APACHE

Analysis of climate feedback PArameter Changes from Heat Evolution

Product User Manual

	Name	Organisation	Date	Visa
Written by :	Michaël Ablain Camille Szczypta Robin Fraudeau Victor Rousseau Zacharie Barrou Dumont	Magellium	23/02/2025	
	Benoit Meyssignac	LEGOS		
Checked by :	Michaël Ablain	Magellium	23/02/2025	
Approved by :	Joël Dorandeu	Magellium	23/02/2025	

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1. Introduction

1.1. Scope and objectives

This document is the **Product User Manual (PUM)** dedicated to the content and format description of the climate sensitivity products.

The PUM is intended for a wide range of end-users who wish to understand and use the product effectively. This document provides detailed specifications for these products, including content, format, naming conventions, and an overview of the retrieval method. It offers key information on the product's characteristics, usage terms, and available technical support, without requiring extensive technical knowledge. This is the primary document that users should read before handling the products.

For comprehensive explanations of processing methods, readers are invited to consult the **Algorithm Theoretical Basis Document** [AD1].

1.2. Document structure

In addition to this introduction, the document is organised as follows:

- Section 2 summarises the algorithms of the processing chain.
- Section 3 presents the product's content.
- Sections 4 presents data policy and product access.

1.3. Applicable documents

Id.	Ref.	Description
AD1	GIECCO-DT-135-MAG_ATBD_climate_sensitivity	Algorithm Theoretical Basis Document (ATBD)

Table 1: List of applicable documents

1.4. Terminology

Abbreviation/acronym	Description
ATBD	Algorithm theoretical basis document

BAR	Barystatic sea level
DOI	Digital Object Identifier
ECS	Equilibrium climate sensitivity
EEI	Earth Energy Imbalance
EWH	Equivalent water height
GM	Global mean
GOHC	Global ocean heat content
GOHU	Global ocean heat uptake
GMSL	Global mean sea level
GMST	Global mean surface temperature
GMSSL	Global mean steric sea level
NetCDF	Network common data form
OHC	Ocean heat content
PUM	Product user manual
SL	Sea level
TOA	Top-of-Atmosphere

Table 2 : List of abbreviations and acronyms

2. Algorithm

2.1. The retrieval methodology

The radiative forcing (F), largely driven by CO_2, causes other elements of the climate system to react by damping or amplifying the warning. This response is referred to as feedback and is quantified by the climate feedback parameter λ, also defined as the parameter which determines the magnitude of the Earth radiative response to a given change in global mean surface temperature (GMST). If λ plays a central role in the Earth's climatic response to an increase in CO2 concentration, it is currently poorly constrained and thus subject to significant uncertainties. The Equilibrium climate sensitivity (ECS), which depends on λ, is therefore very sensitive to the uncertainties in the λ estimates. Reducing the uncertainty in the estimate of ECS thus necessarily involves better estimating the λ parameter, particularly by successfully constraining it more effectively. The difficulty in constraining λ lies in the fact that it can not be directly measured and must therefore be estimated through various methods based on the global energy balance approach (Budyko, 1969), which is defined as:

$$\Delta N = \Delta F + \lambda \Delta T \qquad \text{Equation 1}$$

N represents the Planetary Heat Uptake, which represents the Earth's Energy Imbalance (EEI), and is broken down into a term F, representing the radiative forcing and a term λT, representing the Earth's radiative response, with λ being the climate feedback parameter and T the surface temperature of the Earth at 2 metres. In the current transient regime that characterises contemporary climate change, solving the energy balance equation (Equation 1) allows for an estimation of λ. This estimation can be done in several ways but in our study, we focus on the method based on a linear regression of the energy budget. A major problem with all these observational methods (and also with the used regression approach) is that they provide estimates of the λ parameter during the historical period, which are potentially different from the equilibrium climate feedback parameter λeq, which is the one we are aiming to calculate. Over a defined time period, the historical λ parameter is related to the radiative forcing change (ΔF), the global mean temperature variation (ΔT) and the evolution of planetary heat uptake (ΔN), by the global energy budget also deduced from the Equation 2 and described by the following equation:

$$\lambda = \frac{\Delta N - \Delta F}{\Delta T} \quad \text{Equation 2}$$

We use a differential form of the energy budget and regress ΔN - ΔF on ΔT for time windows of more than 25 years starting from 1957. We use this approach rather than others because regressions are a better estimator of the λ parameter, they make full use of available data and they rely on recent instrumental data without depending on a late 19th century reference state that is still largely unknown.

First, the estimation of λ was carried out using long data series covering the period from 1957 to 2020 (called the Ensemble dataset), allowing for the description and characterization of the temporal variability of this parameter. Secondly, and following the same methodology as before, λ was estimated using shorter series (between 24 and 35 years of annual data) drawn from various EEI datasets available for more recent periods, including in particular the EEI product derived from the MOHeaCAN processing chain.

- ***Study of the temporal variations of λ (Ensemble dataset):*** the data series are considered over the period from 1957 to the present day, depending on their temporal availability.
    - *Temperature T:* the HadCRUT4v2 dataset (Cowtan and Way, 2014), covering the period from 1850 to 2021, was used. It is downloadable here. Several post-processing steps are then applied to the original time series. Firstly, a 15-year low-pass filter is applied to it. The IPCC reference period 1850-1900 is considered as the reference period and the temperature anomaly is therefore recalculated for the period 1957-2021 compared to this reference period. Finally, to correct the temperature values at the ocean level, for which HadCRUT4 considers SST and not an atmospheric temperature at 2m, a coefficient of 1.09 is applied to the time series, following the recommendations of Richardson et al. (2016). As HadCRUT4 is no longer maintained, the new HadCRUT5 dataset (Morice et al., 2021)is also post-processed (strictly in the same way as for HadCRUT4) and recorded for the period 1957-2024.
    - *Radiative forcing F*: the set of 100,000 members of AR6 radiative forcing from the IPCC (Smith et al., 2021) is used to describe the period from 1850 to 2019 and is downloadable here. A set of 500 solutions are randomly extracted from the set of 100,000 members, then filtered via a 15-year low-pass filter. As for temperature, the 1850-1900 period is considered as the reference period and the average value obtained over this 50-year period is therefore removed from

the 500 time series to generate a set of 500 solutions for the period 1957-2019, a set allowing to represent and therefore subsequently to take into account the dispersion and therefore the uncertainty of these radiative forcing time series.

- *Planetary Heat Uptake EEI*: to quantify the EEI, the heat stored in each of the four reservoirs of the climate system (cryosphere, atmosphere, land and ocean) must be added together.
    - Regarding the 3 reservoirs other than the ocean, this represents only 7% of the total absorption and we use the most recent estimate from the GCOS dataset (von Schuckmann et al., 2022). The 3 time series of heat content for each of the reservoirs, available from 1960, were previously filtered via a 15-year low-pass filter. In order to obtain the absorbed heat values, the heat content time series were then derived and summed to obtain the total component of heat absorbed at these 3 reservoirs.
    - The largest proportion of heat is absorbed by the oceans (OHU for Ocean Heat Uptake). To create this time series for the period from 1957 to 2020, several datasets were considered and combined to reduce the constraints and limitations of each dataset. Whatever the type of data considered, all series are initially filtered via a 15-year low-pass filter and extracted over the period of interest, namely from 1957 to 2020. The following are taken into account in this work:
        - OHU ARANN, available here.
        - OHC from 5 in-situ products, namely 2 sets of EN4 (Good et al., 2013), uone of ISHII (Ishii et al., 2017), one of IAP (Cheng et al., 2017, 2020) and one of World Ocean Atlas (Levitus et al., 2012), derived to generate OHU time series and then averaged to create a unique in-situ OHU time series.
        - the thermosteric component of sea level, produced from data measured by tide gauges and altimetric and gravimetric satellite products to which the equations of the sea level budget have been applied, available here. This series is converted to OHC via an expansion coefficient of 0.125 and then derived to obtain an OHU time series.

      Once the 3 OHU series are obtained (average series and associated variance/covariance matrices), each is then expressed as a set of 100 members and then the 3 sets are concatenated to obtain a combined set of 300 members. From this set, an average OHU series and its time series of uncertainties are generated.

      This OHU series is finally added to the heat absorbed series in the other 3 reservoirs to produce the EEI time series necessary for the estimation of the parameter λ, over the period 1957-2020.
- *Linear regression methodology*: We thus have a filtered time series of T, 500 filtered time series of F, and a filtered time series of EEI to which we have an associated uncertainty time series that allows us to deduce the variance-covariance matrix. From this matrix, we randomly generate 500 EEI series. This then allows us, for each considered time window, to estimate the parameter λ by regressing the series of T 500 times with the 500 pairs of EEI-F (500 random series of EEI from the variance-covariance matrix and the set of 500 solutions of F). For a given period, the estimated λ then corresponds to the

median of the 500 lambdas obtained by regression, with the dispersion of the 500 λ providing an indication of the uncertainty associated with λ. This work is carried out on sliding time windows of 25 years and more, starting from 1957, which allows us to obtain N time series of λ, the longest obtained from the 25-year sliding windows and consequently ranging from 1970 to 2005.

- ***Estimation of λ over recent periods :*** the estimation of λ over more recent periods from other EEI datasets is done in the same way as described previously. For T and F, the time series (series T and set of series F, respectively) described previously are used for the calculation of linear regressions. For EEI, 3 other datasets were considered.
  - *EEI DEEP-C :* this dataset is a combination of the ERBS WFOV v3.0 product for the period 1985-1999 and the CERES v4.1 product for the period 2000-2019. It is directly an EEI product available over a 35-year time window, centered on the year 2002.
  - *EEI MOHeaCAN :* this EEI product comes directly from the MOHeaCAN chain. This is the most recent version produced, and as the chain evolves, the new MOHeaCAN EEI product will therefore be considered for the calculation of the parameter λ. Currently, the estimation has been made from the EEI v5.0 product, available for the period 1993-2022 (30 years).
  - *EEI derived from the sea level budget of ESA-CCI:* the thermosteric series of the sea level budget of the ESA SLBC CCI product (Horwath et al., 2022) was also considered. This series was converted to OHC via the expansion coefficient of 0.125, then derived to obtain an OHU series. Finally, to move from OHU to EEI and take into account the heat absorption by the 3 other reservoirs, a factor of 1/0.91 was applied to the time series, available over the 24-year period from 1993 to 2018. The calculated λ is therefore centered on 2005.

  For these 3 EEI datasets, the uncertainty range was also calculated following the same methodology as that described previously for the long time series with a time-variable λ.

2.2. Product limitations

The uncertainty of climate sensitivity depends both on the uncertainty in radiative forcing data and also on the uncertainty in EEI, to which climate sensitivity appears to be particularly sensitive. By improving gravimetric data, on which the calculation of EEI depends, we should reduce the uncertainty in EEI and thus tend to improve the estimation of ECS *in fine*.

2.3. Optimisation strategy

No optimisation strategy in terms of calculation or product definition has been implemented for the product. Indeed, although the time series are long (60 years), the volumes of data manipulated remain modest and do not require an optimisation strategy.

3. Product description

The algorithm outputs three netCDF files intended for users as well as graphs visually representing those products:

- The climate feedback product contains the estimations of the climate feedback parameter, with values regressed from time windows of 25 years or more from 1957 to 2017. More attention is given to the 25 years window and its associated uncertainties are also provided.
- The post-processed input product contains the time series of N, F, and T used in the regressions of the climate feedback parameter, as well as their associated uncertainties.
- The alternative climate feedback product provides climate parameter estimations from alternative sources (ex: the MOHeaCan alti-gravy method) for more recent periods..

3.1. Spatial information

No spatial information is given as only global values are generated.

3.2. Temporal information

All time-series are provided on a yearly basis, from 1957 to 2019.

3.3. File format

The product is delivered as Network Common Data Form version 4 (netCDF4) file with metadata attributes compliant with version 1.7 of the Climate & Forecast conventions (CF V1.7).

3.4. Climate feedback product

3.4.1. File naming convention

The product follows the naming standard:

CS_<START_DATE>_<END_DATE>_<VERSION>.nc

where:

- <START_DATE> and <END_DATE> give the UTC start and end year of the total data coverage in the form YYYY.
- <VERSION> is the four-digit version number, starting with 'V1-0' for the first major version. The first digit changes each time a major version is released ('V2-0', 'V3-0', '4-0', '5-0'), while changes in the second digit indicate reprocessing versions or minor versions ('V1-2', 'V1-3').
- .nc: standard NetCDF filename extension.

Example: CS_1957_2019_v1-0.nc

3.4.2. Product content

A linear regression of ΔN - ΔF on ΔT from the Ensemble dataset is repeated at each iteration of a sliding time window of length w ≥ 25 years between 1957 and 2017. For this period, there are 35 successive 25-year windows, 34 successive 26-year windows, etc., and one single 61-year window. The climate feedback parameter obtained from the regression of a singular window is associated with the central date of that window.

This netCDF file contains the estimated climate feedback parameter for each window length and each window's central date. More attention is given to the 25 years window and thus the time series of the feedback parameter is given for that specific window length as well as its uncertainties in the form of a time series of the 17th percentile and a time series of the 83th percentiles.

Dimensions	**Description**	**Units**	**Data Type**
cdate_Ensemble	central date of N-years window with N >= 25 years	days since 1950-01-01 00:00:00 UTC	double
window_length	period length of the considered window	Number of years	int
Variables(dimensions)	**Description**	**Units**	**Data Type**
CF_Ensemble(cdate_Ensemble, window_length)	Climate Feedback parameter estimated for each central year of each window size	$W.m^{-2}.K^{-1}$	float
CF_Ensemble_25(cdate_Ensemble)	Climate Feedback parameter estimated for each central year of a 25 years window	$W.m^{-2}.K^{-1}$	float

CF_Ensemble_25_17perc (cdate_Ensemble)	17th percentile of the uncertainty envelope of Climate Feedback parameter estimated for each central year of a 25 years window	$W.m^{-2}.K^{-1}$	float
CF_Ensemble_25_83perc (cdate_Ensemble)	83th percentile of the uncertainty envelope of Climate Feedback parameter estimated for each central year of a 25 years window	$W.m^{-2}.K^{-1}$	float

Table 3: Description of the content and format of climate feedback product (NetCDF file)

3.4.3. Metadata

Users will find a number of metadata attributes in the NetCDF file, at the file-level, at the layer-level and at the level of the dimension variables.

3.5. Post-processed input product

3.5.1. File naming convention

The product follows the naming standard:

CS_<START_DATE>_<END_DATE>_<VERSION>_ppi.nc

where:

- <START_DATE> and <END_DATE> give the UTC start and end year of the total data coverage in the form YYYY.
- <VERSION> is the four-digit version number, starting with 'V1-0' for the first major version. The first digit changes each time a major version is released ('V2-0', 'V3-0', 'V4-0', 'V5-0'), while changes in the second digit indicate reprocessing versions or minor versions ('V1-2', 'V1-3').
- .nc: standard NetCDF filename extension.

Example: CS_1957_2019_v1-0_ppi.nc

3.5.2. Product content

This netCDF file contains the post-processed yearly mean and standard deviation of the T, F and N inputs used in the linear regression of the climate feedback parameter.

Dimensions	Description	Units	Data Type
time_Ensemble	decimal years covered by the processed inputs of the Ensemble dataset	days since 1950-01-01 00:00:00 UTC	double
Variables (dimensions)	**Description**	**Units**	**Data Type**
T_Ensemble(time_Ensemble)	Global mean surface temperature anomalies calculated from the HadCRUT5 time series	K	float
F_Ensemble(time_Ensemble)	Mean of the post-processed TOA radiative forcing anomalies calculated from the AR6 time series	$W.m^{-2}$	float
F_Ensemble_std(time_Ensemble)	Standard deviation of the post-processed TOA radiative forcing anomalies calculated from the AR6 time series	$W.m^{-2}$	float
N_Ensemble(time_Ensemble)	Mean of the post-processed Earth energy imbalance calculated from the Ensemble dataset	$W.m^{-2}$	float
N_Ensemble_std(time_Ensemble)	Standard deviation of the post-processed Earth energy imbalance calculated from the Ensemble dataset	$W.m^{-2}$	float

Table 4: Description of the content and format of climate feedback post-processed input product (NetCDF file)

3.5.3. Metadata

Users will find a number of metadata attributes in the NetCDF file, at the file-level, at the layer-level and at the level of the dimension variables.

3.6. Climate feedback from alternative EEI product

3.6.1. File naming convention

The product follows the naming standard:

CS_<START_DATE>_<END_DATE>_<VERSION>_validation.nc

where:

- <START_DATE> and <END_DATE> give the UTC start and end year of the total data coverage in the form YYYY.
- <VERSION> is the four-digit version number, starting with 'V1-0' for the first major version. The first digit changes each time a major version is released ('V2-0', 'V3-0', 'V4-0', 'V5-0'), while changes in the second digit indicate reprocessing versions or minor versions ('V1-2', 'V1-3').
- .nc: standard NetCDF filename extension.

Example: CS_1957_2019_v1-0_validation.nc

3.6.2. Product content

This netCDF file contains the estimated climate feedback parameter, as well as the associated uncertainty, from each of the alternative datasets ESA-CCI, DEEP-C and MOHeaCAN for a sliding time window of 25 years. The file also provides the EEI values and uncertainties from the MOHeaCAN dataset.

Dimensions	Description	Units	Data Type
cdate_ESA-CCI	Central date of the period covered by the ESA-CCI dataset (1994-2016).	days since 1950-01-01 00:00:00 UTC	double
cdate_MOHeaCAN	Central dates of 25-years windows inside the period covered by the MOHeaCAN dataset (1993-2022).	days since 1950-01-01 00:00:00 UTC	double
cdate_DEEP-C	Central dates of 25-years windows inside the period covered by the DEEP-C dataset (1985-2019).	days since 1950-01-01 00:00:00 UTC	double
Variables (dimensions)	**Description**	**Units**	**Data Type**

CF_MOHeaCAN (cdate_MOHeaCAN)	MOHeaCAN Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	float
CF_MOHeaCAN_17perc (cdate_MOHeaCAN)	17th percentile of the uncertainty envelope of MOHeaCAN Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	float
CF_MOHeaCAN_83perc(cdate_MOHeaCAN)	83th percentile of the uncertainty envelope of MOHeaCAN Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	float
CF_ESA-CCI(cdate_ESA-CCI)	ESA-CCI Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	float
CF_ESA-CCI_17perc(cdate_ESA-CCI)	17th percentile of the uncertainty envelope of ESA-CCI Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	float
CF_ESA-CCI_83perc(cdate_ESA-CCI)	83th percentile of the uncertainty envelope of ESA-CCI Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	float
CF_DEEP-C(cdate_DEEP-C)	DEEP-C Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	double
CF_DEEP-C_17perc(cdate_DEEP-C)	17th percentile of the uncertainty envelope of DEEP-C Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	float

CF_DEEP-C_83perc(cdate_DEEP-C)	83th percentile of the uncertainty envelope of DEEP-C Climate Feedback parameter estimated for each central year	$W.m^{-2}.K^{-1}$	float

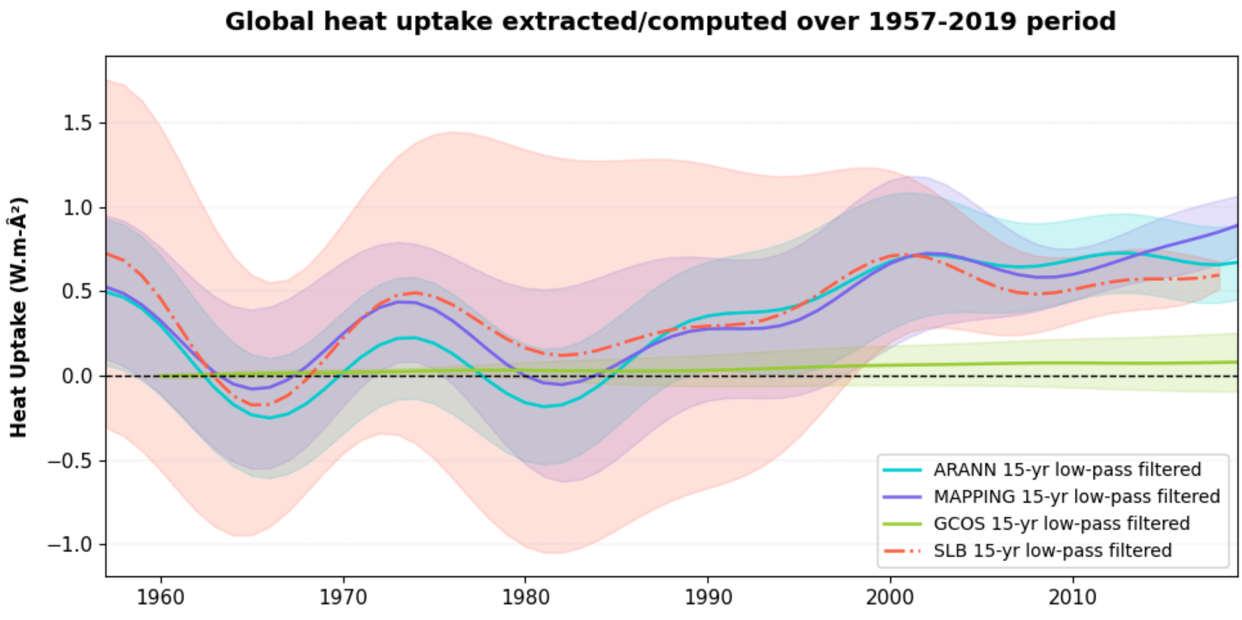
Table 5: Description of the content and format of alternative climate feedback product (NetCDF file)

3.6.3. Metadata

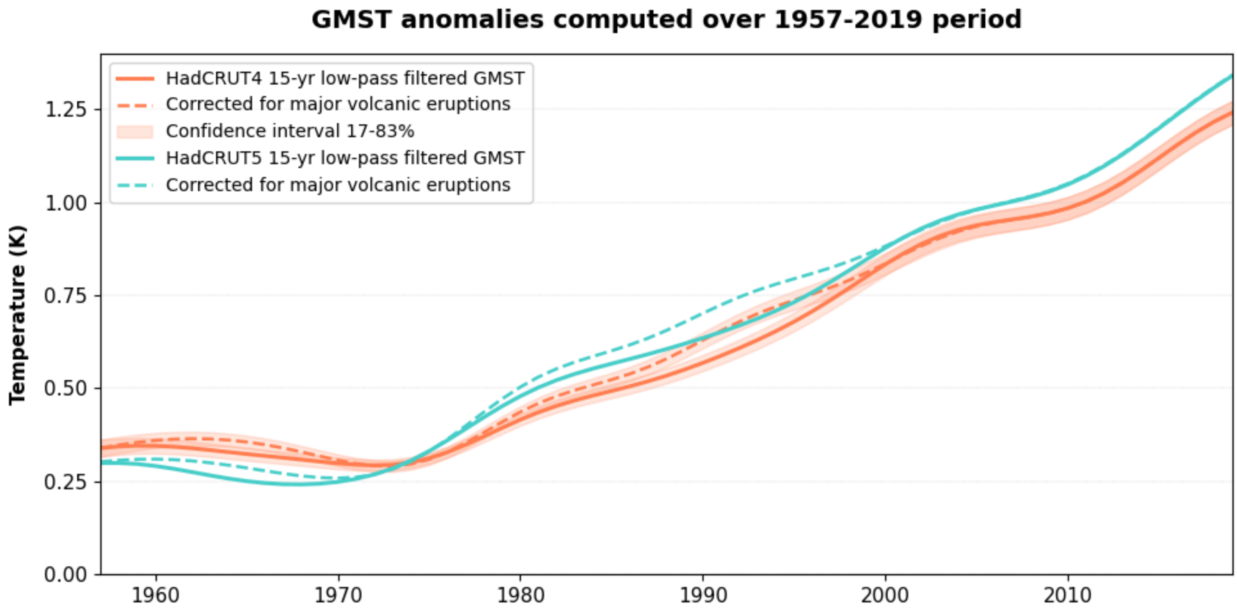
Users will find a number of metadata attributes in the NetCDF file, at the file-level, at the layer-level and at the level of the dimension variables.

3.7. Graphics

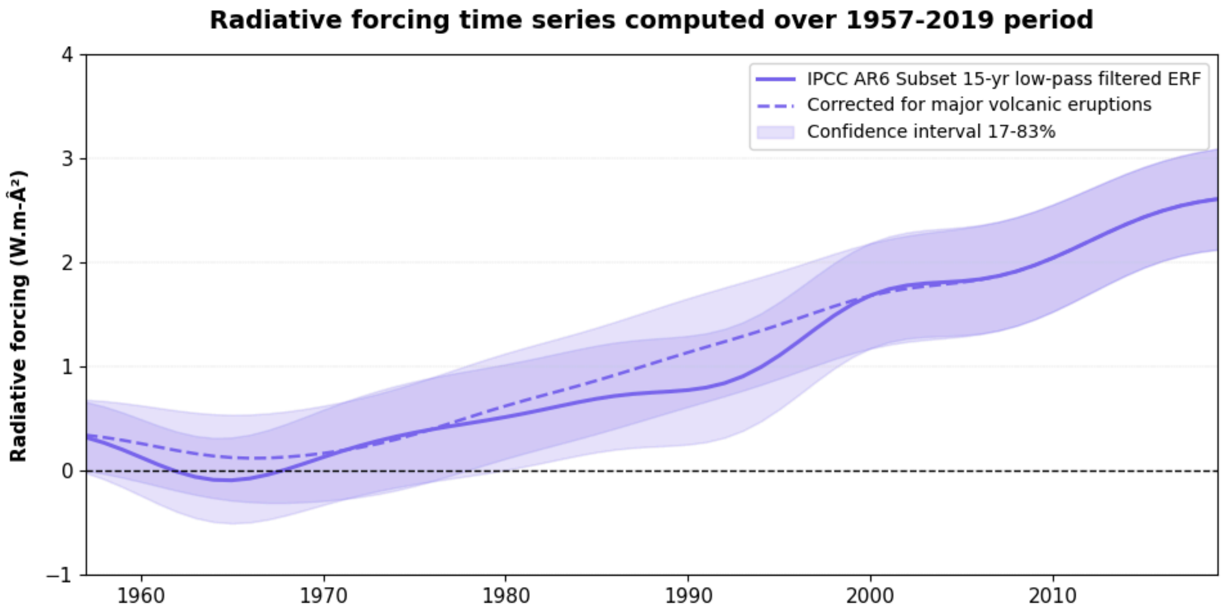
3.7.1. Global heat uptake



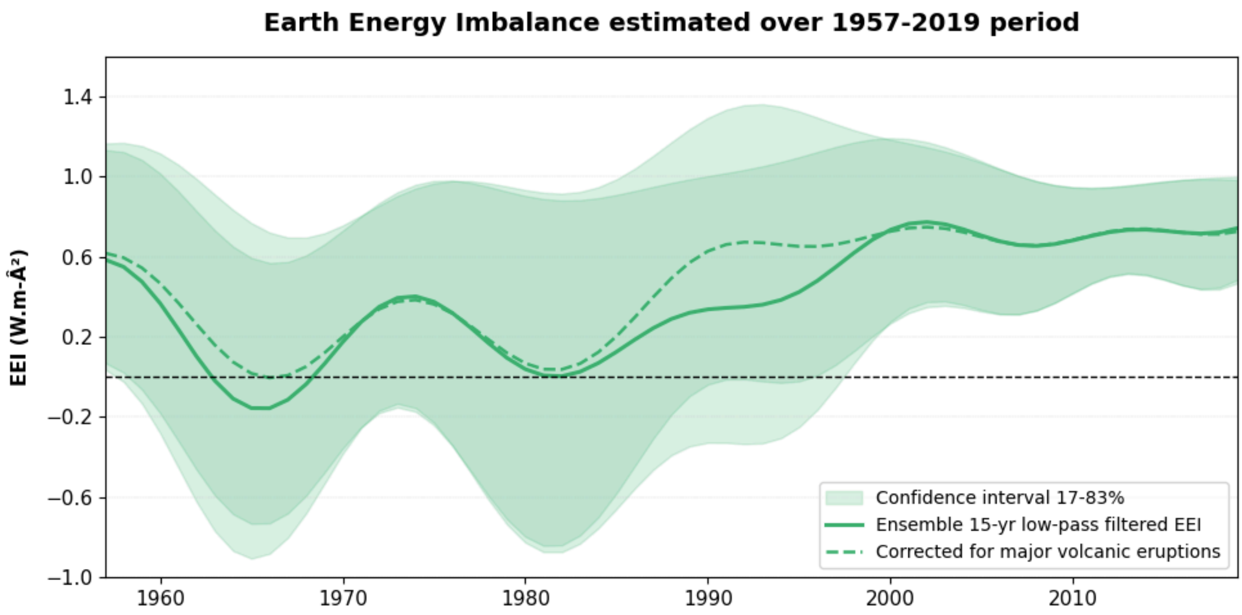
3.7.2. GMST anomalies



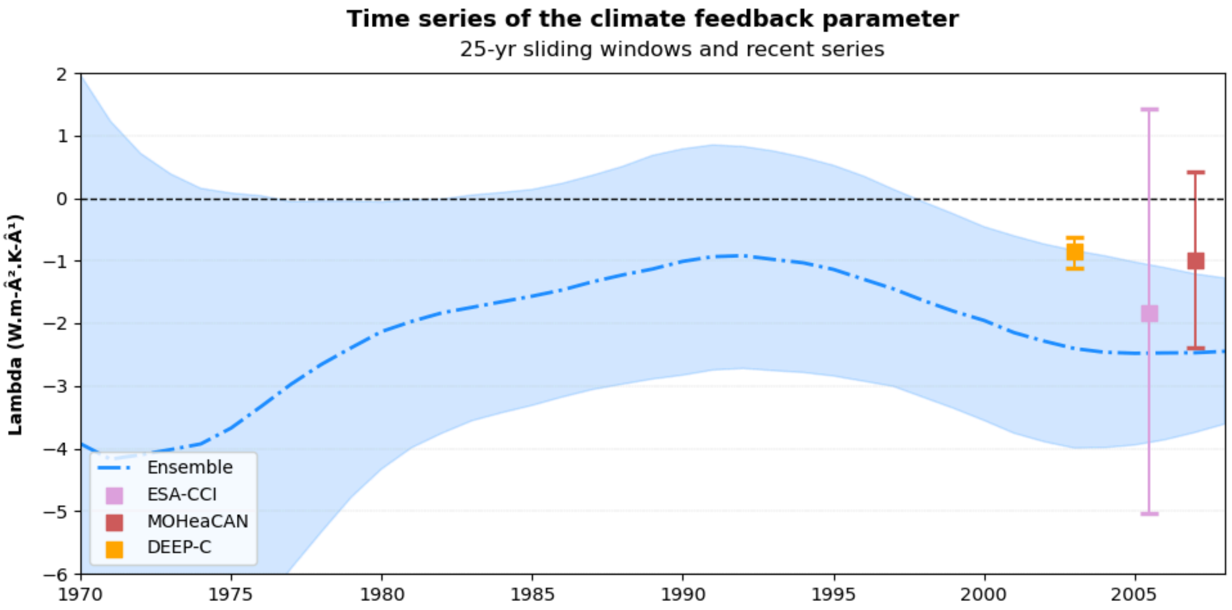
3.7.3. Radiative forcing

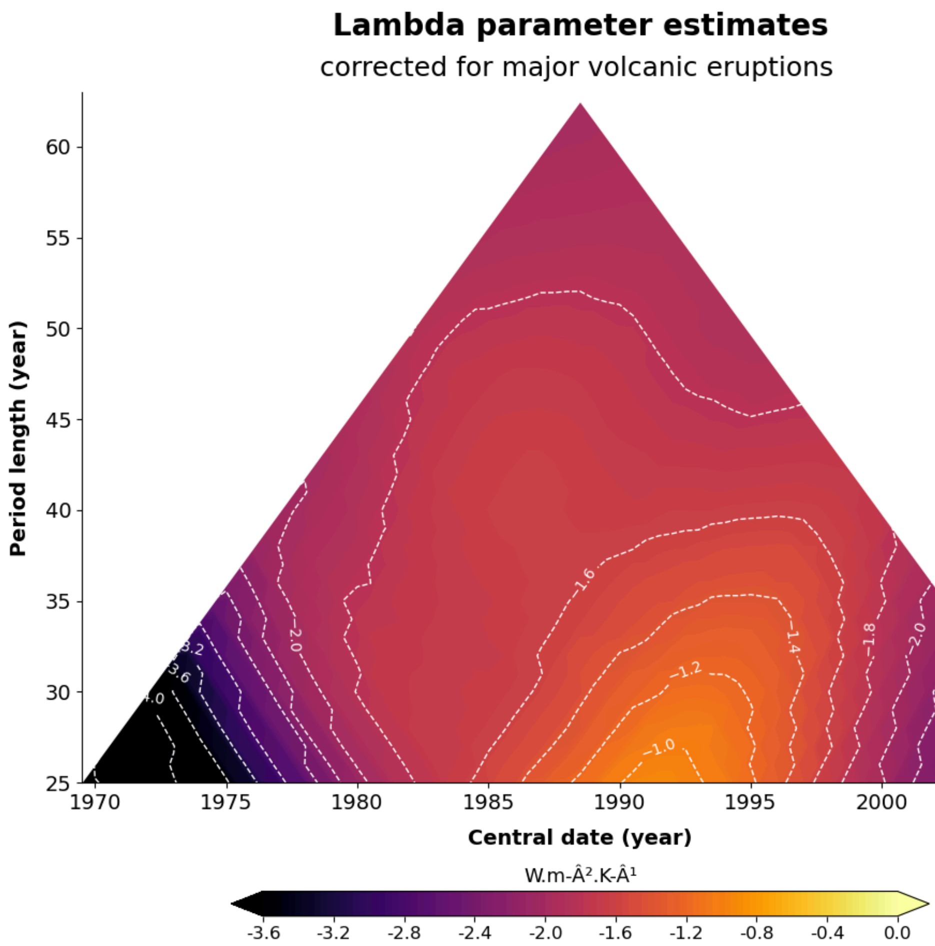


3.7.4. Earth Energy Inbalance



3.7.5. Climate feedback parameter


Time series of the climate feedback parameter
25-yr sliding windows and recent series
Lambda (W.m-Â².K-Â¹)
Ensemble
ESA-CCI
MOHeaCAN
DEEP-C
2
1
0
−1
−2
−3
−4
−5
−6
1970
1975
1980
1985
1990
1995
2000
2005



4. How to access APACHE product?

4.1. Downloading

The data product (NetCDF file), together with the Algorithm Theoretical Basis Document (ATBD) [AD1], can be found and downloaded:

- on the AVISO webpage:

- on the ODATIS ocean cluster (Ocean Data Information and Services) website (authenticated access via FTP):

Once downloaded, NetCDF data can be browsed and used through a number of software, like:

- ncBrowse: https://www.pmel.noaa.gov/epic/java/ncBrowse/
- NetCDF Operator (NCO): http://nco.sourceforge.net/
- Panoply: https://www.giss.nasa.gov/tools/panoply/
- IDL, Matlab, GMT, Python…

Useful information on UNIDATA: http://www.unidata.ucar.edu/software/netcdf/

4.2. Dataset reference

When using the APACHE CS dataset in a publication or study, please cite: "The CS product was produced by Magellium/LEGOS and distributed by AVISO+ (*https://aviso.altimetry.fr*) with support from CNES and ESA (*https://doi.org/10.24400/527896/a01-2020.003* version 1.0)".

4.3. Support

For any technical issues or additional information related to the APACHE products, users are advised to contact the project team:

- Robin Fraudeau (technical coordinator) : robin.fraudeau@magellium.fr
- Benoit Meyssignac (science lead) : benoit.meyssignac@legos.obs-mip.fr
- Michaël Ablain (project manager) : michael.ablain@magellium.fr