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A comprehensive assessment of the carbon footprint of an astronomical institute

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The development and use of research infrastructures accounts for more than 70% of the carbon footprint of the Institute for Research in Astrophysics and Planetology. Our community needs to rethink this crucial facet of astronomical research to engage in effective and perennial reduction strategies.

It is a scientific fact that climate change — at a rate that is unprecedented over at least the last 2,000 years — can be attributed to human influence. The disorder has reached a point where the impacts of climate change are now directly perceptible by a large fraction of humankind, notably in the intensity and frequency of climate and weather extremes, such as floods, heat waves and droughts. The phenomenon seems to be accelerating, and each of the last four decades has been successively warmer than any preceding decade since 1850[1].

The global mean surface temperature has already risen by approximately 1.0 °C above 1850–1900 pre-industrial levels. In an intermediate emission pathway with CO_2 emission rates remaining around current levels until the middle of the century before declining, a 2.0 °C increase would be reached sometime between 2041–2060[1]. In such a world, adverse consequences on food security, water supply, habitat, or biodiversity are expected to affect several hundred million people, with a disproportionately higher risk for vulnerable populations[2] that have the smallest responsibility for climate change[3].

Avoiding such a trajectory, and remaining under a 1.5 °C increase, requires reducing our greenhouse gas (GHG) emission rates by 40–60% by 2030 relative to 2010 levels (implying an even stronger reduction relative to 2022), and reaching net zero emissions by 2050 (when anthropogenic emissions are balanced globally by anthropogenic removals). This implies an average reduction rate of 7.6% every year over the next decade[4]. The magnitude of the challenge is revealed by the recent COVID-19 pandemic, the drastic response to which resulted in CO_2 emissions falling by 6.4% in 2020 before bouncing back[5]. This is roughly the level of reduction we need to achieve every year, sustained over more than a decade. Due to the present-day structure of our societies and their deep dependence on fossil fuels, all sectors of human society are concerned, and only fundamental transformations of our organizations will enable the necessary transition. Distributing the required transformations equitably across society is fundamental for their acceptance, and there is no a priori reason why scientific research should be exempted from this effort.

In the field of astronomy and astrophysics, several carbon footprint estimates have recently been published, including an assessment for the Max Planck Institute for Astronomy in Heidelberg (MPIA)[6], and the Australian[7] and Dutch[8] astronomy communities. While these studies have identified professional air travel and supercomputing as significant sources of GHG emissions, potentially large sources of GHG emissions such as the consumption of goods and services and the use of space- and ground-based astronomical observatories were excluded from these analyses. A much wider scope of an astronomical research institute's activities was investigated for a comprehensive assessment of GHG emissions at the Institute for Research in Astrophysics and Planetology (IRAP) for the reference year of 2019[9].

IRAP is the largest astronomy research institute in France with 116 researchers, 28 postdocs, 78 engineers, technicians and administrative staff, and 41 PhD students employed over the full year of 2019. Scientists at IRAP conduct research on a variety of subjects: the geology of Earth and its ionized spatial environment, stars including the Sun and their planetary systems, the physics and chemistry of the interstellar medium, the formation and evolution of galaxies, compact objects like neutron stars and black holes, and cosmology. Research activities at IRAP include observations, modelling and theory, instrumentation and laboratory experiments. With technical personnel qualified in the field of design, construction, integration and operation of instruments on the ground and in space, IRAP is a major international centre for the development of ground- and space-based astronomical instrumentation. The institute is spread over three different sites in the south of France: two buildings in the city of Toulouse, including one shared with other laboratories, and another shared building in the city of Tarbes.

The assessment of the institute's carbon footprint was conducted by an environmental commission officially established at IRAP in 2018. To acquire the necessary skills, eight IRAP staff members, including all co-authors of this paper, followed a 40-hour training course on the Bilan Carbone, a carbon accounting methodology and set of tools that have been developed and used in France for more than 20 years.

The overall philosophy of the methodology is to identify the most powerful lever arms to achieve significant GHG emission reductions globally, rather than compiling a list of the emissions that are either the most visible, or for which an organization recognizes direct responsibility. An exhaustive approach is key to developing a perennial and effective reduction plan since it reveals the deep changes that may be required to achieve significant permanent reductions. Carbon accounting over a highly restricted scope risks excluding an institute's dominant sources of emissions and hiding the reasons behind certain sources of carbon emissions.

To perform such an assessment, a first step is to make a census of all activities performed at IRAP and then capture all the input flows that these activities critically depend upon, as well as all output flows that the institute produces and delivers to external partners. IRAP's core activities include: (a) instrument development, including hardware and software; (b) astronomical observations, laboratory experiments and data analysis; (c) analytical and numerical modelling of

Table 1 | Summary of IRAP's GHG emissions in 2019

Source	Amount	tCO_2e
Electricity	2,276 ± 80 MWh	138 ± 12
Heating	1,072 ± 36 MWh	108 ± 20
Water	4,744 ± 86 m^3	2 ± 0.3
Air conditioning	12.7 kg (R410A), 0.92 kg (R22), 0.19 kg (R32)	26 ± 6
Waste	155 ± 41 t	55 ± 20
Food	44,500 ± 15,000 meals	85 ± 50
Commuting	$(1.6 \pm 0.3) \times 10^6$ km	174 ± 67
Internal commuting	$(1.0 \pm 0.2) \times 10^5$ km	10 ± 4
Professional travel (flight)	$(5.9 \pm 0.1) \times 10^6$ km	1,126 ± 48
Professional travel (train)	$(2.5 \pm 0.03) \times 10^5$ km	1.2 ± 0.1
Professional travel (car/cab)	$(1.8 \pm 0.06) \times 10^5$ km	42 ± 6
Hotel	3,996 ± 59 nights	75 ± 6
Computer equipment	139 (139–153) units	81 ± 40
Goods and services	3.657 M€	1,335 ± 342
External computing	7±3.5 MhCPU	33 ± 26
External storage	293 ± 129 TB	26 (4–63)
Data flow	293 ± 129 TB	1.5 (0.3–3.2)
Observational data (space)	46 missions	2,800 ± 600
Observational data (ground)	39 observatories	1,300 ± 500
Total		7,418 ± 860

R410A, R22 and R32 are types of refrigerant fluid.

natural phenomena; (d) teaching, training and public outreach; and (e) events and participation in the scientific community. Category (d) extends significantly beyond the perimeter of the institute, and was mostly excluded from the reporting since most of the impact of teaching and training, including the commuting of students, is more appropriately assessed at the level of universities and schools. What remains inside our scope from category (d) are expenses connected to students directly using our resources and facilities (such as electricity used during their internships in the institute), the commuting of students affiliated to IRAP, and regular commuting of the staff between the institute and teaching sites.

According to the ISO 14069 standard, we included the following emission categories in our assessment (usually termed 'scope'): direct emissions from owned or controlled sources (scope 1); indirect emissions from the generation of purchased energy (scope 2); and all other indirect emissions (scope 3). In our case, the latter category dominates IRAP's carbon footprint. The list of sources we considered is given in Table 1. We emphasize that some GHG emissions sources were not included in our assessment, or only partially, because of difficulties in obtaining all the relevant data (for instance, the end use of some products delivered by IRAP, or support activities such as administration, maintenance, and financial and insurance services provided by the hosting institutions). Formally, the carbon footprint reported below is thus a lower limit.

In practice, the assessment of GHG emissions is performed by multiplying 'activity data' that quantify the usage of a given source (for example, kilowatt hours of electricity used, kilometres travelled and so on) with 'emission factors' that quantify its unitary carbon footprint (for instance, $gCO_2e\ kWh^{-1}$ of electricity or $gCO_2e\ km^{-1}$ for a given transportation mode). The purchase of goods and services is included in a similar way, following a so-called cost-based approach that converts the economic value of the purchased goods and services into an estimate for the associated GHG emissions using economic sector-average emission factors (typically equating a k€ or M€ of expenditure on a given family of products, for example, electronic equipment, to $kgCO_2e$ or tCO_2).

Activity data were obtained from a variety of sources, including travel or purchase listings provided by the institute's administration, power or water consumption measurements by our hosting university, or an online survey of the staff. Emission factors were taken from the Base Carbone database of the French Environment and Energy Management Agency (ADEME)[10]. Uncertainties on both activity data and emission factors were adopted following the Bilan Carbone recommendations, or adapted to our specific case when possible.

Results

Table 1 presents our estimates of IRAP's GHG emission by source, while Fig. 1 provides a graphical representation of the data. In total, we estimate that IRAP had a carbon footprint of approximately 7,400 ± 900 tCO_2e in 2019. About 60% of the footprint is attributed to the use of observational data from space missions and ground-based observatories, and the use of these infrastructures is clearly the primary source of IRAP's GHG emissions. The second major contributor (18% of emissions) is related to the purchase of goods and services, of which an estimated 85–90% is attributed to the instrument development projects undertaken at IRAP. Professional travel amounts to 16% of IRAP's carbon footprint, of which 96% is due to air travel. The latter source is very unevenly distributed across the staff, with 20% (50%) of the emissions being attributable to 12 (48) people, out of a total of about 260 employees. Interestingly, there is a very limited effect of seniority in this distribution: the fraction of the staff responsible for 20% (50%) of the emissions has an average age of 46.9 yr (47.3 yr), to be compared with an average of 44.3 yr for the whole staff. There seems to be a much more pronounced effect of gender: 92% (87%) of the persons responsible for 20% (50%) of the emissions are male, to be compared with an average for the whole staff of 75%. Finally, there is a non-negligible fraction of engineers and technicians among the people responsible for most of the GHG emissions from professional travel, and they are primarily involved in the development of future space missions, demonstrating that this activity is an important driver of travel-related emissions at IRAP.

Our results clearly point to the main driver of IRAP's carbon footprint: astronomical research infrastructures. In total, use of data from astronomical facilities and the purchase of goods and services for instrument development account for about 70% of IRAP's carbon footprint. This is a considerable contribution, and one omitted in previous estimates of the carbon footprint of astronomical institutes. In addition, it is likely that a significant fraction of professional trips at IRAP are also connected to instrument development projects, which only strengthens this conclusion.

Whether such a repartition can be considered as generic for the astronomy community remains to be confirmed by performing comprehensive carbon footprint assessments at other institutes. IRAP

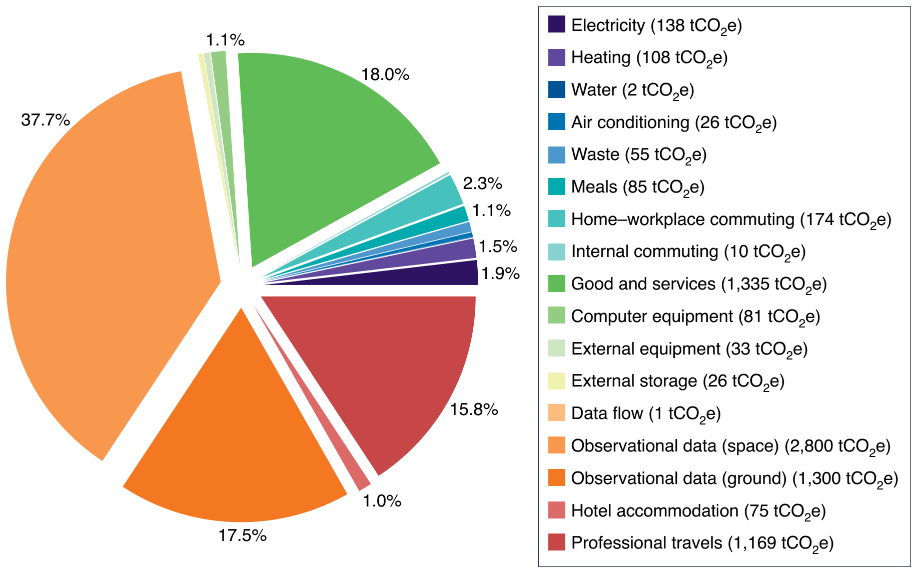

Fig. 1 | Distribution of IRAP's GHG emissions by emission source in 2019. A graphical representation of Table 1.

has a long history in instrument development and observational data analysis that is no doubt reflected in the present result, which already exhibits interesting similarities and differences to other published assessments. At IRAP, flights account for 8.1 tCO_2e per researcher with a PhD degree, which is comparable to the estimates of 8.5 tCO_2e being found for MPIA and 12.0 tCO_2e for the Australian community[6], but much larger than the 2.0 tCO_2e per researcher for the Dutch community[8]. Conversely, the emissions from supercomputing at IRAP amount to 0.2 $tCO_2e\,yr^{-1}$ per researcher, on average, which covers the impact from electricity consumption, equipment, and operations of the computing centres; at MPIA, supercomputing generates an average 4.6 $tCO_2e\,yr^{-1}$ per researcher, from electricity consumption only. Only a small part of the difference can be explained by the carbon intensity of electricity, which is a factor ~4 higher at MPIA with respect to IRAP.

An important factor affecting the final repartition of GHG emissions is that the operation of local infrastructure – heating, electricity, commuting, food, waste and so on – makes a relatively small contribution of about 800 $tCO_2e\,yr^{-1}$ to IRAP's carbon footprint. The energy sources from which electricity and heating are produced have a relatively low carbon footprint, with electricity being predominantly of nuclear origin in France and heating of our largest building arising from biomass burning, with related emission factors being 60–70 $gCO_2e\,kWh^{-1}$. Assuming a worst-case carbon intensity of ~800 $gCO_2e\,kWh^{-1}$ instead – representative of countries like Australia, Poland, China, India, or South Africa – the related sources would increase to about 2,700 $tCO_2e\,yr^{-1}$, comparable to the sum of professional travels and purchase of goods and services at IRAP. A higher carbon intensity of electricity would also affect other sources such as external computing, and to some extent the purchase of goods and services. If IRAP were situated in a country that relies significantly on fossil fuels for electricity production and heating, we estimate that our total 2019 footprint would be at least 10,000 tCO_2e.

Discussion

This assessment shows that performing research in astronomy and astrophysics at IRAP according to the standards of 2019 stimulated GHG emissions equivalent to 28 $tCO_2e\,yr^{-1}$ per person involved in that activity, on average. These emissions are spread across a variety of social and economic sectors and dividing GHG emissions of an activity by the number of people working on it is a standard metric that enables comparison between entities of the activity sector and between different activity sectors. It is a measure of the carbon cost of what this or that activity provides, which is relevant in anticipation of trajectories towards a sustainable future.

The global average target of 2 $tCO_2e\,yr^{-1}$ per capita by 2050 is a budget within which societies should fit what they deem necessary to human life. How emissions could be distributed across activity sectors is a political question that needs to be addressed by a wide-ranging democratic decision process. The place of scientific research should naturally be part of this discussion, informed by a quantitative estimate of its environmental footprint and social benefits. The discussion should not be restricted to the research community alone.

We estimated that the total carbon footprint of IRAP could be reduced by up to 10% by changing our travelling and commuting habits. Since the impact of professional travel is very unevenly distributed across IRAP staff, significant reductions can be achieved by enforcing very reasonable limits that would largely preserve the possibility to meet and exchange in-person with international colleagues. Refurbishing the local infrastructure in line with current standards or goals would only provide an improvement at the per cent level. Achieving stronger reductions to meet France's national reduction targets of 50% by 2030 and 80% by 2050, requires acting on the main shares of our footprint that relate to research infrastructures. Efficient measures have to be taken at a level that essentially reaches beyond the perimeter over which IRAP has some operational control. Revising the criteria for the purchase of goods and services offers some potential for carbon footprint reduction. Since most of the instrumental projects IRAP is involved in are multilateral, however, this solution involves a progressive shift of standards that should be promoted and supported at the institutional level. We further note that establishing both new purchase procedures for research organizations and the environmental footprint information by all suppliers will take years.

The magnitude of the challenge and the necessity to quickly engage in an effective transition calls for acting on all levers: lowering the carbon intensity of our activities, reducing their pace, and shifting our work practices towards less emission-intensive options. In doing so, we should not disregard the second option, especially since it is directly under our control as a community and can have quick and direct effects, as opposed to the uncertain decarbonization trajectories of suppliers and partner organizations. Ultimately, our recommendation for a community-based reduction strategy would be to divert a growing fraction of our budgets to fund the decarbonization of existing operational infrastructures, enhance the research and development of low-carbon technologies on which future projects will be based, and to reduce the cadence and scale of the deployment of new research infrastructures. The latter point cannot be left out of the equation, otherwise any benefit in decarbonizing existing facilities will be promptly wiped out by an increase in the number of facilities. The timescales involved in the development of astronomical research infrastructures lock in our emissions for the next decades, and the problem will only be exacerbated if we continue to postpone the implementation of a far-reaching emissions reduction strategy.

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Competing interests

The authors declare no competing interests.