Comprehensive carbon footprint of Earth and environmental science laboratories: implications for sustainable scientific practice

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Key Points:

- We present a novel method to constrain the carbon footprint of research infrastructures and attribute it to research institutions
- The comprehensive carbon footprint of six laboratories is mostly over 10 $tCO_2e.\ p^{-1}$, often dominated by research infrastructures
- We argue that more sustainable science requires rethinking the deployment of new infrastructures and abandoning the *fast science* ideal

Abstract

To limit global warming below 2°C, a drastic overall reduction from current CO_2 emissions is needed. We argue that scientists should also participate in this effort in their professional activity and especially Earth scientists, on the grounds of maintaining credibility and leading by example. The strategies and measures to reach a low-carbon scientific activity require detailed estimates of the current footprint of laboratories. Here, we present the footprint of six laboratories in Earth, environmental and space sciences, representative of the AGU community, with a comprehensive scope also including international research infrastructures. We propose a novel method to attribute the footprint of any research infrastructure to any given research laboratory. Our results highlight that most laboratories have annual footprints reaching 10-20 tonnes CO_2 equivalent per person (tCO2e.p^{-1}), dominated by infrastructures and specifically satellites in three cases (with footprints up to 11 tCO2e.p^{-1} or 60%), while air-travels and purchases remain within the top three sources in all cases (2-4 tCO2e p^{-1} or 10-30% each). Consequently, footprints related to commuting and laboratory functioning, about 2 tCO2e.p^{-1} (20%) or less, are relatively modest compared to infrastructures, purchases and air-travels. Thus, reduction measures ignoring infrastructures may not be able to achieve reductions larger than 20 to 35% even with flight quotas and a substantial reduction of purchases. Finally, we also discuss how a deeper transformation of scientific practices, away from a *fast science* ideal, could make Earth and environmental sciences more sustainable and at the forefront of a rapid and drastic social bifurcation.

Plain Language Summary

To limit global warming below 2°C, a drastic overall reduction from current CO_2 emissions is needed. We argue that scientists should also participate in this effort in their professional activity and especially Earth scientists, on the grounds of maintaining credibility and leading by example. Here, we present the footprint of six laboratories in Earth, environmental and space sciences, representative of the AGU community, with a comprehensive scope also including international research infrastructures. With a novel method to attribute the footprint of any research infrastructure to research laboratory we find that most laboratories have annual footprints reaching 10-20 tonnes CO_2 equivalent per person, dominated by infrastructures and satellites in three cases, while air-travels and equipment purchases remain within the top three sources in all cases. In comparison, footprints related to commuting and laboratory functioning, are relatively modest. Thus, reduction measures ignoring infrastructures may not be able to achieve reductions larger than 20 to 35% even with flight quotas and a substantial reduction of purchases. Finally, we also discuss how a deeper transformation of scientific practices, away from a *fast science* ideal, could make Earth and environmental sciences more sustainable and at the forefront of a rapid and drastic social bifurcation.

1. Introduction

The sixth series IPCC assessment reports underlined the need for an immediate and rapid decay of greenhouse gases (GHG) emissions to mitigate current warming pathways and associated cascading impacts (IPCC, 2022). Maintaining global warming below 1.5°C implies reducing GHG emissions by ca 45% and 80% by 2030 and 2050, respectively, reaching an average of ca 2 $tCO2e.p^{-1}.yr^{-1}$ on Earth in 2050 (see Fig TS.9 of IPCC, WG3, 2022). Although responsibilities vary, it is clear that substantial reductions must affect all aspects of society, including academia.

Although various discourses of inaction (Lamb et al., 2020) are also present inside scientific laboratories (Carbou and Sébastien, 2023), several lines of argument indicate that academia has a specific responsibility to be exemplary in terms of reducing its GHG footprint. First, various studies, including IPCC assessment reports, highlight that the political feasibility of a rapid decarbonization of society likely requires various forms of social justice and reduction of inequalities (Patterson et al., 2018; Stoddard et al., 2021; IPCC, 2022). It means that privileged actors, including the academic sector, are arguably among those compelled to reduce first and/or at an accelerated pace their GHG emissions.
Then, beyond their moral responsibility (Resnik and Elliot, 2016), the credibility and status of the scientific community broadly working on ecological issues is linked to adopting exemplary practices and lifestyles. Surveys showed for instance that GHG mitigation policies proposed by climate researchers tended to be more or less supported by the public depending on the reported carbon footprints of their proponent (low or high, respectively - Attari et al., 2016, 2019). This emphasizes the importance for geoscientists to be leader in terms of reducing their own GHG footprint.

Efforts towards exemplary practices require a comprehensive assessment of ecological footprints in academia, and an effort in building transparent and reproducible methods. Focusing on GHG, the carbon footprint (CF) measures all direct and indirect GHG emissions (converted to CO2-equivalent emissions, CO2e), more specifically scope 1 (direct process emissions), scope 2 (indirect emissions arising from the purchase of energy) and scope 3 (other indirect emissions including the purchase of goods and services) according to the GHG protocol (WRI and WBCSD, 2004). Methodologies to determine carbon footprint have been existing for more than a decade and applied to various entities and at various scales (Wiedmann et al 2006, Wiedmann and Minx, 2008). Such methods have then been applied to academic institutions, typically research institutes or universities, but most often over limited scopes; the recent assessment over 470 French research laboratories by Mariette et al. (2022) for instance considered a restricted scope 3 focused on mobility. Similarly, many studies on the academic CF have highlighted the dominant share of air-travel (Achten et al., 2013, Le Quéré et al., 2015, Arsenault et al., 2019, Mariette et al., 2022), and focusing on potential measures to reduce it (shift from air to train travel, video call, reorganizing conferences; Langin, 2019). A focus on air-travel is relevant because i) academic work is international in most fields, possibly with a link between scientific visibility and mobility (Berné et al., 2022) and ii) because air travel is carbon intensive and iii) relatively straightforward to quantify. Additionally, air-travel emissions are very unequally distributed among scientists (Le Quéré et al., 2015, Arsenault et al., 2019, Blanchard et al., 2022, Martin et al 2022b, Ben-Ari et al., 2023), making its regulation a potential example of reducing emissions with a concern for social justice at the laboratory scale.

Nevertheless, beyond mobility, various efforts have attempted to quantify the carbon footprint of other aspects of academia, such as that of product and service consumption (e.g., Ozawa-Meida et al., 2013, Alvarez et al., 2014). A broad scope 3 assessment for the Norwegian University of Technology and Science (NTNU), resulted in a total CF of 4.6 $tCO2e.p^{-1}.yr^{-1}$ for each of its 20,000 students with 16% from travels (of staff and students), 19% from energy use and 35% from goods and services, underlining the need to account for a comprehensive scope 3 (Larsen et al., 2013). A compilation of CF estimates for 25 European universities between 2016 and 2020 reported between 2 and 7 $tCO2e.p^{-1}.yr^{-1}$ when mostly limited to scope 1 and 2 and mobility, reaching 10-30 $tCO2e.p^{-1}.yr^{-1}$ when including a more comprehensive scope 3 (ALLEA, 2022). Very recently, an estimation of the CF of purchases for more than 100 French research laboratories concluded that purchases was often the largest share of the footprint, about 50% with 2-4 $tCO2e.p^{-1}.yr^{-1}$, and that laboratories had a typical carbon intensity of 0.32 +/- 0.10 tCO2e/k€ (De Paepe et al., 2023).

CF estimates for large/international research infrastructures have also been released, including satellite and ground telescopes for astronomy (Knödlseder et al., 2022), the GRAND astrophysics project (Aujoux et al., 2021) or the infrastructures used for particle physics such as the CERN (European Center for Nuclear Research, Bloom et al., 2022, Janot et Blondel, 2023). These CF estimates often relied heavily on scope 3 emissions, which could represent a very large share of the annual CF of research institutes when added to their in-situ footprint. A comprehensive CF estimate made for the largest French research institute in astronomy and astrophysics (IRAP) further found that the contribution of satellite and ground observatories amounted to 38% and 18% in 2019, while air-travels and purchases represented lower contributions with 16% and 18%, respectively (Martin et al., 2022a). The magnitude of the CF, nearing 30 $tCO2e.p^{-1}.yr^{-1}$ for the 263 employees of this laboratory, made the authors to suggest that substantial reorganization of research practice and goals were urgently needed in astronomy and astrophysics.

However, such a comprehensive assessment for laboratories in Earth and Environmental Sciences is among the missing pieces to help understanding i) how to advance knowledge on Earth system processes (including the ongoing climate and ecological crisis) while adopting sustainable research practices and ii) how Earth and Environmental scientists can be exemplary, in the prospect of efficiently promoting awareness and actions to face the ecological emergencies.

To address these research challenges, we present here a comprehensive CF assessment for six research laboratories which formed the Observatoire Midi-Pyrénées in 2019, a large French public research institute of Earth, Environmental and Space Sciences. Several of these laboratories have the specificity to rely on substantial use of satellite infrastructures.

2 Data and Methods

2.1. Presentation of the studied laboratories

Staff and activity data of the 6 laboratories composing the Observatoire Midi-Pyrénées (OMP, www.omp.eu) in 2019 are summarized in Table 1. Here we briefly describe their scientific focus. The CESBIO (Centre d'Etude Spatiale de la BIOsphere) focuses on the continental surfaces and more specifically on soil/vegetation/atmosphere interactions, with a strong expertise in remote sensing data. The GET (Géosciences Environnement Toulouse) is a laboratory with prime expertise in geology, geophysics, geochemistry, hydrology and environmental processes in the critical zone. The IRAP (Institut de Recherche en Astrophysique et Planetologie) has broad expertise in observing, modeling and instrumenting all aspects of astrophysics and planetology. The LAERO (Laboratoire d'Aérologie) focuses on the physics and chemistry of the lower atmosphere through observation and numerical modeling. The LEFE (Laboratoire Ecologie Fonctionnelle et d'Environnement) focuses on ecosystem health, ecosystem services and ecological responses to global changes. The LEGOS (Laboratoire d'Etude en Géophysique et Océanographie Spatiales) focuses on the water cycle in the broadest sense, with the physics of the oceanic, hydrological, cryospheric and atmospheric components, including coastal and climatic components, as well as marine biogeochemistry and geochemistry.

For each laboratory we only consider persons with continuous contracts over the whole of 2019, including PhD and postdoctoral researchers, administrative and technical support staff (up to research engineers), and permanent research and teaching staff. Researchers are employed with national institutes with only optional teaching duties, while lecturers and professors (and equivalents) are employed by the university and have a mandatory teaching load.

All six laboratories are joint research units supported by both the French National Center for Scientific Research (CNRS), and the University Toulouse 3 Paul Sabatier (UT3). Additional supports for the various laboratories includes the National Center for Space Studies (CNES), the National Research Institute for Sustainable Development (IRD), the National Institute of Research for agriculture, food and environment (INRAE) and the National Polytechnical Institute of Toulouse (INP). We recall that all results from IRAP have been published in Martin et al., (2022a, b), following Knödlseder et al. (2022) for research infrastructures, and here we simply recast their figures for comparison with the other laboratories of the OMP and to have a broad discussion about Earth, Environment and Space Sciences.

Laboratory	CESBIO	GET	IRAP	LAERO	LEFE	LEGOS
Professors (University employees)	16	38	54	20	32	9
Researchers (employed by other public institute)	16	74	62	17	10	38
Support staff	34	52	78	34	35	44
PhD/Post-doc	44	86	69	19	63	30
Considered Infrastructures	Sat	Sat + Sea	Sat + Obs	Sat + Air	Sat	Sat + Sea
Professional travels, in 10^6 km	0.7	3.8	6.4	1.0	0.9	4.8
Expenses, in 10^6€	1.1	1.8	3.7	1.0	0.6	1.6
Travels (tCO2e)	169	612	1179	174	178	742
Purchases (with IT) (tCO2e)	415	755	1426	464	258	424
Total in-situ (tCO2e)	684	1868	3340	952	704	1460
Total with RI (tCO2e)	1968	2341	7440	1092	708	2581
Total in-situ ($tCO2e.p^{-1}$)	6.2	7.8	12.7	11.0	5.2	12.1
Total with RI ($tCO2e.p^{-1}$)	17.9	9.8	28.3	12.6	5.2	21.4

Table 1: Summary of activity and key sources of CO2 emissions for the six laboratories affiliated to the OMP in 2019. Total Expenses are excluding expenses for professional travels. Abbreviations as following, IT= Information Technology, RI=Research Infrastructure, Sat=Satellites, Obs=ground astronomical observatories, Air=IAGOS infrastructure, Sea= IODP (for GET) and PIRATA (for LEGOS) infrastructure and use of other large research ships.

2.2. GHG budget method and scope

To assess GHG emissions, we followed standard procedure in which 'activity data' that quantify the usage of a given source (e.g., energy consumption in kilowatt hours, or travel distances in kilometers, etc.) are multiplied by associated 'emission factors' (EF) that quantify the unitary carbon footprint of each source (e.g., electricity production or air-travel) (Table 1). To constrain the emissions of commuting, electricity, gas, cooling fluids, and professional travels we followed the standardized approach proposed by Mariette et al. (2022), and used the GES1.5 tool. For air-travels we present results including the indirect radiative forcing of condensation trails, which are equivalent to doubling the footprint derived from CO_2 only (Mariette et al., 2022). Note that professional travels also includes train and car and internal commuting for laboratories with facilities in several towns.

Additionally, we consider the emissions related to expenses (i.e., the GHG emissions resulting from the life-cycle of products or services bought by the laboratory), by considering financial listings and attributing a financial EF, in kgCO2e.k€$^{-1}$, to different categories, such as food, service, clothes, furniture, electronics, machines (e.g., Ozawa-Meida 2013, Alvarez 2014, De Paepe et al., 2023). Purchases are categorized by the administration of French public research and education using a classification called NACRE. For each relevant NACRE category (identified by a code) we have extracted an average emission factor from the Base Carbone database of the French Environment and Energy Management Agency (ADEME, 2023) (as in Martin et al., 2022a, b, see Table S1). This is a simplified approach compared to the one recently described in De Paepe et al., (2023), still under development at the time of data collection and analysis. Thus, future work should likely apply their emission factors more robustly evaluated, and easier to use as they are now implemented in GES1.5. Nevertheless, as we show later, our results are very consistent with this updated method.

We separated from these listings all expenses under NACRE codes starting by "I" which relate to Information Technology (IT), (i.e., screen, printers, computers, components …), to assess their specific importance, and we excluded all expenses related to professional travels (flights and hotels) which are counted based on an alternative method.

Following Martin et al. (2022a, b), we further extended the scope of our assessment to a few more items, even if they could not all be retrieved for the six laboratories (Table S2). We assessed the emission associated with external data storage and computation, and food consumed on campus, making use of an online poll sent to the staff to constrain annual activity in each laboratory in terms of CPU.hour, terabytes (Tb) and total number of meals of various diets. Most external computing in the studied laboratories is performed in France and thus we used an EF of 3.6 gCO2e per CPU.hour relevant for a typical computing center in France (Berthoud et al., 2020). For 1 Tb of data stored during a year in a datacenter, the EF is typically of 12 kgCO2e in France but the median for other countries with less favorable electricity mix is rather 35 kgCO2e (Charret et al., 2020). In the poll, the location of the datacenter was not always filled and beyond France, various country were reported, so for simplicity we used an intermediate EF of 25 kgCO2e per Tb. Last, for food we used EFs of 2.6, 1.1 and 0.5 kgCO2e per classic, flexitarian and vegetarian meal (ADEME, 2023). We also considered water consumption, considering 0.132 kgCO2e.m^{-3} (ADEME, 2023), and waste based on estimates of the volume and frequency of recollection for various waste type (mixed, plastic and paper - Martin et al., 2022b). Last, given that in financial listings hotel nights are often included into a general travel expenses code NACRE (i.e., bundled with train or flight tickets), which is excluded from the financial conversion, we instead used more detailed travel listings to compute the footprint associated with hotel nights spent during travel emissions. Thus, we used the number of nights in missions multiplied by country-dependent EFs in kgCO2e.$night^{-1}$ (UK Government, 2020). However, long missions lasting several weeks dominate the total number of nights, while they may not only rely on hotel accommodations but may involve camping in the field or other accommodations with smaller footprints such as flat renting. As a result, we considered as an upper bound the conversion of all nights with their EFs, and as a lower bound the conversion of all nights during mission of less than 20 days, setting accommodation footprint of longer missions to zero. We thus consider as a best estimate a conversion where we cap to 20 the number of nights spent in hotels for any mission. Last, we note that this estimate may be slightly over-estimated for two reasons. First, because the EF are for one room independently of the number of users in the room, so in case of shared room we may have overestimated the number of nights, and second because the EFs released by the UK government for later years (2022, 2023) tend to be 30% smaller than the ones of 2019, which may both reflect change in methodology and actual reduction of hotel footprint.

Building construction was not counted as it was done more than 30-40 years ago for most parts of the buildings at OMP, and thus could be considered amortized and not relevant for the 2019 budget.

2.3. Carbon footprint of research infrastructures

Beyond purchases, we proposed here a new methodology to account for another potentially major source of green-house gases: the use by Earth scientists of large, international, research infrastructures. Namely, we propose a versatile methodology which we apply to a large array of satellite infrastructures allowing Earth observation from space, but also to a few more infrastructures specifically used by some of the studied laboratories, and relying on ships or aircrafts. We again stress that beyond satellite infrastructures, we do not claim to be exhaustive in estimating the footprint of research infrastructures used by the studied laboratories. The reason is that many of the research infrastructures in the domain of Earth observation are distributed over many sites, laboratories and institutions. Thus, quantifying their total footprint remains very challenging. As a result, whereas our estimate for the footprint of satellite infrastructures is likely a representative first-order estimate, the estimates for other infrastructures, is not exhaustive and thus likely to be a lower bound only. Some elements of uncertainties associated to this limit are discussed in 4.1.

2.3.1 General approach

Our new methodology is an adaptation of the one proposed by Knödlseder et al., 2022, targeted at astronomical space missions, including satellites, rovers and space probes.
Inspired by this pioneer study, we estimate the total footprint of any infrastructure, *i,* for a given laboratory, *l,* over a given time period *Δt,* with the following formulas:

$$F(i,l,dt)=F(i)\frac{Ml(i,l,)Af(i,l,\Delta t)}{M(i,\Delta t)}Ss(i),(Eq.1)$$

where: *F(i)* is the annual GHG footprint of infrastructure *i*; *M* and *Ml* are the numbers of all scientific publications and the ones with at least one co-author from the laboratory l, respectively, during *Δt* using the infrastructure *i*; *Af* is the average fraction of author affiliated with lab *l* within the *Ml* manuscript sub-sampled; *Ss* is the share of the infrastructure used for research purposes.
Thus, for each infrastructure the three terms we must estimate represent: (i) its footprint based on its construction or activity data (in $tCO2e.yr^{-1}$), (ii) the share of the studied lab relative to all other labs (from 0 to 1), and (iii) the share of usage between research and other usage (from 0 to 1). This approach is particularly adapted for infrastructures which produce and deliver data to a broad community, for which the share of usage cannot be specifically attributed to any user, in contrast to infrastructures for which each user has to declare a certain usage, for example beam time for a synchrotron, CPU time for a super computing center (Berthoud et al., 2020), or hours of observation in an astronomical observatory (Knödlseder et al., 2022).
F(i) and *Ss(i)* are estimated for each infrastructure in the following subsections, and we only detail here the general algorithm we developed to determine the share of the lab among the world scientific community (Supplementary Information). Given the various disciplines of the studied laboratories, and the fact that infrastructures do not necessarily maintain a publication list, we

propose to use, by default, a generalist bibliographic database, the Clarivate Web of Science (WOS) database (See Supplementary Methods). Given the size of the database and the number of authors, we also simplify the approach of Knödlseder et al., 2022, by extracting first automatically $M(i,\Delta t)$ and $Ml(i,\Delta t)$ by querying the database to retrieve all work relating to the infrastructure i, over the period Δt, with or without a constraint on the authors' affiliations. Then, to avoid attributing several times emissions when an article using a satellite is signed by authors from several laboratories, we export the metadata of the $Ml(i, \Delta t)$ articles and extract the mean proportion of individual authors from the studied laboratory among those ($Af(i, l, \Delta t)$). Authors with multiple affiliations were counted as fraction as if its part would be split between several institutions (see Supplementary Information). We expect the number of publications associated with one infrastructure in a given laboratory to be highly variable on an annual basis. Thus, we assume that a 5-year average allows a more representative estimate of the share of the infrastructure footprint that should be given to the lab, and thus we used Δt=2015-2019 for all infrastructures. For IAGOS, IODP and PIRATA which maintain a dedicated database of scientific publications, we applied our method on these databases in addition to the WOS database. We assume the dedicated databases to be more comprehensive and accurate, and use them for the final footprint attribution while we give the WOS results for comparison and discussion only.

2.3.2 Satellite infrastructure

Using only scientific publications to determine the proportion of usage to attribute to each lab, implicitly assumes the whole footprint of any mission is only shared among the research community. This was expected for astronomical instruments but it is not obvious for Earth observation satellites. Thus, we excluded all satellite missions which are primarily designed for non-scientific purposes, typically weather forecast satellite (EUMETSAT, METEOSAT and GOES series for example) or GPS constellations, for which scientists are likely a negligible proportion compared to all other public and private users. We also limit ourselves to the main missions with specific scientific instruments and did not considered the large number of "national" observation satellites (such as CBERS, KOMPSAT, etc).

As a result, we consider 44 Earth Observation satellite missions, several containing constellations or successive satellites (e.g., the Landsat series), amounting to 82 individual satellites (Table S3). Most of these missions are mostly scientific, with restricted access and usage limited to specialists, but not all of them. Some of them produce broadly used and broadly accessible data (e.g., the Landsat, SRTM or Sentinel missions; N=11 out of 44, see Table S3) designed to be used by private companies, and public institutions, which are increasingly doing so for various applications. Hence, there was a need for these missions to determine their *Ss*, the share of the total footprint attributable to the scientific community. For the Sentinel missions 30-60% of the 2019-2022 downloads on the ESA platforms were for research (Copernicus, 2024). However, it is likely that a large share of downloads are done through other distributors such as Amazon AWS, or Google Earth Engine, where the proportions of non-scientific users may be larger. Thus, *Ss* for these missions may range from 0 (e.g., a negligible share for scientists, as assumed for weather forecast or GPS satellites) to about 0.6 following the ESA report, so we used a central estimate *Ss*=0.4, as well as lower and higher values for discussion.

To derive *F(i)*, we collected satellite launch mass and converted it with life-cycle emission factor of 50 (+/-10) tCO2e.kg^{-1}, and dividing by the time in years between mission launch and the year of interest 2019 (Knödlseder et al., 2022, Wilson, 2019). For most missions we could not retrieved full mission cost and thus we focus on the estimates derived from launch masses (Table S3). The SRTM mission is an exception as it was fully operated through a Space Shuttle mission for which the weight factor cannot be applied and only the financial estimate was used and converted with and EF of 140 tCO2e.M€$^{-1}$. For recent missions, launched less than 10 years before 2019, we assumed the emissions should nevertheless be distributed over a minimal timescale, *Tmin*=10 yr, consistent with the approach of Knödlseder et al. (2022). The impact of choosing *Tmin*=20 yr on our results is also discussed.

2.3.3 IAGOS Infrastructure at LAERO

The In-Service Aircraft for Global Observation System (IAGOS) infrastructure relies on commercial aircraft embarking instruments measuring atmospheric composition and meteorological variables along the flight (Petzold et al., 2015). The emission factor for scientific instrumentation on-board commercial flights is computed based on the "cost of weight" approach (IATA, 2011). This approach is widely used for estimating the fuel consumption due to additional weight embarked on airliners. It is preferred to emission factors for air cargo (which are one order of magnitude larger), because scientific observations is not the purpose of commercial flights but take advantage of existing airlines (emission factors for air cargo or air travel include in supplement emissions due to the weight of the aircraft itself, its manufacturing, airport infrastructures, etc.). Assuming a typical cost of weight of 0.035 kg of kerosene per kg of extra freight and per flight hour, and an emission factor of 3.83 kgCO2e kg^{-1} for kerosene (ADEME, 2023), we obtain an emission factor of 0.133 kgCO2e (kg freight)$^{-1}$ (flight h)$^{-1}$. This value only includes for CO2 radiative forcing but not for the additional effects of flight contrails.

Following Mariette et al. (2022) to this goal, we finally double this emission factor, up to 0.266 kgCO2e (kg freight)$^{-1}$ (flight h)$^{-1}$ to be consistent with our other estimates of air-travel footprint. The IAGOS instrumentation has a typical weight of 120 kg and about 20,000 h were flown in 2019 (representative of the few previous years) with IAGOS on board, yielding a total footprint of 640 tCO2e.yr^{-1}.

Querying WOS with the keyword 'IAGOS', for 2015-2019 yielded 47 publications worldwide and 20 with at least one author from LAERO. The average author fraction of these publications was 0.45 which indicates that a fraction 0.19 of the total footprint should be attributed to LAERO. The dedicated publication database (IAGOS, 2024) report 93 publications worldwide over 2015-2019 and 40 with an author from the LAERO, with a mean author fraction of 0.36 yielding a global share of 0.15, quite consistent with the WOS estimate. Retaining this latter share we obtain a footprint of 96 tCO2e for the LAERO.
Note that the LEGOS is also part of another infrastructure with a similar design, called SSS for Sea Surface Salinity, but for which we could not performed an overall assessment (see SI).

2.3.4 Oceanographic missions

Two laboratories, the GET and the LEGOS, are frequently involved with oceanographic missions, which involve large international consortia. For example, in 2019, seven agents were funded by the GET to spent 2 months each, and 3 agents from the LEGOS spent a total of 84 days, on oceanographic ships operated by the IODP (Integrated Ocean Discovery Program) and the PIRATA (Prediction and Research moored Array in the Tropical Atlantic) programs, respectively. Such participation is regular for these laboratories. We follow the same approach as for the satellite infrastructure, using Eq. 1 and assuming Ss=1 for both infrastructures, and calculating the average annual footprint of the infrastructure. Typically, we estimate the fuel consumed by the ships for each expedition, in tons or m^3, and then convert it with an emission factor for diesel marine fuel of 3.75 kgCO2eq.kg^{-1} (ADEME, 2023). For some infrastructure depending on available information we also assess, air-travels, freight and purchases but found it to always be minor relative to the fuel used by ships.

2.3.4.1 IODP footprint and share attributed to the GET

For IODP, 85% of all missions are on board the Joides Resolution which use of 33, 17 and 7, tons of fuel per day for all its activities, during transit, station and harbor phases, respectively, as reported by the crew. Given the daily statistics of activity over 2013-2023 (IODP, 2024a), we estimate an annual footprint of 24 $ktCO_2e.yr^{-1}$ for the Joides alone (Table S4). The remaining 15% of missions are operated by a Japanese drilling ship and by 3rd parties missions coordinated by a European consortium for which we could not gather detailed information but simply assume similar footprint which would rise the total by 15% to 27.5 $ktCO_2e.yr^{-1}$. At first order, the footprint of flights taken by scientists to join the boat, may add about 1 $ktCO_2e.yr^{-1}$ (see Supplementary Methods), yielding a total footprint of 28.4 $ktCO_2e.yr^{-1}$.

Querying the WOS database with the keyword 'IODP' over 2015-2019 we found 4 scientific publications for the GET and 577 worldwide. Accounting for a mean author fraction we would obtain a share of 0.065%. Ignoring the IODP data proceedings and non-English publications, we found 10 publications including a GET author out of 1922 in the IODP dedicated publication list (AGI and IODP, 2024). This yields an author fraction of 0.089% representing 25.3 $tCO_2e.yr^{-1}$ for the GET. We note that the publications attributed to GET by the two queries do not completely match, but that the two databases yield similar mean author fraction over the 2015-2019 period.

2.3.4.2 PIRATA footprint and share attributed to the LEGOS

The PIRATA program involves Brazil, the US and France, and is about deploying and maintaining a network of moored buoys in the Tropical Atlantic. There are currently 18 buoys points and regular oceanographic missions are conducted to maintain them and do associated measurements. Limiting our analysis to 2015-2019, we retrieved the cruise duration, typically around 30 days per year per country, and embarked scientists dedicated to PIRATA (typically 6 to 16 depending on the mission), yielding a total of 5444 person.day at sea (PIRATA, 2024a). These numbers ignore embarked scientists dedicated to other research infrastructures, such as AEROSE during US expeditions for example.

Based on technical data from the French Scientific ships and reported data for the Brown US ship, we consider a typical fuel consumption of 0.5 $m3.p^{-1}.d^{-1}$ equivalent to 1.6 $tCO_2e.p^{-1}.d^{-1}$ (See Supplementary methods) leading to a 2015-2019 average of 1.7 $ktCO_2e.yr^{-1}$ (Table S4). Then air-travels appear as negligible, but we estimate freight to add 0.1 $ktCO_2eq.yr^{-1}$ and the instrumented buoys themselves to add 0.4 $tCO_2eq.yr^{-1}$, yielding a total annual footprint of the PIRATA infrastructure of 2.2 $ktCO_2e.yr^{-1}$ (See Supplementary methods).

For 2015-2019, Web of Science retrieves only six publications worldwide out of which five have LEGOS authors, yielding an author share of 15%, while the PIRATA dedicated publication list details 19 publications with at least one LEGOS author out of 99 in total (NOAA, 2024), yielding a mean author share of 5%. In this case the WOS database clearly under-samples the literature and bias up the results, while with the dedicated publications list we obtain an infrastructure footprint of 110 $tCO2e.yr^{-1}$ for the LEGOS.

2.3.4.2 Other Oceanographic missions

In addition to these contributions to international research efforts some researchers may join ship cruises for their own research purpose which means their entire emissions should be attributed to their laboratory. For example, in 2019 at GET, one round trip mission to the Kerguelen islands was done by a researcher, which we estimate to emit 50 tCO2e (Supplementary information). In 2019 at LEGOS, there was the MOANA-MATY 2 mission, a cruise for the SURVOSTRAL program and two missions with unknown motives, with one scientist at sea for 24, 10, 9 and 6 days, respectively. Assuming the emission factor of PIRATA cruises holds (1.6 $tCO2e.p^{-1}.d^{-1}$, SI) yield a total footprint of 78 tCO2e. Given we could not find publications list nor consistent mention of the two former programs, we simply attribute the whole footprint to the LEGOS.

LEGOS also manages other ship-based observatories such as SONEL, and occasionally performs works in the Southern French territory, but we did not retrieve detailed information for 2019 and recommend a future consolidation of the overall footprint of research cruises.

3 Results

3.1 Carbon footprint of research infrastructures

We start with synthesizing our results on international research infrastructures that is the main novelty of our study. With our method, we estimated the annual CF of 44 satellite missions relevant to the Earth and Environmental Sciences, considered as individual infrastructure, to be ranging from 0.3 to 31 $ktCO2e.yr^{-1}$ with a median of 5 $ktCO2e.yr^{-1}$. The global share of attribution to laboratories are typically between 0.01 to 1% with a few outliers above 5% (Fig 1). These values broadly agrees with estimates for astronomical satellite infrastructures (Knödlseder et al., 2022), and to some extent to astronomical ground observatories, though the latter span a broader range of footprint (0.03 to 30 $ktCO2e.yr^{-1}$). We find no clear correlation between the age (first launch) of the satellite infrastructure and its footprint. This reflects the diversity of satellite weights through time and the fact that many old missions (amortized over long period) have had mission extensions (e.g., Landsat, ALOS, Jason) with successive launches increasing the total footprints. Overall, the 44 satellite missions considered in this study represent

6.3 MtCO2e (Table S3), similar to the 4.9 MtCO2e estimated for the Y astronomical space missions (Knödlseder et al., 2022).

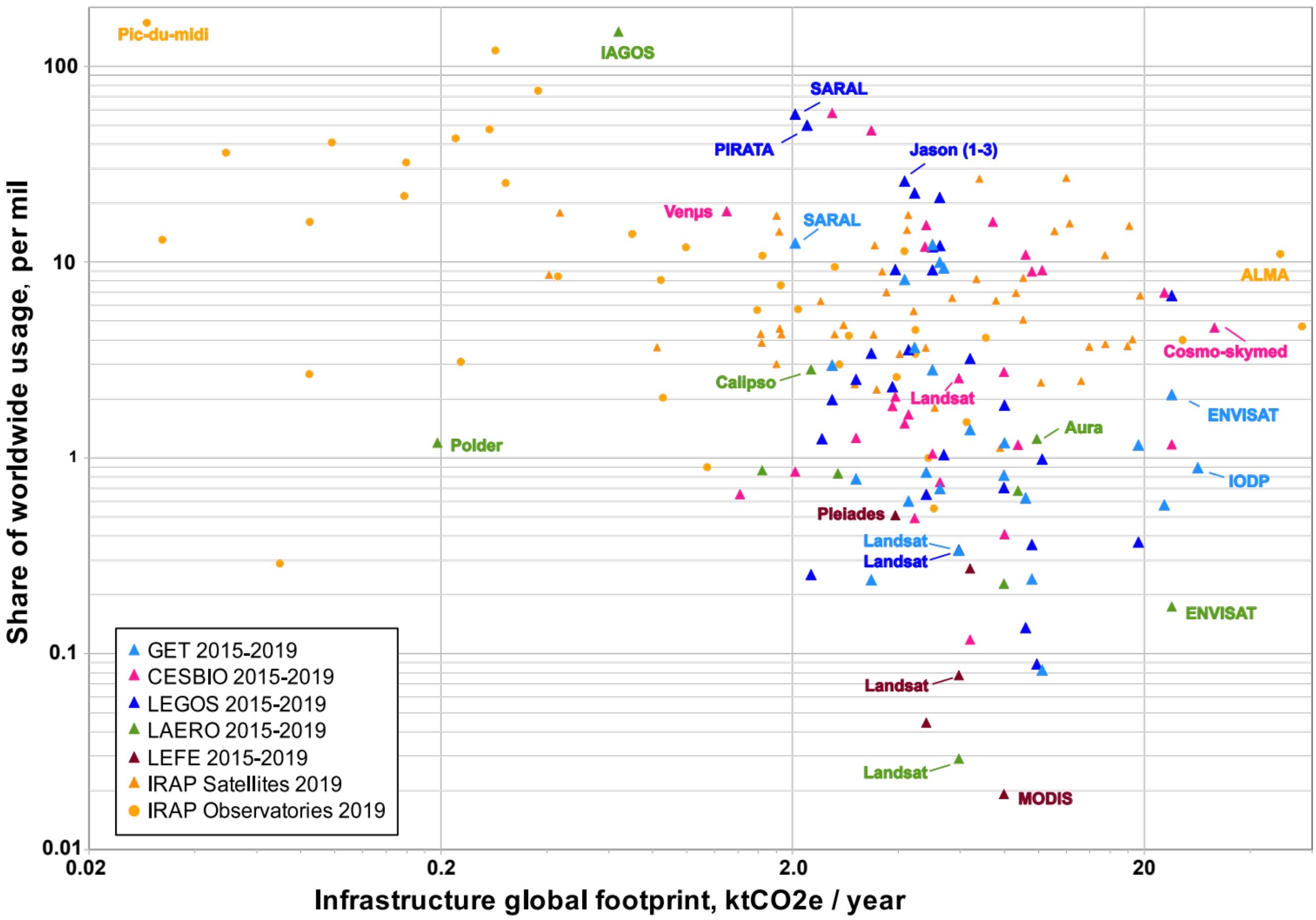

Figure 1: Share of usage of infrastructures by each laboratory against the annual footprint of the studied research infrastructures. Several examples of infrastructures are named for references. For IRAP we differentiate observatories and satellites, as derived with a similar methodology (Knödlseder et al., 2022), while for the other laboratories, all infrastructures are satellites (See Table S3) except IODP, PIRATA and IAGOS.

Turning to the aggregated footprint of all satellite infrastructures for Earth observation, it appears as the dominant share of the CO2e budget for three laboratories, IRAP, CESBIO and LEGOS, equivalent to 2800, 1284 and 933 $tCO2e.yr^{-1}$, respectively, which is typically 40-65% of the total CF (Fig 2, 3). LEGOS and CESBIO rely heavily on satellite infrastructures, as reflected by their numerous publications (263 and 417 over five years, respectively) with keywords associated with a broad diversity of satellites, nearly 30 missions out of 44 (Table S3). For GET and LAERO, where fewer researchers rely on satellite observations, we retrieve 150 and 43 publications associated with 24 and 9 missions for the 2015-2019 period, which represents 1.6 and 0.5 $tCO2e.p^{-1}.yr^{-1}$ or 398 and 45 $tCO2e.yr^{-1}$ for the whole laboratory, respectively. For the

LEFE with only 5 publications associated with 5 satellites over 5 years the footprint is below 5 tCO2e.yr^{-1} or 0.05 tCO2e.p^{-1}.yr^{-1}.

Turning to other infrastructure, for GET, IODP and ship missions to the sub-Antarctic region result in a moderate footprint of 25 and 50 tCO2e, respectively, adding 0.3 tCO2e.p^{-1}.yr^{-1} to the laboratory. For LEGOS, the PIRATA infrastructures and other oceanographic missions have an estimated footprint of 110 and 78 tCO2e, respectively, representing 1.6 tCO2e.p^{-1}.yr^{-1} together. For the LAERO, the IAGOS infrastructure is estimated to be 96 tCO2eq.yr^{-1} or 1.1 tCO2e.p^{-1}.yr^{-1}.

These infrastructures display footprint and attribution in the broad range of the satellite infrastructures and of astronomic infrastructure (Fig 1) and are consistent with the typical footprint attributed to one laboratory for individual satellite mission, mostly between 10 and 100 tCO2e.yr^{-1} (Table S3).

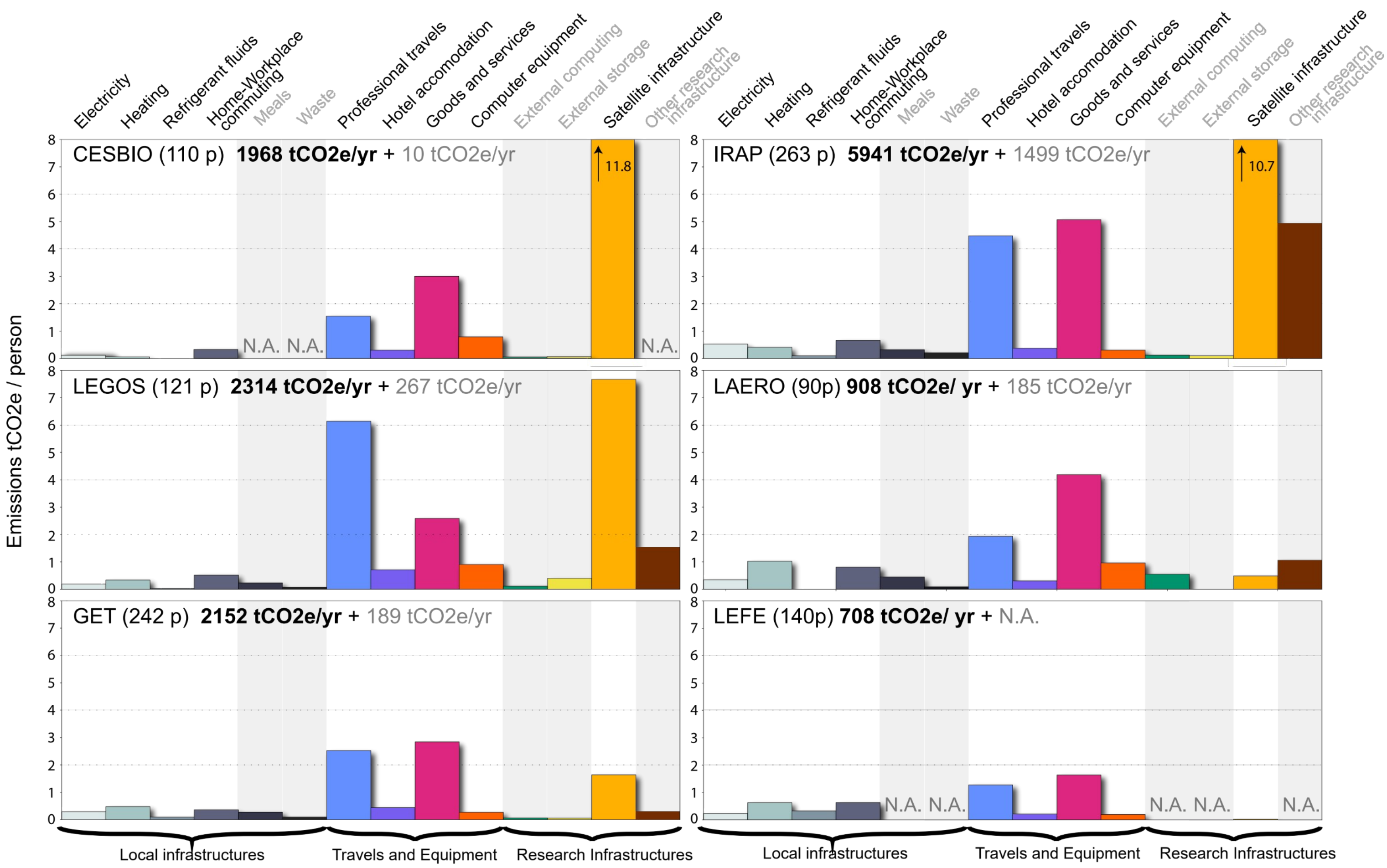

Figure 2: Carbon footprint in tCO2e per person, grouped by sectors, differentiating, local infrastructures, research activities and international research infrastructures. For each laboratory

sources that could be estimated homogeneously for all labs have a white background and their total footprint is in bold black, while sources in shaded areas (with a reported total in grey) are sources that could not be estimated homogeneously for all labs and which are thus excluded from Figure 3.

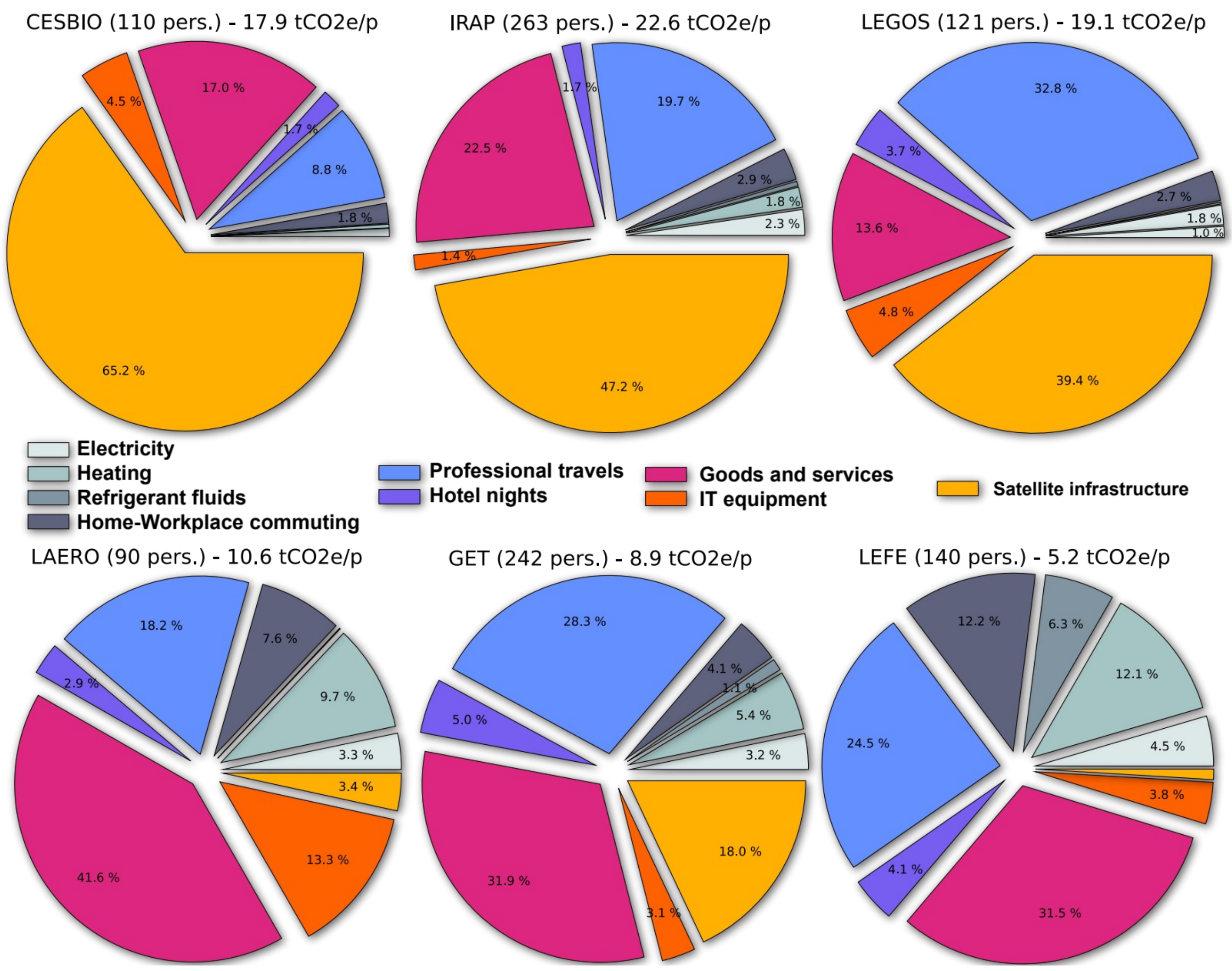

Figure 3: Proportions of the carbon footprint for the sources that could be consistently estimated for each of the six laboratories of the OMP.

3.2 Carbon footprint of laboratory purchases

Purchases are also a major share of the CF, between 2 and 5 $tCO2e.p^{-1}.yr^{-1}$ for the studied laboratories (Fig 2), which typically represent 15 - 40% of the whole footprint (Fig 3), highlighting the need to consider a comprehensive scope 3 emissions when estimating GHG budget for research laboratories (De Paepe et al., 2023). The emissions are typically distributed over a broad range of activities including services, machines and equipment for experimental research, repairs and maintenance, experimental supply and to a minor extent general supply (food, furniture, etc). IT equipment is also representing a substantial share, amounting to a minimum of 5-10% of the purchase emissions (i.e., 0.15 to 0.3 tCO2e.p^{-1}.yr^{-1}) and up to 0.9 and 1.4 tCO2e.p^{-1}.yr^{-1} for LEGOS and LAERO respectively. Importantly, the total emissions are strongly correlated to the total financial budget of the laboratory (R=0.96) with a mean footprint of 388 +/- 72 tCO2e.M€$^{-1}$ spent (excluding travel expenses) and the budget itself is strongly correlated to the staff size (R=0.80) with typically about 10 k€.yr^{-1} spent per agent, with the LEFE and IRAP at the lower and upper end of the spectrum with 4.4 k€.yr^{-1} and 13.9 k€.yr^{-1}, respectively.

Beyond IT equipment of the laboratories, the use of external IT infrastructure also represent a minor increase of the footprint, about 0.1 to 0.5 tCO2.p^{-1}.yr^{-1}. This value, however, is uncertain because of its reliance of a poll with a limited response level, except in LAERO where most researchers relying on external IT where individually asked about their practice.

3.3 Carbon footprint of professional travels

Professional travels also represent a major share (in the top 3 for all laboratories) of the CF, with a mean of 3 tCO2e.p^{-1}.yr^{-1} (Figure 2). ln all cases air-travel represents more than 80-90% of the total travel emissions, consistent with the fact it also represents more than 70-80% of the distance traveled. As a result the total traveled distance is strongly correlated with the total footprint (Table 1). The spread in emissions and traveled distances seems related to the structure and focus of the laboratories. At the upper end with 6.1 tCO2e.p^{-1}.yr^{-1} the LEGOS has many researchers funded by the IRD, an institute with a research focused on collaboration with the Global South countries, and thus often distant field areas. At the lower end with 1.3 tCO2e.p^{-1}.yr^{-1}, the LEFE has most of its researchers with teaching duties and most of its research field areas in Southwest France and the Pyrenees.

Turning to daily commuting to reach the laboratories, we estimate that it represents between 0.3 and 0.8 tCO2e.p^{-1}.yr^{-1}, thus a modest share between 3 and 12% of the total CF. The studied laboratories often have nearly 50% of the total commuting distance traveled by bicycle, train or public transport with very low emissions, while the rest is mostly traveled by car which dominate the emissions.

We also note that even if it may be somewhat overestimated, the CF for hotel nights are substantial from 0.3 to 1 $tCO2e.p^{-1}.yr^{-1}$, which is superior to commuting emissions for 4 out of 6 laboratories.

3.4 Carbon footprint of laboratory in-situ operations

Last, we find that the general operations of the building hosting the equipment and staff of the laboratory always represent a minor share of the footprint. Electricity consumption represents between 0.1 and 0.5 $tCO2e.p^{-1}.yr^{-1}$, while the heating footprint is between 0.3 and 1 $tCO2e.p^{-1}.yr^{-1}$, except for the CESBIO which benefits from a heating system based on biomass and thus has a much lower footprint of 0.05 $tCO2e.p^{-1}.yr^{-1}$. Refrigerant fluids used by some labs in cooling systems add 0.01 to 0.3 $tCO2e.p^{-1}.yr^{-1}$. The footprint of water consumption is estimated at less than 0.01 tCO2e/p for all laboratories, thus excluded from figures for simplicity, while waste disposal is estimated to represent between 0.03 and 0.2 $tCO2e.p^{-1}.yr^{-1}$. In contrast, meals taken at the workplace are representing a larger footprint between 0.23 and 0.45 $tCO2e.p^{-1}.yr^{-1}$, the spread reflecting the diversity of diet habits. Summing all these items yield a footprint of 0.8 and 1.9 $tCO2e.p^{-1}.yr^{-1}$, typically representing between 5 and 20% of the total footprint (Figure 2) except for the CESBIO with a smaller footprint due to its decarbonized heating, and because waste and meals data were not retrieved for this laboratory.

4 Discussion

Our key result is that a comprehensive scope yields large footprints above 10 $tCO2e.p^{-1}.yr^{-1}$, for most Earth, Environmental and Space Science labs, and that a substantial if not dominant part of this footprint is related to research infrastructures, in particular satellites. We thus start this discussion by comparing these footprints to other recent works on the footprint of scientific institutions, and discussing the various uncertainties that affect them. We then briefly discuss reasons for the Earth scientists to be particularly pro-active in reducing their annual footprint before quantifying some classical reduction measures and their limits and ending on less quantitative propositions that rather advocate rethinking how and why we produce knowledge.

4.1 General estimates, comparison to recent work, and major uncertainties

The carbon footprints we report are significantly above many previous estimates for European institutions. Still, excluding research infrastructures, rarely examined in the literature until now, they are in the range of other European universities or research institutes (about 10 $tCO2e.p^{-}$

^{1}.yr^{-1}, ALLEA, 2022) and other French laboratories both in terms of travels (1-3 tCO2e.p-1.yr^{-1}) and expenses (2-4 tCO2e.p^{-1}.yr^{-1}) (See Mariette et al. 2022, De Paepe et al., 2023). We note that our estimate of carbon intensity for purchases, 388 +/- 72 tCO2e.M€$^{-1}$, is about 20% higher than the estimate of De Paepe et al., (2023) for 108 French science and technology labs, at 320 +/- 100 tCO2e.M€$^{-1}$. Thus, we consider that our crude approach yields close enough results and that their more robust methodology, that we recommend for future work, would not affect our conclusions. Yet, this difference shows some uncertainty associated to the use of EF from a national database with limited and generic EF classes. Besides, this financial approaches that links prices and GHG emissions is very dependent on the time when these factors have been computed, and year-to-year comparison should acknowledge potential inflation.

The total footprint with extended scope (including satellites but no other research infrastructures based on ships, aircrafts or ground infrastructures) we have obtained a range from 5 to 30 tCO2e.p^{-1}, and above 15 tCO2e.p^{-1} for the three laboratories with substantial contribution from satellite infrastructure. For the estimated footprint of Earth Observation satellite we identify several dominant sources of uncertainties that should be addressed in future works. First, as identified by Knödlseder et al., (2022), the uncertainties on the emission factor (50 tCO2e.kg^{-1} or 1450 kgCO2e.M€$^{-1}$) remain high, and we urge actors from the space sector to release and publish additional estimates for various satellite missions. At this stage we have no way to differentiate the footprint of a new versus a follow-up mission, or a mission made of many small satellites (e.g., cubesats or nanosats) versus one large satellite of identical weight. Another issue is the time over which the footprint is distributed in order to, in a sense, amortize the footprint over a certain duration and derive an annual footprint. Especially the minimal write-off time was set to 10 years to be comparable to Knödlseder et al., 2022. Doubling this minimal time of amortization would reduce the footprint by about by 15% for most laboratories, 20% for the GET and 25% for the CESBIO, but leave satellite as a top source of CO2 in the laboratory heavily using them.

Another major uncertainty is on Ss, the share to science. Indeed, many satellites used by Earth scientists have mixed applications (military, meteorological, industrial …) and we could find no specific way to estimate the share of usage of each application. We have assumed a typical value of Ss=0.4 based on user reports of the Copernicus Sentinel satellites and applied this for 11 missions. If those missions had Ss=0.2 or Ss=0.6 the satellite footprint would only change by +/- 5% for GET, LEGOS, and LAERO reflecting the fact that many of the satellite they use are more specialized (e.g., for gravimetry, ocean waves or atmospheric chemistry). In contrast the uncertainty would reach 15% and 20% for the CESBIO and LEFE, respectively. Consistently, setting Ss=0 would reduce even more the total satellite footprint by about 10% for GET and

LEGOS, 15% for LAERO, 30% for CESBIO and 40% for LEFE. Last, if we assume that even for specialized missions some public or commercial use exist, and thus set *Ss*=0.4 for the same 11 missions and *Ss*=0.6 for all the others, this would reduce the satellite footprint by 30-35% for most laboratories (Table S3). Nevertheless, although there is clearly room for improving the estimation of the footprint of satellites, we consider that their order of magnitude will not change and therefore will remain a substantial or even dominant part of the budget for the studied laboratories.

Attempting to constrain the footprint of other research infrastructures taking parts in various Earth and Space science laboratory is even more challenging, given their diversity in size and nature. Collecting and aggregating data to derive the footprint of more research infrastructures remains a challenge for the scientific communities, with important pioneering examples from astrophysics (Aujoux et al., 2021, Knödlseder, et al., 2022), meteorology (Stevens et al., 2021), or particle physics (Bloom et al., 2022). Still, the example of IRAP shows that ground infrastructures may be far from negligible and actually represent another dominant part of the budget (Fig 2 and Martin et al., 2022a). The footprint of other infrastructures are smaller, and can range from small (IODP) to moderate (IAGOS) when attributed to a given laboratory. Still, we encourage more efforts in assessing this contribution for several reasons. First, infrastructures not yet assessed may increase substantially the global footprint of laboratories, as it was the case for IRAP. Second, including infrastructures may allow to correctly attribute emissions, and associated responsibilities, and may remove some sources from a given lab and redistribute it globally. For example air-travels to reach an IODP oceanographic cruise, as well as days at sea, should not be entirely attributed to the footprint of the laboratory. Of even larger impact, an oceanographic cruise dedicated to a given laboratory may emit up to 1.6 tCO2e.d^{-1}.p^{-1} (See SI) and weight heavily in one lab's budget. For the GET the direct and entire attribution of all days at sea would represent 672 tCO2e, more than 20 times the 25 tCO2e we obtain when distributing the footprint over the international user community. This may also be true for instruments acquired by a laboratory but actually deployed within an observatory. We could not trace in details such practices although several laboratories are taking part or even coordinating such international observatories, such as HYBAM or M-TROPICS, for the GET, and OSR-SO for the CESBIO. Still a preliminary observation for the CESBIO was that at least 63 tCO2e were associated with OSR-SO maintenance in 2019, among which 44 tCO2e of equipment purchases, which represent 13% of the CESBIO non-IT purchases. Depending on the usage of the CESBIO of the data produced by this observatory, and on the contribution of other laboratories to OSR-SO, the global footprint of the CESBIO could actually be reduced. In contrast attributing to the

CESBIO its share of footprint associated to observatories managed by other laboratories would increase its footprint. For now, it is unclear whether attributing properly the footprint of these medium scale infrastructures will increase or decrease significantly the budget of the studied laboratories.

In any case, our study highlights that it is absolutely necessary to include Scope 3 emissions, and more specifically, we insist on not only focusing on air-travels but also on purchases and research infrastructures.

4.2 Typical reduction measures and their quantitative impact

The comprehensive CF we presented allow us to estimate the effects of typical measures aiming at reducing them. Given the diversity of size and practice of the studied laboratories, we present the relative effect of these measures, although their effect in terms of tCO2e saved may be quite variable. Importantly we give the average effects for these measures for laboratories with substantial infrastructure footprint and for the two laboratories where the infrastructures are a small part of the budget (LEFE and LAERO).

First we start with commonly discussed measures, relating to building efficiency or environmentally friendly daily practice such as diets and commuting habits. Measures allowing to reduce by 50% electricity and heating, as prescribed by the national strategy to reduce carbon emissions, would typically yield global reduction of 1 to 3% and up to 4 and 7% for the LAERO and LEFE. Measures increasing carpooling and modal report to bike and public transport would represent a drop by only 0.5-2% of the global footprint if they achieve a reduction by 50% of the commuting distances traveled by cars, but up to 3 and 6% for the LAERO and LEFE. A similar reduction of 0.5-2%, would be obtained if halving the footprint of lunch meals, for example by contracting the food provider to serve more vegetarian diet and ban beef. Measures targeting waste or water would have even less impact on the CF. Thus, achieving all these measures that certainly require substantial efforts, would only have a limited impact, which even for the LEFE would remain about 15%.

Turning to measures that would affect more directly scientific practices but could probably be achieved with a limited impact on scientific output, we could envision measures affecting mobility and equipment. For example imposing train travel within metropolitan France would reduce the total footprint by 2-3%. More substantial reductions could be achieved by targeting long distance flights and frequent travelers. Indeed, the distribution of flights is often very unequal with few individuals representing a large share of the air-travel footprint (Martin et al., 2022a, Berné et al., 2022, Ben-Ari et al., 2023). Thus, flight quotas, which are already experimented by some pioneer laboratories in France (IGE, IRIT, LOCEAN), could be a high-impact measure leading to a reduction of up to 20-60% of the travel footprint (Ben-Ari et al., 2023). Various implementation of quotas are possible (e.g. by research team, reportable over 2 or 3 years, accounting for career stage) but for a first-order estimate, we consider a flight quota of 10,000 $km.p^{-1}.yr^{-1}$, attributed to each non-support staff (typically 60-70% of the total staff, Table 1). Assuming full usage and an average emission factor between medium-haul and long-haul flights (i.e., 0.17 $kgCO2e.km^{-1}$ as in Ben-Ari et al., 2023), we obtain a footprint equivalent to a reduction varying between 0% (LEFE) to 80% (LEGOS) of the 2019 travel footprint, which means 0% to 23% of reduction of the comprehensive footprint (Figure 4). Note that these numbers would increase by a few percents if we consider a stricter limit of 5,000 km per year or if we consider only 50% of the quotas would be used. For IRAP and LEGOS, this is clearly one of the most impacting measure, but with effects hard to predict on how we practice science. Indeed, video conferencing is popular and becomes more common as a replacement for flying to attend meetings or jurys, or to collaborate with distant colleagues. It is also often put forward as a solution in serious games (Gratiot et al., 2023). Still, visibility and thus career may be correlated to flying (Berné et al., 2023), even if others argued against such link (Wynes et al., 2019), and if such correlation may reflect previous practices that have rapidly evolved since the Covid crisis. In any case, beyond scientific visibility, data collection through fieldwork alone may consume a large part of quotas in some Earth, Environmental, and Space science laboratories, such as GET where missions labeled as fieldwork represent 40% of the overall mission footprint, much more than the average of other French laboratories (~7%, Ben-Ari et al., 2023). The impact on inclusion of researchers with a disability, or family constraints, may also be a source of tension when attempting to organize modal report, but some hybrid or virtual meetings may actually be more inclusive.

In terms of expenses, a detailed analysis of the impact of seven measures to reduce expenses over a database of French laboratories was performed by De Paepe et al. (2023). Most measures focused on reducing purchases by extending lifetime, or pooling equipment, or avoiding disposable devices. For life and health science, and science and technology such measures could reduce the footprint of expenses by up to 40% (De Paepe et al., 2023), which depending on the lab would mean a reduction of 7 to 13% and up to 20 and 17% for the LAERO and LEFE (Figure 4). The single measure of halving IT Purchases by extending their lifetime (if needed by paying extra warranty) represents a reduction of 2% for several labs and 6% for the LAERO. Again the impact of these measures on scientific productivity or labs' financial budget is unclear. Extra work is associated with replacing plastic by glass, which involves cleaning, or pooling lab equipment, which requires additional organization among various labs. Financial rules concerning warranties and second-hand purchases may also need to be adapted.

Whatever the associated impacts, if all these measures would be applied, they would achieve 15-20 % reduction for labs relying most on research infrastructure (CESBIO and IRAP) and about 35% for other labs (Figure 4).

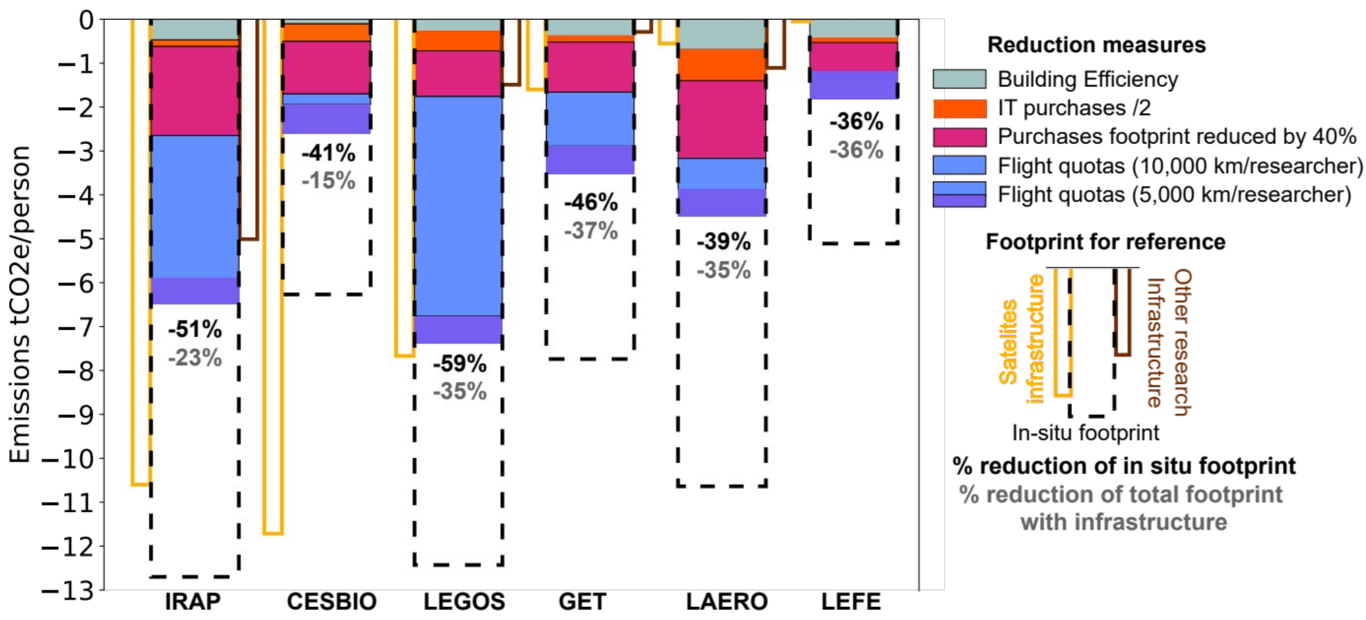

Figure 4: Reduction of the footprint achievable through a set of measures (halving building electricity and heating; halving IT purchases; 40% reduction of the purchases footprint following the measures of De Paepe et al., 2023; and flight quotas), compared to the current total in-situ footprint (dashed) and the research infrastructure footprints for each laboratory. The numbers indicate the total achievable reductions in % of the in-situ (black) and total (= in situ + infrastructures, grey) footprints.

The large share of research infrastructures is strictly capping the potential of reduction (in relative value), and we underlined that the scope of considered infrastructures for various labs may be underestimated. In absolute terms, satellite infrastructures represent several $tCO2e.p^{-1}.yr^{-1}$ and about 10 $tCO2e.p^{-1}.yr^{-1}$ for several labs. Reducing substantially the footprint of large research infrastructures cannot be limited to decarbonizing the existing ones, but also likely requires a reduction of the frequency and/or size of the newly deployed infrastructures (Knödlseder et al., 2022), informed by environmental life-cycle assessments (e.g., Janot and Blondel, 2023). Given that research infrastructures are by definition objects shared and managed by large communities, often international consortia, the challenge of defining a sustainable strategy for research infrastructures is by essence collective and political, and thus is beyond the hands of any single scientist or laboratory. Thus, the implication of international scientific institutions such as the American Geophysical Union or the European Geoscience Union could be essential to weigh in negotiations about the future of scientific infrastructures.

4.3 Other avenues to limit the carbon footprint of laboratories and research infrastructures

Here we discuss structural changes in the organization of scientific activity that may allow more substantial reduction of laboratories footprint and facilitate the implementation of measures presented above. In recent decades, scientific activity has been organized under the ideal of excellence, where funding is conditioned to the results of an intensive competition, at national and international scale. Recurrent funding is thus limited and scientists are pushed to compete with promises of breakthrough, backed by cutting-edge technologies and infrastructures. In this "fast-science" competition, the credibility of scientists and institutes is mostly assessed with publication indicators, as well as their ability to capture new research credits. Below, we briefly outline how turning away from this model, could allow to reduce the ecological footprint of laboratories, among other changes.

First, in order to publish new results at an ever faster rate, as seen from an exponentially growing number of publications over the last decades (e.g., Bornmann and Mutz, 2015), scientists devote substantial amount of resources to acquire, analyze and interpret data. Given the significant correlation between laboratory financial budget and purchase CF (Table 1, De Paepe et al., 2023), a relationship which probably also holds in the case of travel CF, we posit that the growing trend in publications is closely associated with the GHG footprint of scientific research. However, this growth of publication is correlated to a decline in disruptive publications and patents, even for the most renowned journal (Park et al., 2023), signing increasing level of waste - not to mention potential influence on the occurrence of scientific misconducts (Gross, 2016, Roy and Edwards, 2023). Thus, rethinking scientific institutions toward the framework of "slow-science", i.e., "doing less but better" (Stengers, 2018, Frith, 2020, Urai and Kelly, 2023) could preserve scientific knowledge production while reducing laboratories CF, with likely co-benefits in terms of working conditions and health (e.g., Hall, 2023).

Second, promoting and organizing collaboration rather than competition would facilitate the pooling of equipment and infrastructures (at various scales) rather than their duplication, and reduce the need for long-distance travel to acquire new data by using instead a fair network of collaboration with international colleagues, both allowing to reduce major sources of GHG emissions. Recurrent collective funding instead of episodic individual funding through grants, could allow to avoid the incentive to "use up" remaining funding (at the end of the year or of the project) into equipment. More indirectly it could favor work focusing on analyzing and interpreting archived data rather than work pushing for novel data acquisition through large grants, which is rarely fully exploited.

Last, promoting broader recognition of the role of scientists within society (actionable and socially-relevant science) rather than only focusing on innovation and mere knowledge production, could also allow scientists to spend more time on academic activities that can be achieved locally, with low-tech equipment and/or no or reduced research infrastructures. Such activities could include research-actions or participatory-science (see Lee et al., 2020), developing collaboration with policy centers, or ethics-driven engagement in various ways with diverse types of public to promote systemic understanding of the ongoing crisis and its link with social, political and economic institutions (see Fragnière, 2022, Gardner et al., 2021). This last proposition is important as greater scientific engagement is expected by the public (e.g., on issues related to climate change, Cologna et al., 2021), does not compromise scientific credibility (Kotcher et al., 2017), while it could contribute to more rapid mobilization and adoption of political measures to address the climate and biodiversity emergencies (Gardner et al., 2021, Capstick et al., 2022). Another general direction includes reflexive approaches of (geo)sciences in which we analyze our own scientific activity, frequently with an interdisciplinary approach including social sciences, trying to address interconnected questions such as how, why and for whom we work, and with which consequences (see recent examples in geoscience, Stewart and Hurth 2020, Reimer et al., 2021). In practice, these activities could be promoted by being explicitly valued within guidelines of academic jurys (for recruitment or promotion).

5 Conclusion

We have presented a comprehensive estimate of the green-house gas footprint of six laboratories from the Earth, Environment and Space Sciences (EESS). The main novelty of these budgets is that the scope 3 also includes research infrastructures, and notably satellite infrastructures. We have generalized the methodology of Knödlseder et al., (2022), to attribute a meaningful fraction of the footprint of research infrastructures to research laboratories. This fraction is obtained by counting the affiliated authors among publications associated with the infrastructures, retrieved from the global Web of Science database. The method is applied to 44 satellite missions used by geoscientists as well to 3 other international infrastructures relying on ships or planes.

Consistently with Knödlseder et al., (2022), we found that altogether, satellite infrastructures is a dominant share of the budget for three laboratories, between 40 and 65%, reaching 7 to 11 tCO2e.p^{-1}. Other type of research infrastructures were only partially assessed, but represented up to 1.5 tCO2e.p^{-1}, and a comprehensive integration of all research infrastructures into the GHG footprint of laboratories remains a challenge for future research. Together with infrastructures, air travels and purchases (mostly of scientific and IT equipment) represent other major shares of the budget, typically between 2-4 tCO2e.p^{-1} for each source, and bring the annual footprint above 10 tCO2e.p^{-1} for five out of six laboratories. As a consequence, radical footprint reduction strategies, based on flight quotas and diverse reductions of purchased equipment may reach reductions between 40% and 60% of the in-situ laboratory footprint, but is limited to reduction of 15 - 30% of the total footprint for the laboratories heavily using research infrastructures. We finally suggest that a deep reorganization of scientific activity away from a competitive fast-science ideal may be an essential step for more sustainable scientific practice.

To remain exemplary and thus contribute to political actions towards addressing ecological emergencies (Attari et al., 2016, 2019, Gardner et al., 2021), we urge the EESS community, to publicly engage into quantitative plans for ecological footprint reduction. For example, laboratories, departments, or institutes could commit into targets consistent with the 6th IPCC report (IPCC, 2022) with a reduction target of about 45% of their 2019 in-situ footprint achieved by 2030, and continued reduction beyond this date, as already pioneered by some laboratories (e.g., Pellarin et al., 2023). In parallel, we call on collective discussion across the EESS community, including large organization such as AGU and EGU, funding agencies, and space agencies, toward a rethinking the deployment of new infrastructure. Indeed, a reduction of the size and deployment frequency of new research infrastructures is probably the only way to reduce the overall environmental footprint of scientific institutions. We believe that, these two specific goals, rather than seen as a sanction or constraints, should be embraced as stimulating, long-term challenge for the emergence of a more sustainable, meaningful and heatlthier scientific practice, at the individual and collective scale (Hall, 2023, Urai and Kelly, 2023).

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Open Research

Data relevant to the carbon footprint of IRAP is available from Martin et al., 2022b. Data concerning emission factors is publicly available from UK Government (2020) and ADEME (2023). Data concerning activity and publications for the IAGOS, PIRATA and IODP infrastructures is publicly available online at AGI and IODP, (2024), IAGOS, (2024), IODP (2024), NOAA, (2024) and PIRATA (2024). Other estimates of carbon footprint derived from laboratory activity data and infrastructure data are available through the Supplementary Table 2 to 4 which are available online at https://doi.org/10.5281/zenodo.10776609. Data concerning satellite missions characteristics is available from online as summarized in Table S3.

To estimate the carbon footprint associated with travels we used the GES1.5 (https://apps.labos1point5.org/ges-1point5) online tool developed by Labos1.5 (https://labos1point5.org/).

References

Achten, W. M. J., Almeida, J., & Muys, B. (2013). Carbon footprint of science: More than flying. *Ecological Indicators*, *34*, 352–355. https://doi.org/10.1016/j.ecolind.2013.05.025

Agence De l'Environnement et de la Maîtrise de l'Energie (ADEME). (2023). French Emission Factor Database. https://base-empreinte.ademe.fr/documentation/base-carbone last accessed 06/02/2024.

All European Academies (ALLEA). (2022). *Towards Climate Sustainability of the Academic System in Europe and beyond* (Report, 1st ed.). DE: All European Academies. Retrieved from https://doi.org/10.26356/climate-sust-acad

Alvarez, S., Blanquer, M., & Rubio, A. (2014). Carbon footprint using the Compound Method based on Financial Accounts. The case of the School of Forestry Engineering, Technical University of Madrid. *Journal of Cleaner Production*, *66*, 224–232. https://doi.org/10.1016/j.jclepro.2013.11.050

American Geosciences Institute (AGI) and International Ocean Discovery Program (IODP), (2024), Scientific Ocean Drilling Database, http://iodp.americangeosciences.org/vufind/Search/Advanced, Last accessed: 20/02/2024)

Arsenault, J., Talbot, J., Boustani, L., Gonzalès, R., & Manaugh, K. (2019). The environmental footprint of academic and student mobility in a large research-oriented university. *Environmental Research Letters*, *14*(9), 095001. https://doi.org/10.1088/1748-9326/ab33e6

Attari, S. Z., Krantz, D. H., & Weber, E. U. (2016). Statements about climate researchers' carbon footprints affect their credibility and the impact of their advice. *Climatic Change*, *138*(1), 325–338. https://doi.org/10.1007/s10584-016-1713-2

Attari, S. Z., Krantz, D. H., & Weber, E. U. (2019). Climate change communicators' carbon footprints affect their audience's policy support. *Climatic Change*, *154*(3), 529–545. https://doi.org/10.1007/s10584-019-02463-0

Aujoux, C., Kotera, K., & Blanchard, O. (2021). Estimating the carbon footprint of the GRAND project, a multi-decade astrophysics experiment. *Astroparticle Physics*, *131*, 102587. https://doi.org/10.1016/j.astropartphys.2021.102587

Ben-Ari, T., Lefort, G., Mariette, J., Aumont, O., Jeanneau, L., Santerne, A., et al. (2023). Flight Quotas Hold the Most Significant Potential for Reducing Carbon Emissions from Academic Travel. Retrieved from https://eartharxiv.org/repository/view/5995/

Berné, O., Agier, L., Hardy, A., Lellouch, E., Aumont, O., Mariette, J., & Ben-Ari, T. (2022). The carbon footprint of scientific visibility. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ac9b51

Berthoud, F., Bzeznik, B, Gibelin, N., Laurens, M., Bonamy, C., et al. (2020). Estimation de l'empreinte carbone d'une heure.coeur de calcul. UGA - Université Grenoble Alpes; CNRS; INP Grenoble; INRIA. https://hal.science/hal-02549565

Blanchard, M., Bouchet-Valat, M., Cartron, D., Greffion, J., & Gros, J. (2022). Concerned yet polluting: A survey on French research personnel and climate change. *PLOS Climate*, *1*(9), e0000070. https://doi.org/10.1371/journal.pclm.0000070

Bloom, K., Boisvert, V., Britzger, D., Buuck, M., Eichhorn, A., Headley, M., et al. (2022, August 23). Climate impacts of particle physics. arXiv. https://doi.org/10.48550/arXiv.2203.12389

Bornmann, L., & Mutz, R. (2015). Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references. *Journal of the Association for Information Science and Technology*, *66*(11), 2215–2222. https://doi.org/10.1002/asi.23329

Capstick, S., Thierry, A., Cox, E., Berglund, O., Westlake, S., & Steinberger, J. K. (2022). Civil disobedience by scientists helps press for urgent climate action. *Nature Climate Change*, *12*(9), 773–774. https://doi.org/10.1038/s41558-022-01461-y

Carbou, G., & Sébastien, L. (2023). The discourses of climate inaction in the scientific community. *Ecologie & politique*, *67*(2), 71–91. In French with English abstract. https://www.cairn-int.info/journal-ecologie-et-politique-2023-2-page-71.htm?contenu=resume

Charret, G., Arnaud, A., Berthoud, F., Bzeznik, B., Defize, A., Delay, Y., et al. (2020). *Estimation de l'empreinte carbone du stockage de données* (report in French). CNRS - GRICAD. Retrieved from https://cnrs.hal.science/hal-03573790

Cologna, V., Knutti, R., Oreskes, N., & Siegrist, M. (2021). Majority of German citizens, US citizens and climate scientists support policy advocacy by climate researchers and expect greater political engagement. *Environmental Research Letters*, *16*(2), 024011. https://doi.org/10.1088/1748-9326/abd4ac

Copernicus. (2024), Sentinel Data Access Annual reports 2019-2022, https://scihub.copernicus.eu/twiki/do/view/SciHubWebPortal/AnnualReports, last accessed 20/02/2024.

De Paepe, M. D., Jeanneau, L., Mariette, J., Aumont, O., & Estevez-Torres, A. (2023, April 14). Purchases dominate the carbon footprint of research laboratories. bioRxiv. https://doi.org/10.1101/2023.04.04.535626

Fragnière, A. (2022). *The Public Engagement of Academics: from academic freedom to professional ethics* (Report of the Working Group on Research and Engagement) (p. 94). University of Lausanne: Competence Centre in Sustainability Interdisciplinary Centre for Ethics Research. Retrieved from https://www.unil.ch/centre-durabilite/en/home/menuinst/recherche/recherche-et-engagement.html

Frith, U. (2020). Fast Lane to Slow Science. *Trends in Cognitive Sciences*, *24*(1), 1–2. https://doi.org/10.1016/j.tics.2019.10.007

Gardner, C. J., Thierry, A., Rowlandson, W., & Steinberger, J. K. (2021). From Publications to Public Actions: The Role of Universities in Facilitating Academic Advocacy and Activism in the Climate and Ecological Emergency. *Frontiers in Sustainability*, *2*. Retrieved from https://www.frontiersin.org/articles/10.3389/frsus.2021.679019

Gratiot, N., Klein, J., Challet, M., Dangles, O., Janicot, S., Candelas, M., et al. (2023). A transition support system to build decarbonization scenarios in the academic community. *PLOS Sustainability and Transformation*, *2*(4), e0000049. https://doi.org/10.1371/journal.pstr.0000049

Gross, C. (2016). Scientific Misconduct. *Annual Review of Psychology*, *67*(1), 693–711. https://doi.org/10.1146/annurev-psych-122414-033437

Hall, S. (2023). A mental-health crisis is gripping science — toxic research culture is to blame. *Nature*, *617*(7962), 666–668. https://doi.org/10.1038/d41586-023-01708-4

In-service Aircraft for a Global Observing System (IAGOS). (2024), Scientific publication database, https://www.iagos.org/scientific-publications-2/, last accessed 20/02/2024.

International Air Transport Association (IATA). (2011). Guidance Material and Best Practices for Fuel and Environmental Management. IATA, 236 pp.

International Ocean Discovery Program (IODP). (2024), IODP coring overview spreadsheet, http://iodp.tamu.edu/database/IODP-JRSO_stats.xlsx, Last accessed: 20/02/2024)

IPCC, (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

Janot, P., & Blondel, A. (2022). The carbon footprint of proposed e^+e^- Higgs factories. *The European Physical Journal Plus*, *137*(10), 1122. https://doi.org/10.1140/epjp/s13360-022-03319-w

Kotcher, J. E., Myers, T. A., Vraga, E. K., Stenhouse, N., & Maibach, E. W. (2017). Does Engagement in Advocacy Hurt the Credibility of Scientists? Results from a Randomized National Survey Experiment. *Environmental Communication*, *11*(3), 415–429. https://doi.org/10.1080/17524032.2016.1275736

Knödlseder, J., Brau-Nogué, S., Coriat, M., Garnier, P., Hughes, A., Martin, P., & Tibaldo, L. (2022). Estimate of the carbon footprint of astronomical research infrastructures. *Nature Astronomy*, *6*(4), 503–513. https://doi.org/10.1038/s41550-022-01612-3

Lamb, W. F., Mattioli, G., Levi, S., Roberts, J. T., Capstick, S., Creutzig, F., et al. (2020). Discourses of climate delay. *Global Sustainability*, *3*, e17. https://doi.org/10.1017/sus.2020.13

Langin, K. (2019). Climate scientists say no to flying. *Science*, *364*(6441), 621–621. https://doi.org/10.1126/science.364.6441.621

Larsen, H. N., Pettersen, J., Solli, C., & Hertwich, E. G. (2013). Investigating the Carbon Footprint of a University - The case of NTNU. *Journal of Cleaner Production*, *48*, 39–47. https://doi.org/10.1016/j.jclepro.2011.10.007

Lee, K. A., Lee, J. R., & Bell, P. (2020). A review of Citizen Science within the Earth Sciences: potential benefits and obstacles. *Proceedings of the Geologists' Association*, *131*(6), 605–617. https://doi.org/10.1016/j.pgeola.2020.07.010

Le Quéré, C., Capstick, S., Corner, A., Cutting, D., Johnson, M., Minns, A., et al. (2015). *Towards a culture of low-carbon research for the 21st Century* (Working Paper No. 161) (p. 35). - Tyndall Centre for Climate Change Research. Retrieved from https://tyndall.ac.uk/working-papers/towards-a-culture-of-low-carbon-research-for-the-21st-century/

Mariette, J., Blanchard, O., Berné, O., Aumont, O., Carrey, J., Ligozat, A., et al. (2022). An open-source tool to assess the carbon footprint of research. *Environmental Research: Infrastructure and Sustainability*, *2*(3), 035008. https://doi.org/10.1088/2634-4505/ac84a4

Martin, P., Brau-Nogué, S., Coriat, M., Garnier, P., Hughes, A., Knödlseder, J., & Tibaldo, L. (2022a). A comprehensive assessment of the carbon footprint of an astronomical institute. *Nature Astronomy*, *6*(11), 1219–1222. https://doi.org/10.1038/s41550-022-01771-3

Martin, P., Brau-Nogué, S., Coriat, M., Garnier, P., Hughes, A., Knödlseder, J., & Tibaldo, L. (2022b, April 26). The carbon footprint of IRAP. arXiv. Retrieved from http://arxiv.org/abs/2204.12362

National Oceanic and Atmospheric Administration (NOAA). (2024). PIRATA publication list https://www.aoml.noaa.gov/phod/pne/publications.php, last accessed: 20/02/2024

Ozawa-Meida, L., Brockway, P., Letten, K., Davies, J., & Fleming, P. (2013). Measuring carbon performance in a UK University through a consumption-based carbon footprint: De Montfort University case study. *Journal of Cleaner Production*, *56*, 185–198. https://doi.org/10.1016/j.jclepro.2011.09.028

Patterson, J. J., Thaler, T., Hoffmann, M., Hughes, S., Oels, A., Chu, E., et al. (2018). Political feasibility of 1.5°C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, *31*, 1–9. https://doi.org/10.1016/j.cosust.2017.11.002

Petzold, A., Thouret, V., Gerbig, C., Zahn, A., Brenninkmeijer, C.A.M., Gallagher, M., Hermann, M., Pontaud, M., Ziereis, H., Boulanger, D., Marshall, J., Nédélec, P., Smit, H.G.J., Friess, U., Flaud, J.-M., Wahner, A., Cammas, J.-P., Volz-Thomas, A. and Team, I., (2015). Global-scale atmosphere monitoring by in-service aircraft – current achievements and future prospects of the European Research Infrastructure IAGOS. *Tellus B: Chemical and Physical Meteorology*, 67(1), p.28452. https://doi.org/10.3402/tellusb.v67.28452

Prediction and Researched Moored Array in the Tropical Atlantic (PIRATA). (2024). PIRATA cruise summary, https://www.pmel.noaa.gov/gtmba/pirata-cruises, last accessed: 20/02/2024

Reimer, C., Ruder, S.-L., Koppes, M., & Sundberg, J. (2023). A Pedagogy of Unbecoming for Geoscience Otherwise. *Annals of the American Association of Geographers*, *113*(7), 1711–1727. https://doi.org/10.1080/24694452.2022.2151406

Resnik, D. B., & Elliott, K. C. (2016). The Ethical Challenges of Socially Responsible Science. *Accountability in Research*, *23*(1), 31–46. https://doi.org/10.1080/08989621.2014.1002608

Roy, S., & Edwards, M. A. (2023). NSF Fellows' perceptions about incentives, research misconduct, and scientific integrity in STEM academia. *Scientific Reports*, *13*(1), 5701. https://doi.org/10.1038/s41598-023-32445-3

Stengers, I. (2018). *Another Science is Possible: A Manifesto for Slow Science*. John Wiley & Sons.

Stevens, B., Bony, S., Farrell, D., Ament, F., Blyth, A., Fairall, C., et al. (2021). EUREC^{4}A. *Earth System Science Data*, *13*(8), 4067–4119. https://doi.org/10.5194/essd-13-4067-2021

Stewart, I. S., & Hurth, V. (2021). Selling planet Earth: re-purposing geoscience communications. In G. Di Capua, P. T. Bobrowsky, S. W. Kieffer, & C. Palinkas (Eds.), *Geoethics: Status and Future Perspectives* (p. 0). Geological Society of London. https://doi.org/10.1144/SP508-2020-101

Urai, A. E., & Kelly, C. (2023). Rethinking academia in a time of climate crisis. *eLife*, *12*, e84991. https://doi.org/10.7554/eLife.84991

UK Government. (2020). Conversion factors condensed set 2019. Last accessed 07/12/2023 at https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019

Wiedmann, T., & Minx, J. (2008). A Definition of 'Carbon Footprint.' In C. C. Pertsova (Ed.), *Ecological Economics Research Trends* (pp. 1–11). Hauppauge NY, USA: Nova Science Publishers.

Wiedmann, T., Minx, J., Barrett, J., & Wackernagel, M. (2006). Allocating ecological footprints to final consumption categories with input–output analysis. *Ecological Economics*, *56*(1), 28–48. https://doi.org/10.1016/j.ecolecon.2005.05.012

Wilson, A. R. (2019). *Advanced methods of life cycle assessment for space systems*. PhD thesis. University of Strathclyde. Retrieved from 10.48730/nrjb-r655

World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) (2004) The Greenhouse Gas Protocol, a Corporate Accounting and Reporting Standard, revised edition.

Wynes, S., Donner, S. D., Tannason, S., & Nabors, N. (2019). Academic air travel has a limited influence on professional success. *Journal of Cleaner Production*, *226*, 959–967. https://doi.org/10.1016/j.jclepro.2019.04.109