MOHeaCAN

Estimating the global Ocean Heat Content and the Earth Energy Imbalance products from space

Product User Manual

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Document evolution sheet

Ed.	Rev.	Date	Purpose evolution	Comments
1	0	01/03/2020	Creation of document	
1	1	09/09/2020		Feedback from MTR
1	2	18/12/2020	Release of first product version (v1-0)	Consideration of observations and requests from ESA's first review Integration of a regional grid of GIA in altimetry data (sections 2.1 and 2.2) Additional information in product content section Update of the section 4 related to data access
1	3	26/04/2021	Release of new product version (v2-0)	Use of a new ocean mass solutions ensemble.
1	4	09/09/2021	Release of new product version (v2-1)	Addition of the elastic correction for the recent melting and contributions from other climate reservoirs to EEI (β coefficient).
1	5	08/12/2021	Release of new product version (v3-0)	Use of a new C3S altimetry data version (vDT 2021) Use of a new ocean mass solutions ensemble (V1.5) Add gap filling algorithm on Ocean Mass data New format of OHC-EEI netCDF file (splitted in 2 different files) New method for compute temporal derivative of GOHC
1	6	30/06/2022	Release of new product version (v4-0)	Use of a new ocean mass solutions ensemble (V1.5.1) Correction on altimetry data (wet tropospheric correction data on Jason-3 observations) Use of a time varying IEEH New method for computing EEI from regional OHC grids
1	7	07/10/2022	Minor updates	Rename flag variables in mask

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1. Introduction

1.1. Executive summary

Since the industrial era, anthropogenic emissions of greenhouse gases (GHG) in the atmosphere have lowered the total amount of infrared energy radiated by the Earth towards space. Now the Earth is emitting less energy towards space than it receives radiative energy from the sun. As a consequence there is an energy imbalance (EEI) at the top of the Atmosphere (Hansen et al., 2011; Trenberth et al., 2014). It is essential to estimate and analyse the Earth Energy Imbalance (EEI) if we want to understand the Earth's changing climate. Measuring the EEI is challenging because the EEI is a globally integrated variable whose variations are small (of the order of several tenth of $W.m^{-2}$, (von Schuckmann et al., 2016) compared to the amount of energy entering and leaving the climate system (of ~340 $W.m^{-2}$, (L'Ecuyer et al., 2015)). An accuracy of <0.3 $W.m^{-2}$ at decadal time scales is necessary to evaluate the long term mean EEI associated with anthropogenic forcing. Ideally an accuracy of <0.1 $W.m^{-2}$ at decadal time scales is desirable if we want to monitor future changes in EEI which shall be non-controversial science based information used by the GHG mitigation policies (Meyssignac et al., 2019).

EEI can be estimated by an inventory of heat changes in the different reservoirs - the atmosphere, the land, the cryosphere and the ocean. As the ocean concentrates the vast majority of the excess of energy (~93%) in the form of heat (Trenberth et al., 2016), the global Ocean Heat Content (OHC) places a strong constraint on the EEI estimate.

In the MOHeaCAN project, the OHC is estimated from the measurement of the thermal expansion of the ocean based on differences between the total sea-level content derived from altimetry measurements and the mass content derived from gravimetry data (noted the space geodetic or the "Altimetry-Gravimetry" approach). This space geodetic approach provides consistent spatial and temporal sampling of the ocean, it samples nearly the entire global oceans, except for polar regions, and it provides estimates of the OHC over the ocean's entire depth. It complements the OHC estimation from Argo (direct measurement of in situ temperature based on temperature/salinity profiles).

MOHeaCAN project's objectives were to develop novel algorithms, estimate realistic OHC uncertainties thanks to a rigorous error budget of the altimetric and gravimetric instruments, in order to reach the challenging target for the uncertainty quantification of 0.3 $W. m^{-2}$ which then allow our estimate to contribute to better understand the Earth's climate system.

1.2. Scope and objectives

This document is the Product User Manual (PUM) of the MOHeaCAN project initially supported by ESA and which is now supported by CNES. The PUM is dedicated to the content and format description of the MOHeaCAN product. This product gathers estimates of the OHC at global and regional scales and EEI's evolution over **April 2002 - December 2020**.

This is the primary document that users should read before handling the products. It provides an overview of processing algorithms, technical product content and format and main validation results. Details on the algorithms are given in the algorithm theoretical basis document (ATBD) [AD1].

1.3. 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 MOHeaCAN product's content.
- Sections 4 presents data policy and product access.

1.4. Applicable documents

Id.	Ref.	Description
AD1	GIECCO-DT-067-MAG_ATBD	Algorithm Theoretical Basis Document (ATBD)

Table 1: List of applicable documents

1.5. Terminology

Abbreviation/acronym	Description
ATBD	Algorithm theoretical basis document
DOI	Digital Object Identifier
EEH	Expansion efficiency of heat
EWH	Equivalent water height
GM	Global mean
GOHC	Global ocean heat content
GOHU	Global ocean heat uptake
GMOM	Global mean of ocean mass
GMSL	Global mean sea level
GMSSL	Global mean steric sea level
NetCDF	Network common data form
OHC	Ocean heat content
OM	Ocean mass
PUM	Product user manual
SL	Sea level
SSL	Steric sea level
TOA	Top-of-Atmosphere

Table 2 : List of abbreviations and acronyms

2. Algorithm

2.1. The retrieval methodology

Interested readers can find details on the retrieval algorithm in ATBD [AD1] and can also refer to Marti et al. (2022) for comparison of the OHC-EEI MOHeaCAN (V2.1) product against independent data.

In the MOHEACAN processing chain, the EEI is deduced from the Global change in Ocean Heat Content (GOHC) which is a very good approximation since the oceans store 90% of the heat kept by the Earth system (von Schuckmann et al., 2020). The GOHC is estimated with the regional OHC change grids which are themself estimated from space data from altimetry and gravimetry missions. This approach provides access to the EEI.

Global mean time series of SL, OM and SSL are also estimated from their regional grids. These time series are not used for the calculation of the GOHC but are given as additional information.

Finally, uncertainties of the global mean sea level and ocean mass (GMSL and GMOM respectively) time series are estimated and propagated to the GOHC time series and the EEI. The state-of-the-art on the precise knowledge of these uncertainties does not allow us for the moment to carry out this methodology of uncertainties propagation at regional scales.

Ocean heat content and expansion efficiency of heat

When corrected for changes in ocean mass (OM), sea level (SL) change provides an estimate of the thermal expansion change of the ocean. The relationship between sea level change (ΔSL), ocean mass change (ΔOM) and ocean thermal expansion change (ΔSSL) is expressed by the sea level budget equation:

$$\Delta SSL = \Delta SL - \Delta OM$$

Once the ocean thermal expansion is retrieved (considering that halosteric sea level change is neglected at regional scales) OHC change can be derived by dividing the thermal expansion change by the integrated expansion efficiency of heat (IEEH, mYJ^{-1}) and referenced to a chosen time step :

$$\Delta OHC_{alti-gravi} = \frac{\Delta SSL + TSSL_{ref}}{IEEH} - \frac{TSSL_{ref}}{IEEH_{ref}}$$

The MOHEACAN processing chain uses a new estimation of the regional grid of the IEEH which allows OHC change to be calculated at regional scales. IEEH calculation is described in the ATBD [AD1] (see also Marti et al. (2022)).

Earth energy imbalance

The Global Ocean Heat Uptake (GOHU) corresponds to temporal variations of the GOHC, it represents almost 90% of the EEI. It is therefore simply inferred from the time derivative of the GOHC on a monthly basis.

$$GOHU(t) = \frac{d\,GOHC_{filtered,\,adjusted}(t)}{dt}$$

We can obtain the EEI with the equation:

$$EEI(t) = GOHU(t) * \frac{1}{\alpha}, with\ \alpha = 0.9$$

The adjustment with the ɑ coefficient allows to account for contributions from other climate reservoirs (land, cryosphere and atmosphere) to the EEI (von Schuckmann et al., 2020). As the high-frequency content of GOHC contains signals which are not related to the EEI imbalance (see limitations section), the OHC change grids and the resulting GOHC first need to be filtered-out from signals lower than 3 years before calculating GOHU and then EEI.

Input data: sea level and ocean mass variations

SL input data are the sea-level products distributed by the Copernicus Climate Service (C3S). More specifically, the most recent version of the SL products is used (vDT2021). They are daily products defined on a 0.25° x 0.25° resolution grid. We corrected this data for the global isostatic adjustment and also to take into account the elastic correction for the recent melting. A correction for the Jason-3 wet tropospheric correction drift was also applied.

GRACE and GRACE-FO missions provide OM variations. We used an ensemble of 288 GRACE(-FO) solutions derived from different processing centres and a combination of state of the art post-processing parameters (update of Blazquez et al., 2018, v1.5.1). They are defined on a 1°x 1° resolution grid and on a monthly basis.

However, some gaps are present in the OM variations in particular between the GRACE and GRACE-FO missions. A gap filling algorithm is therefore used on OM data before generating the OHC/EEI product. The mask variables in the product distinguish between months for which there is data from observations and those for which there is data from extrapolation. (more details in Table 3 and Table 4).

Spatial and temporal characteristics of the MOHeaCAN OHC/EEI product are limited by the gravimetry observations both at spatial and temporal scales. Indeed, the effective temporal and spatial resolutions of GRACE(-FO) products is 1 month and 300 km against about 10-days at about 100 km for level-4 altimetry products. As the regional OHC change grids in the MOHeaCAN project have been defined at 1°x1° resolution and on a monthly basis and a preprocessing of SL and OM grids is necessary.

Estimation of the OHC/EEI uncertainties.

The uncertainties are calculated for all the global time series: GMSL, GMOM, GMSSL, GOHC and EEI. The proposed approach consists in providing a variance-covariance matrix (∑) of each time series. Once the variance-covariance matrices are known, the trend uncertainties can be derived for any time-spans over each time series. The method is based on the study performed by Ablain et al. (2019) dedicated to the GMSL trend and acceleration uncertainties.

At this stage of the MOHeaCAN project, the uncertainties cannot be fully provided at regional scales.

The OHC MOHeaCAN product samples nearly the entire global oceans, except for polar regions and marginal seas, and it provides estimates of the OHC change over the ocean's entire depth.

2.2. Product limitations

Uncertainties and limitations on the altimetry and gravimetry measurements directly propagate into the OHC change and EEI variables.

Users should also bear in mind the global variables in MOHeaCAN product actually correspond to a more restricted area, about 85% of the oceans only, because of the IEEH spatial availability.

The space geodetic methodology "altimetry-gravimetry" provides access to the steric sea level change over the entire water column.Note that the IEEH used to derive the OHC change does consider the effects from the deep oceans (below 2000 m), but the measurements performed in the deep ocean layers from in-situ sensors remain sporadic both spatially and across time. This means that most of the deep ocean signal of the IEEH is close to the climatology.

The contribution of salinity effects to sea level rise is negligible at the global scale but significant at regional scales. As some studies recently highlighted, in-situ datasets from Argo present a drift from 2016 due to anomalies on the conductivity sensors (Wong et al., 2020). Barnoud et al. (2021) showed that this affects the HSSL estimates. To prevent the impact of this drift, we decided to calculate the OHC without removing the halosteric component to the total steric sea level.

Users should use EEI data with awareness because the high-frequency content of OHC change and GOHC contains signals not related to the EEI imbalance. Firstly, the OHC change and GOHC contain high-frequency signals (< 2-3 years) which are due to errors in space gravimetry measurements but also in altimetry measurements (e.g. phase shift of the annual signals between these measurements). Moreover, the OHC change and GOHC also contain a residual signal (< 2-3 years) related to the ocean variability at small temporal scale but not related to ocean warming due to climate change. For these reasons it is necessary to filter out these high-frequency signals. At this stage of the study, we filter this high-frequency content at 3 years, before estimating the EEI and its variations as reliably as possible. EEI variations cannot be estimated for time scales lower than 2-3 years at this stage of the MOHeaCAN project.

The correction for the glacial isostatic adjustment (GIA) used on sea level grids from altimetry was chosen to fit with the recent study by Prandi et al., 2020 for an estimation of the sea level trends uncertainties at regional scales (see section 2.7 in ATBD [AD1]).

2.3. Optimisation strategy

No optimisation strategy in terms of calculation or product definition has been implemented for the MOHeacAN product. Indeed, although the time series are long (19 years), the volumes of data manipulated remain modest and do not require an optimisation strategy.

3. Product description

The MOHeaCAN product is delivered in two distinct files. The main one contains the essential variables like Global Ocean Heat Content, Earth Energy Imbalance time series and their relative variance-covariance matrices. The second is only available upon request, and contains more variables than the first product like time series of OM, SL and SSL change gridsIt also includes additional variables that were not used for the GOHC calculation, such as the GMOM, GMSL and GMSSL time series, but which may nevertheless be of interest to users.

3.1. Spatial information

All 2-D fields of the MOHeaCAN product are displayed on a 1° lon-lat grid (WGS84) and are defined on the global ocean except on marginal seas, near coasts and above high latitudes (>66°N and <66°S).

3.2. Temporal information

All time-series are provided on a monthly basis, from April, 2002 to December 2020. The EEI is derived from the temporal derivative of the GOHC after filtering-out the high-frequency signals in the OHC lower than 3 years in order to assess the long-term EEI variable.

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. Product with essential variables

3.4.1. File naming convention

The product follows the naming standard:

OHC-EEI_<START_DATE>_<END_DATE>_<VERSION>.nc

where:

- <START_DATE> and <END_DATE> give the UTC start and end date of the total data coverage in the form YYYYMM with Y, M as year and month respectively.

- <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'), while changes in the second digit indicate reprocessing versions or minor versions ('V1-2', 'V1-3').
- .nc: standard NetCDF filename extension.

Example: OHC-EEI_200208_201512_v1-0.nc

3.4.2. Product content

3.4.2.1. Dimensions

1 dimension is defined:

- time

3.4.2.2. Variables

For reminder, the variable GOHC in this product is not absolute quantities but anomalies with respect to a reference (see ATBD [AD1]).

Variables(dimensions)	Description	Units	Data Type	Scale factor
time(time)	Time	days since 1950-01-01 00:00:00 UTC	double	none
gohc(time)	Global ocean heat content from the 'altimetry-gravimetry' methodology using the local integrated expansion efficiency of heat - this global OHC was obtained from the local OHC change grids	joules per square meter	float	none
eei(time)	Earth energy imbalance from the 'altimetry-gravimetry' methodology - application of a 3-year filter on the OHC change	watts per square meter	float	none
gohc_var_covar_matrix(time, time)	Variance covariance matrix of errors on global ocean heat content (gohc)	square joules per meter to the power of 4	float	none
eei_var_covar_matrix(time, time)	Variance covariance matrix of errors on Earth energy imbalance (eei)	square watts per meter to the power 4	double	none

gohc_mask(time)	mask to apply on OHC data for masking interpolated data (1 for observed data and 0 for extrapolated data)	none	int	none
eei_mask(time)	mask to apply on EEI data for masking interpolated data (1 for observed data and 0 for extrapolated data)	none	int	none

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

3.5. Extended product

3.5.1. File naming convention

The product follows the naming standard:

OHC-EEI_<START_DATE>_<END_DATE>_<VERSION>_extended.nc

where:

- <START_DATE> and <END_DATE> give the UTC start and end date of the total data coverage in the form YYYYMM with Y, M as year and month respectively.
- <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'), while changes in the second digit indicate reprocessing versions or minor versions ('V1-2', 'V1-3').
- .nc: standard NetCDF filename extension.

Example: OHC-EEI_200208_201512_v1-0_extended.nc

3.5.1.1. Product content

3.5.1.2. Dimensions

3 dimensions are defined:

- time
- latitude
- longitude

3.5.1.3. Variables

For reminder, the variables noted SL and OM in this document are not absolute quantities but anomalies with respect to a reference (see ATBD [AD1]). The SL variable provided by C3S altimetry is the anomaly of sea surface height around the mean sea surface, i.e. the temporal mean of sea surface height above the reference ellipsoid over 1993-2012. The OM values are temporal variations with respect to the 2005–2015 period. SSL, OHC variables and all the related global variables (GMSL, GMOM, GMSSL) are therefore also anomalies. Global variables are provided in this product to the user for information but are not used in the global OHC computation (see section 2.1.).

Variables(dimensions)	Description	Units	Data Type	Scale factor
time(time)	Time	days since 1950-01-01 00:00:00 UTC	double	none
latitude(latitude)	Latitude of data	degrees_north	float	none
longitude(longitude)	Longitude of data	degrees_east	float	none
crs	Describes the grid_mapping used by the 2-D variables of the file	none	float	none
gmsl(time)	Global mean sea level	meters	float	none
gmom(time)	Global mean ocean mass	meters	float	none
gmssl(time)	Global mean steric sea level	meters	float	none
integrated_expansion_eff_of_heat_global	Global value of the integrated expansion efficiency of heat	meters per joule	float	none
integrated_expansion_eff_of_heat_global_uncertainty	Uncertainty of the global value of the integrated expansion efficiency of heat	meters per joule	float	none
integrated_expansion_eff_of_heat_grid(time, latitude, longitude)	Integrated Expansion efficiency of heat used to compute OHC from steric sea level: local values computed from Argo solutions	meters per joule	float	none
sl_var_covar_matrix_global (time, time)	Variance covariance matrix of errors on global mean sea level time-series (altimetry data - error budget approach)	square meters	float	none
om_var_covar_matrix_global(time, time)	Variance covariance matrix of errors on global mean ocean mass time-series (gravimetry data - ensemble approach)	square meters	float	none

ssl_var_covar_matrix_global(time, time)	Variance covariance matrix of errors on global mean steric sea level time-series (sum of ssl_var_covar_matrix and om_var_covar_matrix)	square meters	float	none
ohc_grids(time, latitude, longitude)	Grids of ocean heat content	meters	double	none
om_grids(time, latitude, longitude)	Grids of ocean mass from GRACE(-FO) gravimetry	meters	int	0.0001
sl_grids(time, latitude, longitude)	Grids of sea level from Altimetry - C3S data (downsampled from 0.25° to 1°)	meters	int	0.0001
ssl_grids(time, latitude, longitude)	Grids of steric sea level from Altimetry - Gravimetry	meters	int	0.0001
sl_mask(time)	mask to apply on SL data for masking interpolated data (1 for observed data and 0 for extrapolated data)	none	int	none
om_mask(time)	mask to apply on OM data for masking interpolated data (1 for observed data and 0 for extrapolated data)	none	int	none
ssl_mask(time)	mask to apply on SSL data for masking interpolated data (1 for observed data and 0 for extrapolated data)	none	int	none
ohc_mask(time)	mask to apply on OHC data for masking interpolated data (1 for observed data and 0 for extrapolated data)	none	int	none

Table 4 : Description of the content and format of MOHeaCAN product - extended version (NetCDF file)

3.6. 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.

4. How to access MOHeaCAN 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: https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/ocean-heat-content-and-earth-energy-imbalance
- on the ODATIS ocean cluster (Ocean Data Information and Services) website (authenticated access via FTP): https://www.odatis-ocean.fr/en/data-and-services/data-access/direct-access-to-the-data-catalogue#/metadata/72463f1c-eb8b-4892-a13b-540b2bcc8338

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 MOHeaCAN OHC/EEI dataset in a publication or study, please cite: "The OHC/EEI product from space altimetry and space gravimetry 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 4.0)".

4.3. Support

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

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- Michaël Ablain (project manager) : michael.ablain@magellium.fr

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