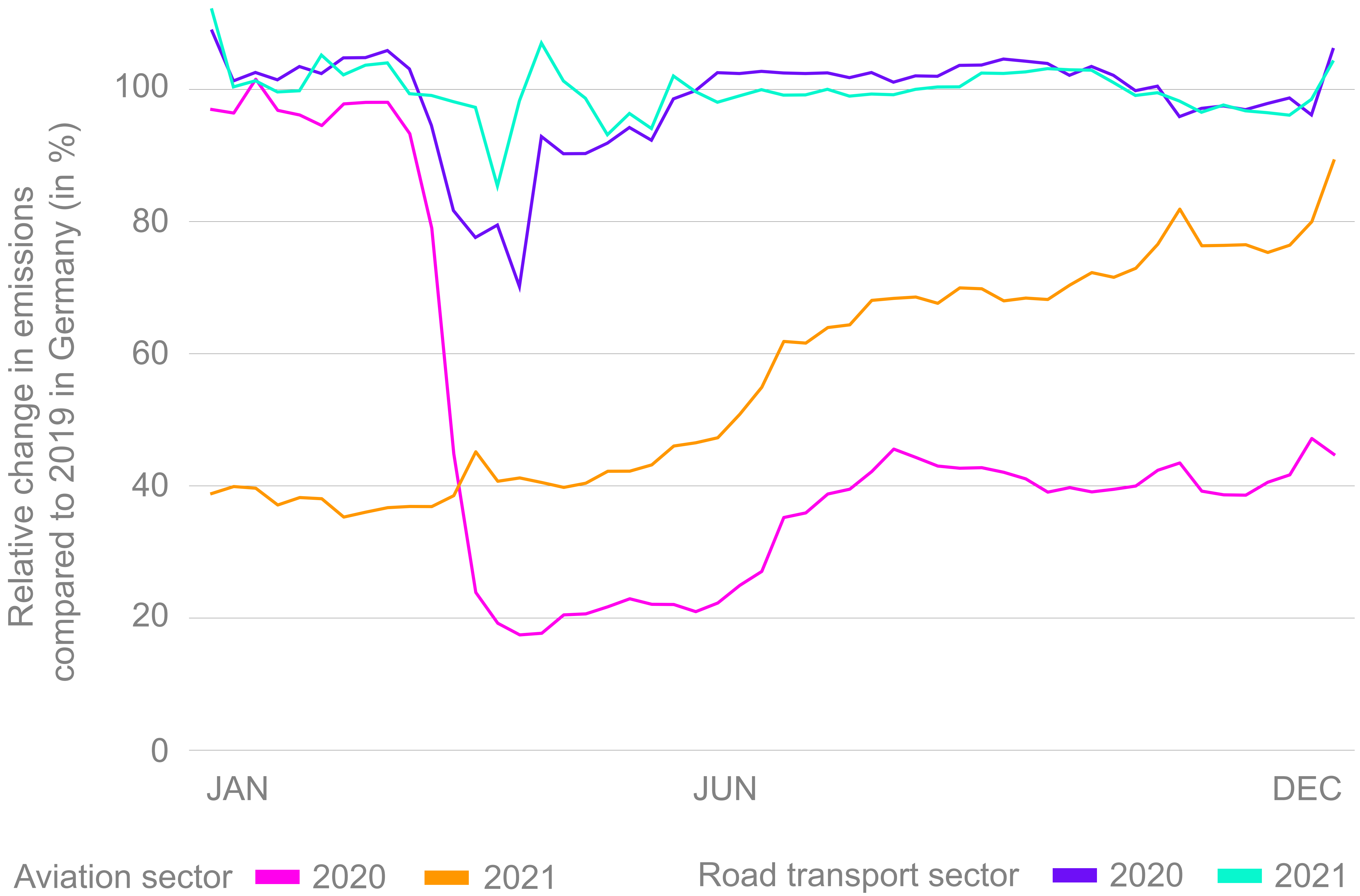


Figure 12 **The relative change in emissions for 2020 and 2021 from road transport activity (passenger cars and light duty vehicles) and aviation compared to 2019 in Germany.**

Figure based on data from https://carbonmonitor.org

Aerial view of a fossil fuel terminal.
Photo: Kalyakan / Adobe Stock

The amount of fossil fuel emissions changes from year to year and between seasons. This is due to different climate conditions over the years affecting e.g. heating, and societal disruptions such as the COVID-19 pandemic.

This societal information is necessary to properly interpret the rises and falls in carbon dioxide concentrations, especially at measurement stations located in urban and industrialised areas.

Further, to follow up on the success of the emission reductions, we need to combine societal and weather information.

TOWARDS A GLOBAL CARBON OBSERVATION SYSTEM

Image: rangizz / Adobe Stock

This bulletin shows examples of how observational data can provide insights into the state of the atmosphere, the land ecosystems and the ocean, and how data can provide guidance for climate action. With the global stocktake, the parties to the Paris Agreement assess the world's progress towards the main goal of the agreement. For that, they need scientific evidence based on systematic observation. Observational data and related modelling complement inventories. Together, they provide integrated information on the three major fluxes that drive the concentration of greenhouse gases in the atmosphere. To achieve this, a comprehensive global greenhouse gas observation system is urgently needed. The European ICOS research infrastructure can be used as a blueprint for such a system.

by **Dr Werner L. Kutsch**

The first steps towards this global integration have been initiatives to collect, harmonise, and publish open global data sets on greenhouse gases. The generation of these data sets has been initiated and developed further by the scientific community.

Data used to calculate CO_2 fluxes between oceans and the atmosphere are collected in a global database, called 'SOCAT, the Surface Ocean CO_2 Atlas". ICOS Ocean stations contribute data to SOCAT and are active within the ocean carbon observation community. The ICOS Ocean Thematic Centre supports the overall SOCAT data management.

Ecosystem data are collected in FLUXNET, a global cooperative framework of scientists. FLUXNET has compiled two large global data releases and provided a standardised software for data post-processing and quality control. The ICOS Ecosystem Thematic Centre has contributed to these developments and applies the FLUXNET standards when publishing ICOS data to ensure global comparability.

Atmosphere data on greenhouse gases are monitored in the framework of the World Meteorological Organization (WMO) Global Atmospheric Watch (GAW) and collected in several databases, such as the World Data Center for Greenhouse Gases operated by the Japanese Meteorological Agency. ICOS is a contributing network of the WMO GAW, and thus far the only operational network that provides near real-time greenhouse gas information.

"

A comprehensive global greenhouse gas observation system is urgently needed, and the European ICOS infrastructure may be used as a blueprint for such a global system.

These voluntary data integration initiatives have enabled numerous scientific studies used in the Intergovernmental Panel on Climate Change (IPCC) assessment reports. They are an important source of information for the annual Global Carbon Budgets reported to the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties by the Global Carbon Project.

More actionable products and services will become available from a global greenhouse gas monitoring system that is currently under development under coordination of WMO and UNFCCC. They will support the upcoming global stocktake.

We have reached a state of global climate emergency. The growth rate of CO_2 in the atmosphere will be the ultimate proof of our success. To limit the temperature increase to 1.5°C, we need to act fast.

Policymakers have to take bold, effective actions to steer their societies towards curbing human-induced greenhouse gas emissions. This is not negotiable.

A global greenhouse gas observation system can support climate action by providing the scientific base for decisions, and by supporting the upcoming global stocktake.

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A summer cabin next to a lake, in Central Finland
Photo: nblxer / Adobe Stock

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A tower in Loobos, the Netherlands reaches above the trees to observe the carbon flux between the pine forest and the air above it.
Photo: Konsta Punkka / ©ICOS ERIC

THE OCEAN, OUR ALMOST UNKNOWN HELPER

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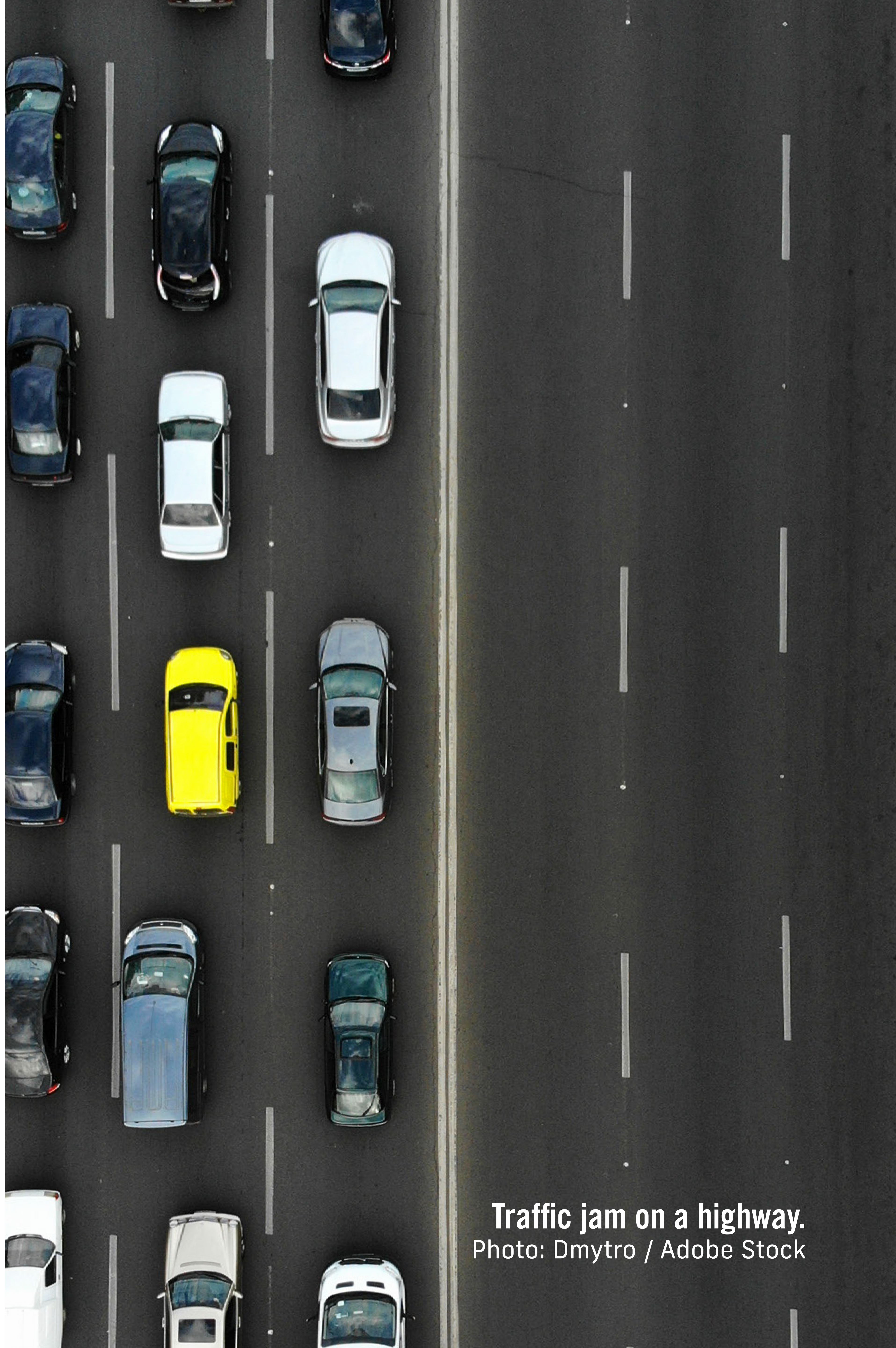

Traffic jam on a highway.
Photo: Dmytro / Adobe Stock

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SOCAT **https://www.socat.info/**
Global Carbon Project **https://www.globalcarbonproject.org/**
Carbon Monitor **https://carbonmonitor.org/**

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Figure 1 **https://doi.org/10.18160/20Z1-AYJ2**
High-resolution, near-real-time fluxes over Europe from CTE-HR for 2017-2022

Figures 2, 3 and 4 **https://doi.org/10.18160/CEC4-CAGK**
European Obspack collection

Figures 5, 7 and 8 **https://doi.org/10.18160/PAD9-HQHU**
ICOS L2 Ecosystem 2022-1

Figure 6 **https://doi.org/10.18160/2G60-ZHAK**
ICOS Warm Winter Ecosystem historic data

Figure 9 **https://doi.org/10.25921/1h9f-nb73** SOCAT 2022
https://doi.org/10.18160/BCFM-GNVA ICOS L2 Ocean 2021-1

Figure 10, 11 and 12 **https://doi.org/10.18160/03WD-A389**
Emission data from the chapter
"The unpredictable behaviour of human emissions"

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