What is the way forward for sustainable Earth Science and for Space Observation?

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(1) GET, UMR 5563; (2) LEGOS, UMR 5566; (3) IRAP, UMR 5277; (4) LAERO, UMR5560;

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Many other colleagues from each lab "commission environnement" are acknowledged for helping to produce the budgets presented here.

Introduction

The last IPCC reports underlines the need for an immediate and rapid decay of greenhouse gases (GHG) emissions. To maintain global warming below 1.5°C emissions should be **reduced by ca 45% and ca 80% before 2030 and 2050**, respectively, reaching an average of **ca 2 tCO2e /pers** on Earth (see Fig TS.9 of IPCC, WG3, 2022). Although responsibilities vary, it is clear that substantial reductions must be implemented across all aspects of society including academia.

Actually, given their role in informing and alerting the public about climate change, it can be argued that the scientific community should have a leading role and demonstrate exemplarity in terms of reducing their environmental impact. Below, we present very exhaustive GHG budget for four Earth and Space Science laboratories, and question the way forward for sustainable research.

Figure 1: Overall GHG budget for 4 OMP's laboratories (2019)

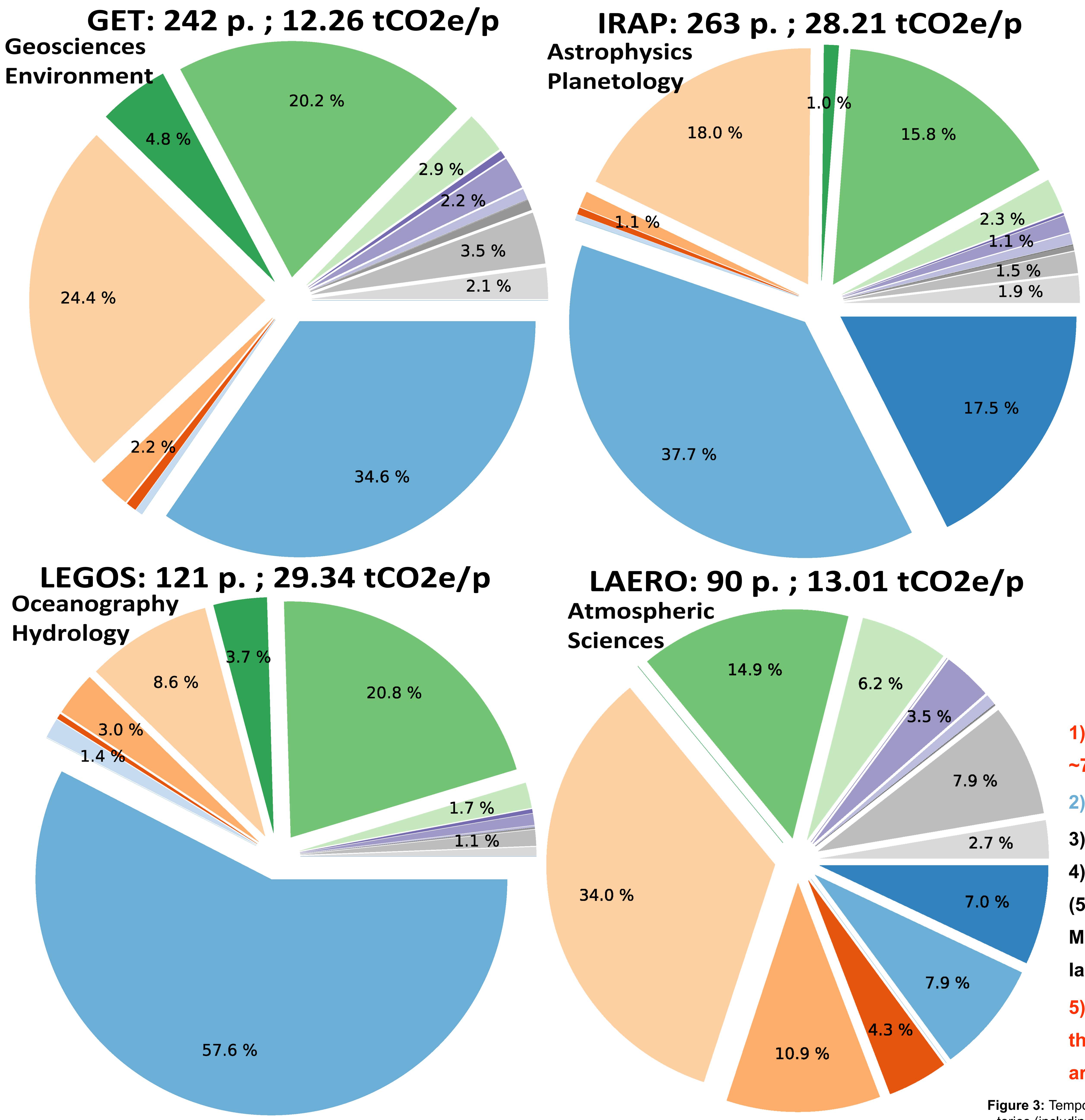


Table 1: Emissions (tCO2e/p) by sources and lab

Sources	GET	IRAP	LEGOS	LAERO	
Electricity	0.27	0.52	0.18	0.35	Local Infrastructure 5-15%
Heating	0.44	0.41	0.33	1.03	
Cooling Fluids	0.09	0.10	0.03	0.01	
Water	0.00	0.01	0.00	0.00	
Waste	0.09	0.21	0.03	0.10	
Meals	0.28	0.32	0.23	0.45	
Int. Commuting Building	0.06	0.04	0.08	0.05	
Commuting	0.36	0.66	0.52	0.81	Transport 20-25%
(Air-)Travels	**2.53**	**4.45**	**6.26**	**1.94**	
Hotels	0.60	0.29	1.10	N.A.	
Expenses	**3.06**	**5.08**	**2.59**	**4.42**	
IT equipment	0.27	0.31	0.91	1.41	IT 5-15%
Ext. computing	0.09	0.13	0.11	0.56	
Ext. IT Storage	0.06	0.10	0.41	N.A.	
Data flow	N.A.	0.01	N.A.	N.A.	
Infrastructures (Space)	**4.06**	**10.65**	**16.53**	**1.06**	External 15-50%
Infrastructures (Earth)	N.A.	4.94	N.A.	0.91	

Take Home Messages

1) Scientific activity per lab member ~ 1.5-3 average French ~7-15 times 2050 sustainable goal (2 tCO2e/y).

2) Satellite footprint is up to 50% of the total.

3) Expenses and airtravel are 30-50% (>> local structures)

4) Emissions are inequally distributed ! Ex: in IRAP, 20% (50%) of flights' CO2e is due to 12 (45) people (i.e., 5-15%, Martin et al., 2022), experimentalists spend more, only some lab members work with remote sensing, etc

5) Substantial reduction (which are urgent) will require re-thinking our activity: slow science ? local field work ? more archive data and less new satellite missions ?

Methods to estimate the GHG budget for each OMP laboratory

In-situ (see Martin et al., 2022)

We followed the method proposed by Labos1.5 using the online tool GES1.5 (Mariette et al., 2022) which estimate total emissions in CO2 equivalent (CO2e) combining emission factors (EF) to activity data, including:

-- Expenses (on goods and services) with a set of EF for each code NACRES, applied to the financial budget.
-- **Business travels**, based on mission listings (incl. plane contrails).
-- **Building consumptions**, based on administrative data.
-- **Commuting** based on a anonymous survey with 40-60% reply rate among the different staff categories.

Additionally we developped our methodology to estimated CO2e from:
-- **Meals**, and **external computing** and data storage (derived from the survey).
-- **Waste, water, building construction** (not amortized yet) **and hotel nights**.

Space infrastructure (except for IRAP done as in Martin et al., 2022)

We adapted the methodology of Knodleser et al., 2022 used to estimate the carbon footprint related to astronomical observations from satellite and from ground observatories.

1) **The carbon footprint of a satellite:** was derived from their payload weight and a EF of 50 MtCO2e /kg (as in Knodleser et al 2022). *One exception the Shuttle Radar mission where we use a financial EF and the mission total cost.*
Assuming 2% of the original CO2e is added for each year of mission operation, we get the total footprint of a satellite $\mathbf{CO2_{sat}}$

2) **Repartition over time:** assumes an amortization time, $\mathbf{T_a=30}$ **yr**, representing the typical duration of scientific interest in the mission, rather than the mission lifetime. *Exception: We used the mission lifetime (>30 yr) for Landsat (50 yr) and SPOT (36 yr)).*

3) **Share of emission to each lab:** For optical, Earth-Observation satellite we assume the scientific usage fraction is $\mathbf{F_{res}=0.6}$ (Fig 2), while it is 1 for other satellite (Table 2). In Web of Science, we extracted all articles having keywords associated with each satellite/instruments in their title / keywords/abstract (not full text) for each lab ($\mathbf{N_{lab}}$), and in the world ($\mathbf{N_{world}}$). *Issues : some papers are missed... some papers are from other fields, especially for satellite with a common name (GRACE) and in the years near of before the launch date. Still given we use N_{lab} / N_{world} to attribute a share of CO2 to each lab, some of these errors may cancel out.*

4) **The annual footprint:** of a lab associated to each satellite is:
Then the sum for all satellite is smoothed over 5 years (Figure 3).

$$CO2_{sat}(yr) = \frac{CO2_{sat}}{T_a} \frac{N_{lab}}{N_{world}} F_{res}$$

Uncertainties

Uncertainties are hard to estimate but several independent components have 50% to 80% uncertainties and the final uncertainties on the total (from quadratic sum) are between 10 and 30%.

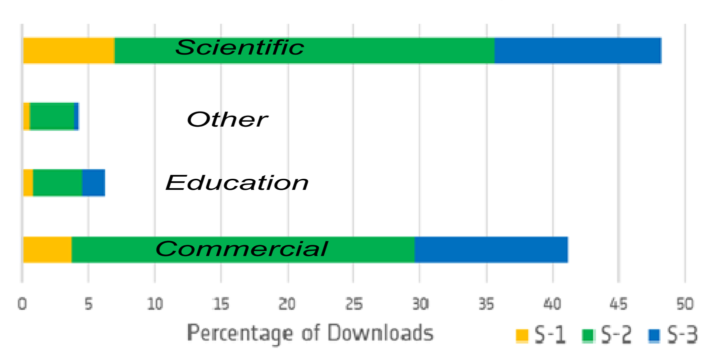
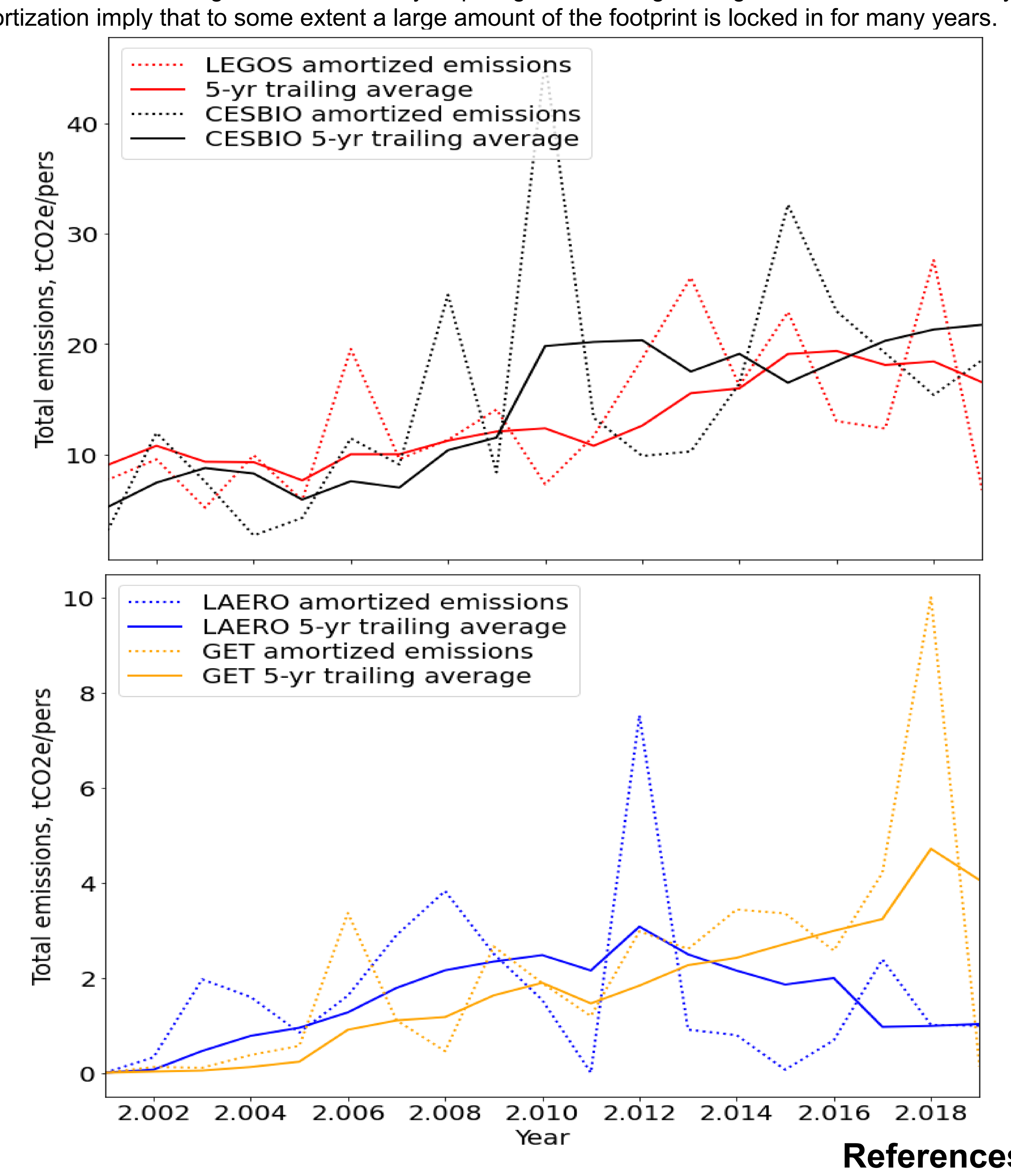


Figure 2: Percentage of downloads per user type for Sentinels-1, -2, -3 in 2020. From the Sentinel annual users' report.

Table 2: List of the considered satellites (except for IRAP), with the one with non scientific usage in red.

Satellite / Instrument	Payload (kg)	Articles	Total emissions (ktCO2e)
Landsat	13963	26159	**785**
GRACE	864	4235	**60**
MODIS-ASTER	8307	28491	**511**
SPOT	12250	2241	**676**
Pleiades	1960	370	**120**
JASON	1500	1003	**86**
Topexposeidon	2402	2273	**154**
Rapideye	780	562	**50**
TRMM	3524	4299	**240**
GPM	17500	2923	**1015**
Sentinel 1	4600	3514	**267**
Sentinel 2	2400	4643	**139**
Sentinel 3	2500	577	**143**
Sentinel 5P	820	323	**45**
Terrasar-X	1230	1655	**80**
Cosmo-skymed	7600	563	**494**
ERS-1	2154	1884	**127**
ENVISAT	8140	4231	**488**
ERS-2	2516	1493	**166**
Radarsat-1	2750	460	**187**
Radarsat-2	2300	1316	**150**
RCM	4200	1854	**223**
JERS-1	1400	331	**78**
ALOS	5930	1600	**344**
SRTM (*)	1450 (*)	2549	**203**
CryoSat	1470	592	**86**
IceSat	970	1649	**54**
EO-1	588	1232	**39**
SeaSat	2300	1758	**115**
SMAP	952	927	**54**
Meghatropiques	1000	1174	**61**
SMOS	670	1866	**42**
Venus	260	67	**14**
IceSat-2	1514	301	**82**

Figure 3: Temporal evolution of the amortized carbon footprint of satellite research in four OMP laboratories (including CESBIO (Ecology)). The footprint is proportional to publications using satellites and thus to the proportion of staff using satellite, much larger in CESBIO and LEGOS than in GET or LAERO. Also note the large annual variability requiring a smoothing average. Last note that the 30-y amortization imply that to some extent a large amount of the footprint is locked in for many years.



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