MOHeaCAN

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

Product User Manual

	Name	Organisation	Date	Visa
Written by :	Michaël Ablain Rémi Jugier Florence Marti Robin Fraudeau	Magellium	26/04/2021	
	Benoit Meyssignac Alejandro Blazquez	LEGOS		
Checked by :	Michaël Ablain	Magellium	26/04/2021	
Approved by :	Joël Dorandeu	Magellium	26/04/2021	

Document reference:	MOHeaCAN-DT-006-MAG_PUM
Edition.Revision:	1.3
Date Issued:	26/04/2021
Customer:	ESA
Ref. Market, consultation:	ESA/AO/1-9101/17/I-NB
Data Set Version:	v2-0 (26 April 2021)

Distribution List

	Name	Organisation	No. copies
Sent to:			
Internal copy:	Project Folder	Magellium	1 (digital copy)

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		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	Use of a new ocean mass solutions ensemble.

Dissemination level

PU	Public	x
PP	Restricted to other programme participants	
RE	Restricted to a group specified by the consortium	
CO	Confidential, only for members of the consortium	

Contents

List of tables

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 a 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 "Altimetry-Gravimetry"). This "Altimetry-Gravimetry" 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 supported by ESA ([AD1], [AD2]), 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 **August 2002 - August 2016**.

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 [AD3].

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.
- Section 4 summarises the validation activities performed on the MOHeaCAN product.
- Sections 5 and 6 present data policy and product access.

1.4. Related documents

1.4.1. Applicable documents

Id.	Ref.	Description
AD1	ESA AO/1-9101/17/I-NB	Invitation to Tender for EO SCIENCE FOR SOCIETY PERMANENTLY OPEN CALL FOR PROPOSALSEOEP-5 BLOCK 4
AD2	MAG-19-PTF-019-v1.0.pdf	Technical, management and financial proposal
AD3	MOHeaCAN-DT-001-MAG_ATBD	MOHeaCAN Algorithm theoretical basis document

Table 1. List of applicable documents

1.4.2. Reference documents

All references are given in Section 5.

1.5. Terminology

Abbreviation/acronym	Description
AD	Applicable document
DOI	Digital Object Identifier
EEH	Expansion efficiency of heat
EWH	Equivalent water height
GM	Global mean
GOHC	Global ocean heat content
GMOM	Global mean of ocean mass
GMSL	Global mean sea level
GMSSL	Global mean steric sea level
NetCDF	Network common data form
OM	Ocean mass
RD	Reference document
SL	Sea level
SSL	Steric sea level
TBC	To be completed
TBD	To be defined
TOA	Top-of-Atmosphere

Table 3. List of abbreviations and acronyms

2. Algorithm

2.1. The retrieval methodology

Interested readers can find details on the retrieval algorithm in [AD3] and can also refer to Marti et al. (In preparation) for comparison of the OHC-EEI MOHeaCAN product against independent data.

In the MOHEACAN processing chain, the EEI indicator is deduced from the Global change in Ocean Heat Content (GOHC) which is a very good approximation since the oceans store 93% of the heat kept by the Earth system (Church et al., 2011).

The GOHC is itself estimated from space data from altimetry and gravimetry missions. It can be obtained in 2 different and consistent ways, either from regional time series or from global mean time series. These two approaches provide access to the same EEI indicator. However, they have complementary interests. On one hand, the global approach allows the uncertainties of the global mean sea level and ocean mass (GMSL and GMOM respectively) time series to be propagated to the GOHC time series and the EEI indicator. 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. On the other hand, the regional approach allows us to know the 2D distribution of ocean heat content, which is essential for understanding climate change 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, OHC changes can be derived by dividing the thermal expansion changes by the expansion efficiency of heat (EEH - ε,mYJ^{-1}):

$$\Delta OHC_{alti-gravi} = \frac{\Delta SSL}{\varepsilon}$$

Although the EEH depends on sea water temperature and salinity, we assume here it does not vary in space (over ocean depth) and over time, at least over the study period (Russell et al., 2000). Kuhlbrodt and Gregory, (2012) also highlighted that changes in the global thermal expansion efficiency of heat are likely negligible on decadal time scales. So far the EEH has been calculated from hydrographic data based on expendable bathythermograph and CTD (Kuhlbrodt and Gregory, 2012; Levitus et al., 2009; Melet and Meyssignac, 2015; Russell et al., 2000) at global scale. It has never been calculated precisely with Argo data. It has also never been calculated regionally.

The MOHEACAN processing chain uses a new estimation of the global EEH but also a regional grid provided by Meyssignac et al., 2020 which allows OHC to be calculated at regional scales.

Earth energy imbalance indicator

The EEI indicator corresponds to temporal variations of the GOHC. It is therefore simply inferred from the time derivative of the GOHC on a monthly basis.

$$EEI(t) = \frac{d\,GOHC_{filtred,\,adjusted}(t)}{dt}$$

As the high-frequency content of GOHC contains signals which are not related to the EEI imbalance (see limitations section), the GOHC first needs to be filtered-out from signals lower than 3 years before calculating EEI.

For information, we also provide the EEI deduced after filtering-out signals lower than 2 years and 1 year, in order to conduct more in-depth analyses on the rapid variations of the EEI although they are not representative of climate change to date.

Input data: sea level and ocean mass variations

SL input data are the sea-level products distributed by the Copernicus Climate Service (C3S). They are daily products defined on a 0.25° x 0.25° resolution grid. We corrected this data for the global isostatic adjustment.

GRACE and GRACE-FO missions provide OM variations. We used an ensemble of 216 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). They are defined on a 1°x 1° resolution grid and on a monthly basis.

Spatial and temporal characteristics of 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. Therefore the regional OHC grids in the MOHeaCAN project have been defined at 3°x3° 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 (Σ) 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 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 over the ocean's entire depth.

2.2. Product limitations

Uncertainties and limitations on the altimetry and gravimetry measurements directly propagate into the OHC 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 EEH spatial availability.

"Altimetry-Gravimetry" methodology provides access to the steric sea level change over the entire water column while the EEH used to derive the OHC does not consider the effects from the deep oceans (below 2000 m). The impact of this lack of consistency is expected to be small because deep layers are currently less affected by thermal expansion than the surface layers of the ocean. The contribution of salinity effects to sea level rise is negligible at the global scale but significant at regional scales. At both scales, we considered steric sea level changes to be comparable to ocean thermal expansion changes. At this stage of the project, the OHC regional results are therefore based on a strong but well identified assumption.

The retrieved EEI assumes to only include the ocean heat uptake: 93% of total EEI. The energy stored in the atmosphere, land and, cryosphere reservoirs represents only 7% of the total contribution. It is low compared to what is held back by the oceans and not taken into account in our EEI estimation.

Users should use EEI data with awareness because the high-frequency content of GOHC contains signals not related to the EEI imbalance. Firstly, the GOHC contains 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 GOHC also contains 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 recommend filtering 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 local scale (see section 2.7 in [AD3]). As GIA is an area of active research, the applied regional GIA is made available in the MOHeaCAN product and users are given the possibility to substract the correction and employ the one of its convenience.

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 (18 years), the volumes of data manipulated remain modest and do not require an optimisation strategy.

3. Product description

3.1. Spatial information

All 2-D fields of the MOHeaCAN product are displayed on a 3° 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 August, 2002 to August 2016. The EEI is derived from the temporal derivative of the GOHC after filtering-out the high-frequency signals lower than 1-2-3 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. 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'), 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

3.5. Product content

3.5.1. Dimensions

4 dimensions are defined:

- lat
- lon
- time
- time_eei

If time is a N-length vector, "time_eei" is (N-1)-length vector.

3.5.2. Variables

For reminder, the variables noted SL and OM in this document are not absolute quantities but anomalies with respect to a reference [AD3]. 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, GOHC) are therefore also anomalies.

The regional OHC maps provided in the MOHeaCAN product do not show data over the entire oceans because of the EEH spatial availability. In the interests of users, it was decided not to mask the 2D fields of SL and OM information, i.e. to provide all the available data over the entire ocean. Users are thus able to generate their own OHC/EEI indicators using the EEH of their choice. However, users should keep in mind that all global variables (GMSL, GMOM, GMSSL, GOHC) are consistent because they are computed considering the same ocean coverage, the one defined by the EEH spatial availability and described by the "argo_mask" variable.

Variables(dimensions)	Description	Units	Data Type	Scale factor
time(time)	Time	days since 1950-01-01 00:00:00 UTC	float	none
time_eei(time_eei)	Time for EEI data	days since 1950-01-01 00:00:00 UTC	float	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
gmsl_no_signal(time)	Global mean sea level, annual and semi-annual signals removed	meters	float	none
gmom(time)	Global mean ocean mass	meters	float	none
gmom_no_signal(time)	Global mean ocean mass, annual and semi-annual signals removed	meters	float	none
gmssl(time)	Global mean steric sea level	meters	float	none
gmssl_no_signal(time)	Global mean steric sea level, annual and semi-annual signals removed	meters	float	none
expansion_eff_of_heat_global	Global value of the expansion efficiency of heat	meters per joule	float	none
expansion_eff_of_heat_uncertainty	Uncertainty on the expansion efficiency of heat value	meters per joule	float	none
surface_TOA	Reference surface for Top of Atmosphere fluxes	square meters	float	none
gohc(time)	Global ocean heat content from the 'altimetry-gravimetry' methodology using the expansion efficiency of heat- this global OHC was derived from regional OHC grids	joules per square meter	float	none
gohc_no_signal(time)	Global ocean heat content from the ‘altimetry-gravimetry' methodology using the expansion efficiency of heat - annual and semi-annual signals removed - this global OHC was derived from regional OHC grids	joules per square meter	float	none

gohc_global(time)	global ocean heat content from the 'altimetry-gravimetry' methodology using the expansion efficiency of heat - this global OHC was obtained from the global mean steric sea level time series	joules per square meter	float	none
gohc_global_no_signal(time)	global ocean heat content from the 'altimetry-gravimetry' methodology using the expansion efficiency of heat - annual and semi-annual signals removed - this global OHC was obtained from the global mean steric sea level time series	joules per square meter	float	none
eei_1y(time_eei)	Earth energy imbalance from the 'altimetry-gravimetry' methodology - application of a 1-year filter on ocean heat content (OHC) time series - this global OHC was derived from regional OHC grids	watts per square meter	float	none
eei_2y(time_eei)	Earth energy imbalance from the 'altimetry-gravimetry' methodology - application of a 2-year filter on ocean heat content (OHC) time series - this global OHC was derived from regional OHC grids	watts per square meter	float	none
eei_3y(time_eei)	Earth energy imbalance from the 'altimetry-gravimetry' methodology - application of a 3-year filter on ocean heat content (OHC) time series - this global OHC was derived from regional OHC grids	watts per square meter	float	none
eei_1y_global(time_eei)	Earth energy imbalance from the 'altimetry-gravimetry' methodology - application of a 1-year filter on ocean heat	watts per square meter	float	none

	content (OHC) time series - this global OHC was obtained from the global mean steric sea level time series			
eei_2y_global(time_eei)	Earth energy imbalance from the 'altimetry-gravimetry' methodology - application of a 2-year filter on ocean heat content (OHC) time series - this global OHC was obtained from the global mean steric sea level time series	watts per square meter	float	none
eei_3y_global(time_eei)	Earth energy imbalance from the 'altimetry-gravimetry' methodology - application of a 3-year filter on ocean heat content (OHC) time series - this global OHC was obtained from the global mean steric sea level time series	watts per square meter	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_var_covar_matrix_global(time, time)	Variance covariance matrix of errors on global ocean heat content (ssl_var_covar_matrix adjusted from the expansion efficiency of heat)	square joules per meter to the power of 4	float	none
eei_1y_var_covar_matrix_global(time_eei, time_eei)	Variance covariance matrix of errors on earth energy imbalance (eei_1y_global)	square watts per meter to the power 4	float	none

eei_2y_var_covar_matrix_global(time_eei, time_eei)	Variance covariance matrix of errors on earth energy imbalance (eei_2y_global)	square watts per meter to the power 4	float	none
eei_3y_var_covar_matrix_global(time_eei, time_eei)	Variance covariance matrix of errors on earth energy imbalance (eei_3y_global)	square watts per meter to the power 4	float	none
water_ratio(latitude, longitude)	Water ratio between 0 and 1 for each grid cell computed from distance to coast information	none	int	0.0001
cell_surface(latitude, longitude)	Informs on the surface of each grid cell as compared to surface of cell located at the equator - between 0 and 1	none	int	0.0001
om_grids(time, latitude, longitude)	Grids of ocean mass from GRACE gravimetry (downsampled from 1° to 3°)	meters	int	0.0001
sl_grids(time, latitude, longitude)	Grids of sea level from Altimetry - C3S data (downsampled from 0.25° to 3°)	meters	int	0.0001
ssl_grids(time, latitude, longitude)	Grids of steric sea level from Altimetry (C3S) - Gravimetry (GRACE)	meters	int	0.0001
expansion_eff_of_heat_grid(latitude, longitude)	Expansion efficiency of heat used to compute OHC from steric sea level: regional values computed from Argo solutions (Meyssignac et al., in preparation)	meters per joule	float	none
gia_regional_grid(latitude, longitude)	Global Isostatic Adjustment correction used in the recent study by Prandi, P., Meyssignac, B., Ablain, M., Spada, G. and Ribes, A.: How reliable are local sea level trends observed by satellite altimetry ?,	millimeters per year	float	none

	Prep., 2020.: Ensemble mean of the regional GIA results for model ICE-5G, with various viscosity profiles (27 profiles). The methodology is also described in Spada and Melini, 2019 (doi:https://doi.org/10.5194/ gmd-12-5055-2019).			
ohc_grids(time, latitude, longitude)	Regional ocean heat content from the 'altimetry-gravimetry' methodology - derived from the regional steric sea level with a regional expansion efficiency of heat	joules per square meter	float	none
argo_mask	Mask derived from the Expansion efficiency of heat map computed from different Argo data	none	ubyte	none

Table 4. Description of the format of MOHeaCAN product (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), 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, it should be cited using this DOI reference: http://doi.org/10.24400/527896/a01-2020.003.

4.3. Support

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

- Florence Marti (technical coordinator) : florence.marti@magellium.fr
- Benoit Meyssignac (science lead) : benoit.meyssignac@legos.obs-mip.fr
- Michaël Ablain (project manager) : michael.ablain@magellium.fr

5. References

- Ablain, M., Meyssignac, B., Zawadzki, L., Jugier, R., Ribes, A., Spada, G., Benveniste, J., Cazenave, A., and Picot, N.: Uncertainty in satellite estimates of global mean sea-level changes, trend and acceleration, Earth Syst. Sci. Data, 11, 1189–1202, https://doi.org/10.5194/essd-11-1189-2019, 2019.
- Blazquez, A., Meyssignac, B., Lemoine, J., Berthier, E., Ribes, A., and Cazenave, A.: Exploring the uncertainty in GRACE estimates of the mass redistributions at the Earth surface: implications for the global water and sea level budgets, Geophys. J. Int., 215, 415–430, https://doi.org/10.1093/gji/ggy293, 2018.
- Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., Broeke, M. R. van den, Monaghan, A. J., and Velicogna, I.: Revisiting the Earth's sea-level and energy budgets from 1961 to 2008, Geophys. Res. Lett., 38, https://doi.org/10.1029/2011GL048794, 2011.
- Hansen, J., Sato, M., Kharecha, P., and von Schuckmann, K.: Earth's energy imbalance and implications, Atmospheric Chem. Phys., 11, 13421–13449, https://doi.org/10.5194/acp-11-13421-2011, 2011.
- Kuhlbrodt, T. and Gregory, J. M.: Ocean heat uptake and its consequences for the magnitude of sea level rise and climate change, Geophys. Res. Lett., 39, https://doi.org/10.1029/2012GL052952, 2012.
- L'Ecuyer, T. S., Beaudoing, H. K., Rodell, M., Olson, W., Lin, B., Kato, S., Clayson, C. A., Wood, E., Sheffield, J., Adler, R., Huffman, G., Bosilovich, M., Gu, G., Robertson, F., Houser, P. R., Chambers, D., Famiglietti, J. S., Fetzer, E., Liu, W. T., Gao, X., Schlosser, C. A., Clark, E., Lettenmaier, D. P., and Hilburn, K.: The Observed State of the Energy Budget in the Early Twenty-First Century, J. Clim., 28, 8319–8346, https://doi.org/10.1175/JCLI-D-14-00556.1, 2015.
- Levitus, S., Antonov, J. I., Boyer, T. P., Locarnini, R. A., Garcia, H. E., and Mishonov, A. V.: Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems: GLOBAL OCEAN HEAT CONTENT, Geophys. Res. Lett., 36, n/a-n/a, https://doi.org/10.1029/2008GL037155, 2009.
- Marti, F., Blazquez, A., Meyssignac, B., Ablain, M., Fraudeau, R., Jugier, R., Larnicol, G., Benveniste, J., and Restano, M.: Monitoring the Ocean Heat Content and Earth Energy Imbalance from space, In preparation.
- Melet, A. and Meyssignac, B.: Explaining the Spread in Global Mean Thermosteric Sea Level Rise in CMIP5 Climate Models*, J. Clim., 28, 9918–9940, https://doi.org/10.1175/JCLI-D-15-0200.1, 2015.
- Meyssignac, B., Boyer, T., Zhao, Z., Hakuba, M. Z., Landerer, F. W., Stammer, D., Köhl, A., Kato, S., L'Ecuyer, T., Ablain, M., Abraham, J. P., Blazquez, A., Cazenave, A., Church, J. A., Cowley, R., Cheng, L., Domingues, C. M., Giglio, D., Gouretski, V., Ishii, M., Johnson, G. C., Killick, R. E., Legler, D., Llovel, W., Lyman, J., Palmer, M. D., Piotrowicz, S., Purkey, S. G., Roemmich, D., Roca, R., Savita, A., Schuckmann, K. von, Speich, S., Stephens, G., Wang, G., Wijffels, S. E., and Zilberman, N.: Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance, Front. Mar. Sci., 6, https://doi.org/10.3389/fmars.2019.00432, 2019.
- Meyssignac, B., Padilla Polo, S., and Blazquez, A.: Accurate estimate of the Expansion Efficiency of Heat (EEH) coefficient at global and regional scales, Prep., 24th August, 2020.
- Prandi, P., Meyssignac, B., Ablain, M., Spada, G., and Ribes, A.: How reliable are local

sea level trends observed by satellite altimetry ?, Prep., 2020.

- Russell, G. L., Gornitz, V., and Miller, J. R.: Regional sea level changes projected by the NASA/GISS Atmosphere-Ocean Model, Clim. Dyn., 16, 789–797, https://doi.org/10.1007/s003820000090, 2000.
- von Schuckmann, K., Palmer, M. D., Trenberth, K. E., Cazenave, A., Chambers, D., Champollion, N., Hansen, J., Josey, S. A., Loeb, N., Mathieu, P.-P., Meyssignac, B., and Wild, M.: An imperative to monitor Earth's energy imbalance, Nat. Clim. Change, 6, 138, 2016.
- Trenberth, K. E., Fasullo, J. T., and Balmaseda, M. A.: Earth's Energy Imbalance, J. Clim., 27, 3129–3144, https://doi.org/10.1175/JCLI-D-13-00294.1, 2014.
- Trenberth, K. E., Fasullo, J. T., von Schuckmann, K., and Cheng, L.: Insights into Earth's Energy Imbalance from Multiple Sources, J. Clim., 29, 7495–7505, https://doi.org/10.1175/JCLI-D-16-0339.1, 2016.