Dynamic Atmospheric Correction using ERA5 product handbook

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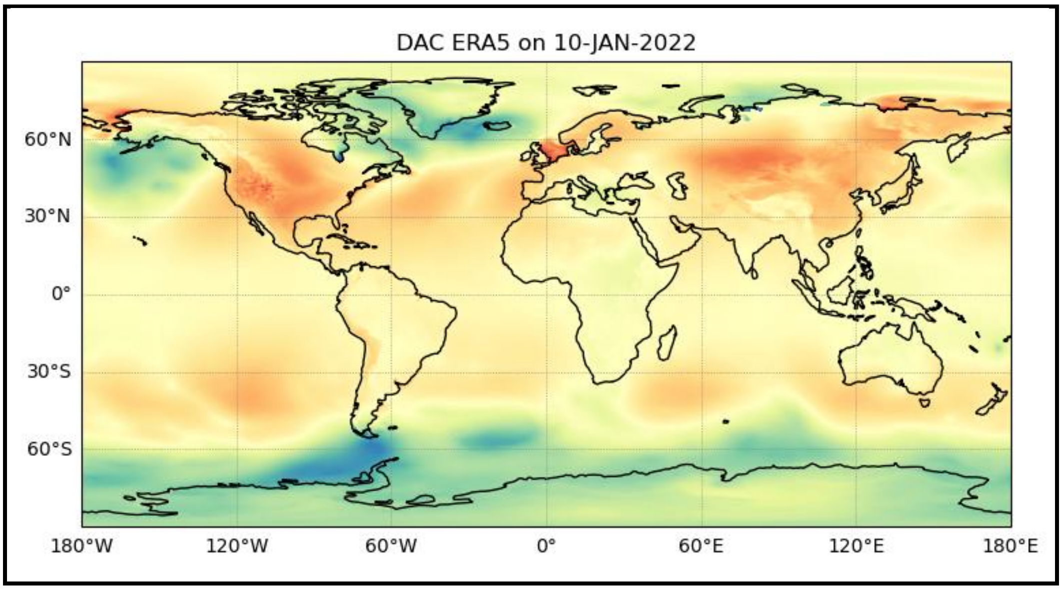

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Chronology Issues:		
Issue:	Date:	Reason for change:
1.0	10/07/25	1st issue

List of Acronyms:

CLS	Collecte Localisation Satellites
CMEMS	Copernicus Marine Environment Monitoring Service
CNES	Centre National d'Etudes Spatiales
DAC	Dynamic Atmospheric Correction
DAC-ERA-interim	DAC forced by the ERA-Interim meteo reanalysis
DAC-OPER	DAC forced by operational ECMWF analysis
DUACS	Data Unification and Altimeter Combination System
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Fifth generation ECMWF atmospheric reanalysis of the global climate covering the period from January 1940 to presen
FTP	File Transfer Protocol
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
MDT	Mean Dynamic Topography (difference between Mean Sea Surface (MSS) and Geoid)
NetCDF	Network Common Data Format
SLA	Sea Level Anomaly (a.k.a. sea surface height with respect to a mean sea surface)

List of figures

1. Overview of this document

This document is the user manual for the Dynamic Atmospheric Correction DAC-ERA5 product. This product has been computed by CNRS-LEGOS and CLS, in the frame of a CNES funded project.

2. The DAC-ERA5 product

2.1. Acknowledgments

When using the products, please cite in the text the following :

This product "DAC-ERA5" was produced by CNES/CNRS-LEGOS/CLS as part of the FESDAC project, and is distributed by AVISO+ with the support of CNES, (2025). Dynamic Atmospheric Correction using ERA5 meteorological reanalysis (Version 1.1) [Data set]. CNES. https://doi.org/10.24400/527896/A01-2025.006

A reference paper is in preparation:

Kocha C. , M. Lievin, Y. Pageot, C. Rubin, V. Quet, F. Octau, M.I. Pujol, P. Prandi, S. Philipps, G. Dibarboure, I. Denis, C. Nogueira Loddo, T. Guinle, F. Bignalet-Cazalet : "Three decades of sea level multi-mission satellite data reprocessed to improve mesoscale quality while ensuring climate scale consistency", in preparation.

This other reference can be cited:

Loren Carrere, Marine Lievin , Quentin Dagneaux, Cécile Kocha , Florent Lyard, Damien Allain, Yannice Faugère , Gérald Dibarboure , Nicolas Picot : "Using ERA5 meteorological reanalysis to improve the Dynamic Atmospheric Correction for altimetry", presentation at OSTST meeting 2020 : https://ostst.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/DAC_ERA5_carrere_et_al.pdf

2.2. User's feedback

Each and every question, comment, example of use, and suggestion will help us improve the future product. You're welcome to ask or send them to aviso@altimetry.fr.

3. Reminder of the content of the DAC-OPER product

3.1. Why do we need a DAC correction ?

The high frequency oceanic signals are badly sampled by altimeter measurements (10 days cycle for T/P-Jason-Sentinel-6 series, 35 days cycle for Envisat-AltiKa series …). This high frequency variability is thus aliased into the lower frequency band (periods over 20 days for T/P-Jason sampling), and pollutes the ocean variability estimation made from altimetry for climate and mesoscale application for example.

Historically, an Inverted Barometer (IB) correction was used for altimetry formulating the static response of the ocean to atmospheric pressure forcing and ignoring wind effects.

Several studies have pointed out that the ocean has a clear dynamic response to pressure forcing at high frequencies (periods below 3 days) and at high latitudes, and that wind effects prevail around the 10 days period (Fukumori et al. 1998; Ponte and Gaspar 1999; Mathers 2000; Fu 2003; Webb and de Cuevas 2002 2003). Thus, this high frequency variability aliased in the altimeter measurements needs to be corrected from independent dynamic model.

Former performances studies made on altimetry have proven the efficiency of a DAC correction combining the high frequencies of the barotropic model forced by atmospheric pressure and wind, to the low frequencies of the IB model (Carrere and Lyard 2003).

3.2. DAC-OPER construction

The operational DAC (DAC-OPER) is a combination of the high frequencies of a barotropic ocean model forced by atmospheric pressure and wind (historically MOG2D model is used, Carrere and Lyard, 2003) and the low frequencies of the inverse barometer (IB), with a filtering cutting-period of 20 days to separate HF and LF :

$$DAC = MOG2D\_HF + IB\_LF$$

Historically the operational DAC is based on MOG2D model forced by the ECMWF operational analysis, but since August 2024, it uses the T-UGO model (DAC V4.0).

The 20 days filtering period was chosen to fit exactly to the Nyquist period of the reference altimeters TP-Jason-S6 sampling.

3.3. S1 and S2 processing

The S1 and S2 oceanic variability is induced by both gravitational forcing and atmospheric forcing at diurnal and semi-diurnal frequencies respectively. Those signals are well modelled by tide models, in particular thanks to data assimilation in the FES tidal solutions (Lyard et al 2021).

Moreover, the ECMWF operational analysis are available every 6 hours, thus the very high frequency atmospheric signals S1 and S2 are badly sampled which makes the model forcing not complete for these frequencies.

In order to homogenise the tides and DAC processing for altimetry for these frequencies, the S1S2 pressure forcing is removed in the DAC computation, using monthly S1S2 climatologies computed from ECMWF 6h pressure fields (Ponte and Ray, 2002).

4. Description of the DAC-ERA5 dataset construction and performances

This section gives a brief description of the DAC-ERA5 dataset construction and performances. The method and the validation diagnostics are further described in the previous paper Carrere et al. (2016).

And some validation results are described in the paper in preparation Kocha et al. (2025) and in Carrere et al. (2020) and Lievin et al. (2020).

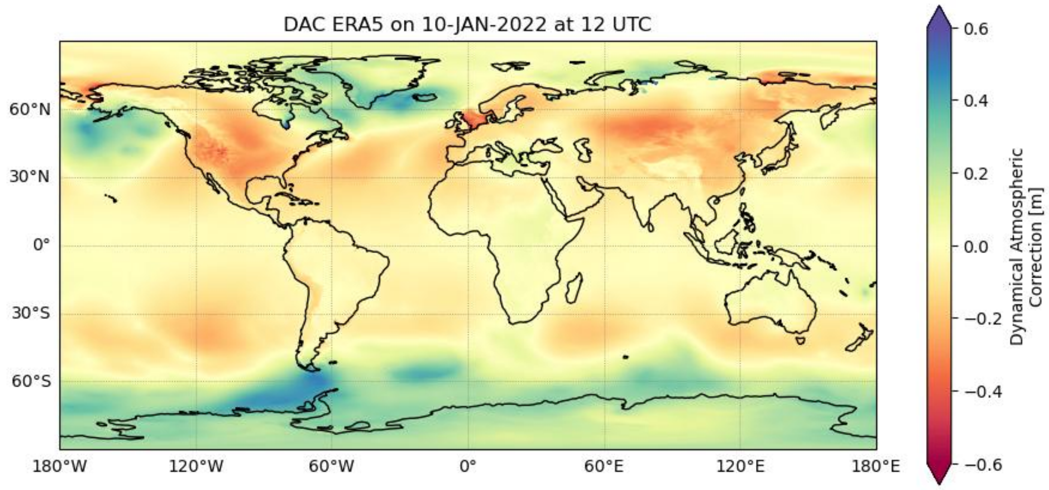

Figure 1: DAC-ERA5 amplitude (m) for the date January 10th 2022.

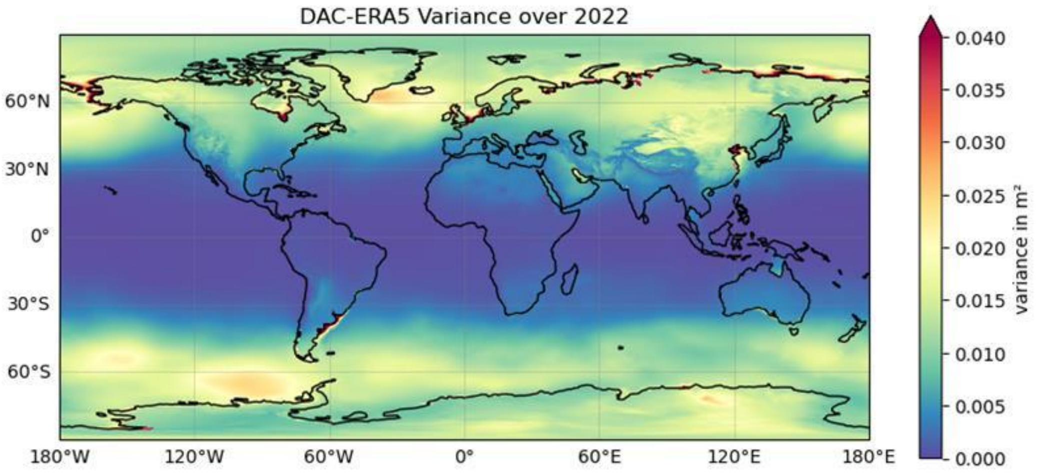

Figure 2: variance of the DAC-ERA5 time series on year 2022.

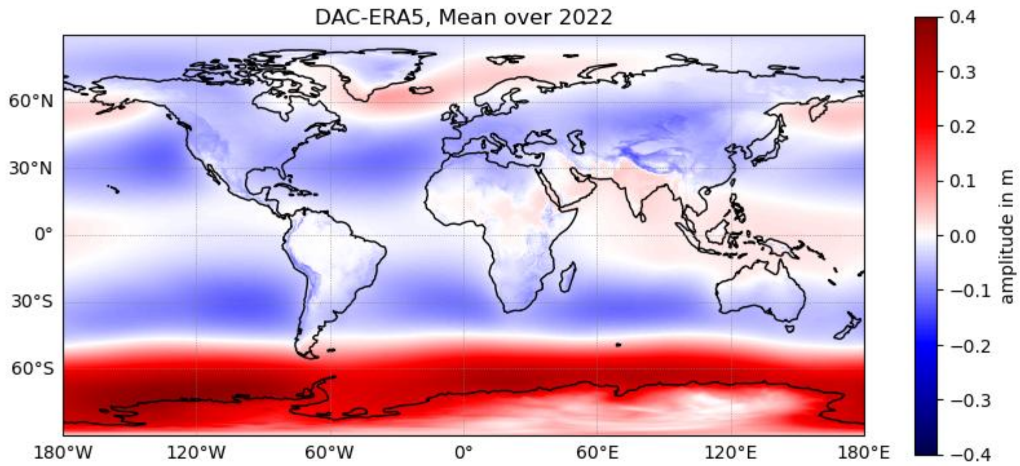

Figure 3: Mean of the DAC-ERA5 time series on year 2022.

4.1. Dataset construction

DAC-ERA5 computation followed method similar to the one used for the previous DAC reanalysis (Carrere et al. 2016), which was dealing with the DAC-ERA-interim reprocessing and was based on ERA-interim atmospheric reanalysis.

4.1.1. DAC-ERA5 main improvements

DAC-ERA5 main improvements include:

- New bathymetry field, inherited from FES2014 tidal solution and improved in most shelves and coastal regions (cf Lyard et al. 2021);
- New hydrodynamic model: T-UGO model (Toulouse-Unstructured Grid Model; Lyard et al. 2006). As MOG2D model, T-UGO native grid is a Finite-Element grid which allows refining the resolution in regions of interest (shallow waters and coastal seas, and on continental shelves breaks).
- Use a long-term atmospheric reanalysis (ERA5 from ECMWF) which ensures better accuracy and homogeneity of the data across the 30 years altimetry period. ERA5 also benefits from a higher time frequency (1 hour compared to 6 hours for operational ECMWF). ERA5 is used to force T-UGO ocean model and to compute the IB.

4.1.2. ERA5 forcing for the DAC

ERA5 meteorological reanalysis benefits from a higher temporal sampling (1h vs 6h) compared to the operational ECMWF dataset and also from a better spatial resolution (31 km) on most ancient period: the use of this dataset allows improving the quality of old altimeter missions and then participate to a better altimeter database for climate and mesoscale applications.

Meteo database	ECMWF operational	ERA-Interim	ERA5
Spatial resolution	O1280 / **9 km** -> N640 / 137 levels	N128 / **79 km** / 60 levels	**N320 / 31 km / 137 levels**
Temporal sampling	6h analysis	6 h analysis	**1h analysis**
Model and assimilation system	Evolving operational model/data assimilation system, currently Cy46r1 => discontinuities when changing model versions	Meteo reanalysis, data assimilation system based on **Cy31r2 (2006)**	Meteo reanalysis, data assimilation system **Cy41r2 (2016)**, more data assimilated
Altimeter products	Operational products NRT and RT	Reprocessed products DT-2014, and CCI products: ERAi used for old missions only	New reprocessed products to come...

Figure 4: characteristics of the different ECMWF meteorological datasets.

For the purpose of the DAC-ERA5 generation, the ERA5 data have been filtered to remove very HF noise: a low-pass filter with a 6 hours cutting-frequency is applied while preserving the atmospheric tidal pics at S1 S2 S3 S4 S5 and M2 frequencies.

The fields msl, 10u and 10v have been filtered.

4.1.3. Atmospheric tides processing

The tidal frequencies are present in the ERA5 forcing, thus the T-UGO sea level time series contain this variability too. In order to ensure the coherency of the DAC and tide corrections for altimetry, the variability due to atmospheric tides needs to be removed in the T-UGO sea level.

A harmonic analysis of T-UGO sea level is performed to extract the tidal pics at FES2014 assimilated frequencies + S1 frequency too (on the FES2014 assimilated period).

Then the T-UGO is corrected from these tidal pics to avoid multiple altimeter correction of these frequencies. In the end, the DAC-ERA5 does not include FES2014 assimilated waves (including S2) nor S1 one. As the same waves have been assimilated in FES2022 tide model, the DAC-ERA5 dataset is also fully consistent with this tide solution.

Notice that despite the correction of the tidal pics described above, the DAC-ERA5 dataset still contains some residual variability at S1, S2 and other frequencies.

In addition to the frequencies listed above, DAC-ERA5 also contains new signals:

- S3 and S5 frequencies which are not included in the DAC-OPER and DAC-ERA-Interim datasets;
- S4 frequency : this wave is also contained in FES2014 spectrum but not assimilated, so it has been kept in the DAC-ERA5 product.

4.1.4. Time frame and resolution

The DAC-ERA5 dataset is available on nearly the entire altimeter era : **01/02/1992 to 31/12/2022.**

Time sampling of the dataset is 1 hour.

To ease construction, distribution and use, the TUGO HF sea level is interpolated on a cartesian regular grid of 1/8°, which allows keeping a good local accuracy compared to the FE native grid.

The IB is computed using ERA5 atmospheric pressure (MSL pressure filed) on the same grid.

The DAC-ERA5 dataset is distributed on the same regular grid of 1/8°.

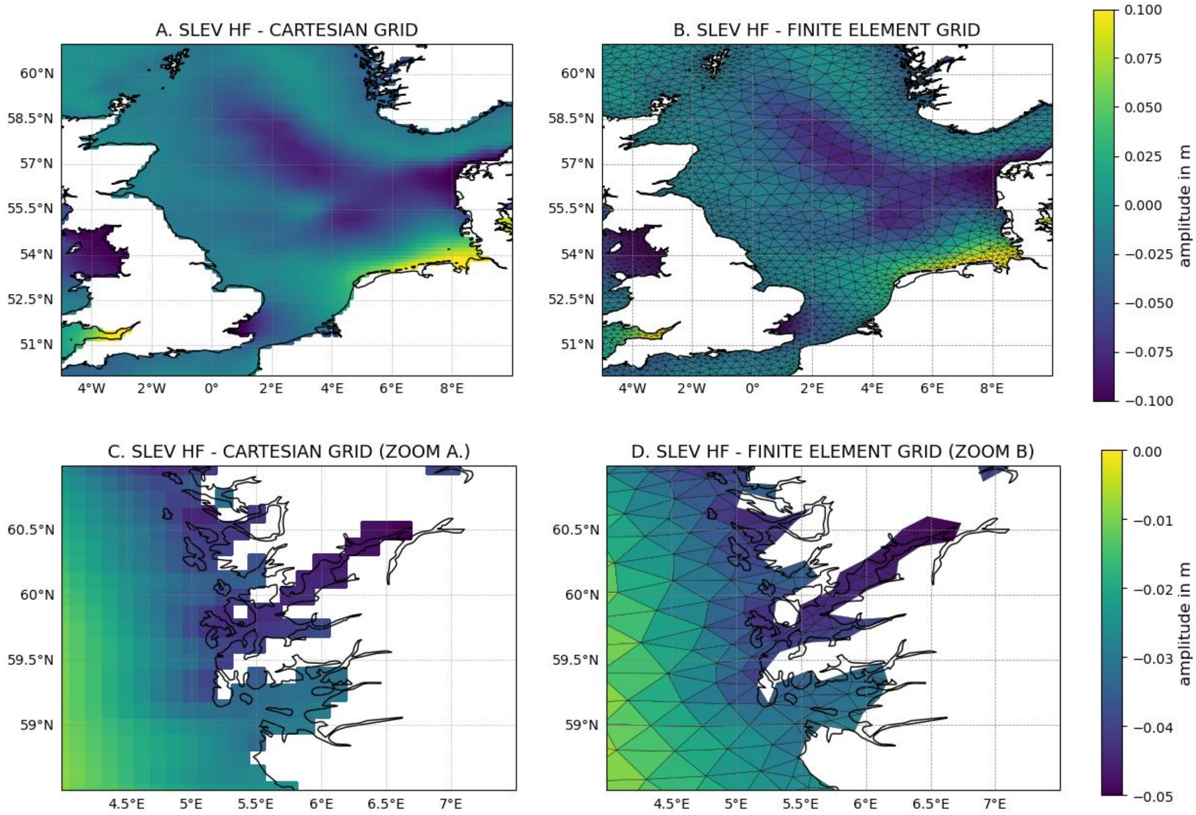

Figure 5: comparison of the cartesian and finite element grids - zoom on North sea

4.1.5. Extrapolated procedure

An extrapolation procedure is applied on the TUGO HF sea level cartesian grids. This extrapolation aims at minimizing missing DAC-ERA5 solution in coastal regions and particularly in fjords or estuaries that are not well sampled by the native global FE mesh.

A basic extrapolation procedure is performed over 4 pixels over the coasts (cf example on figure below).

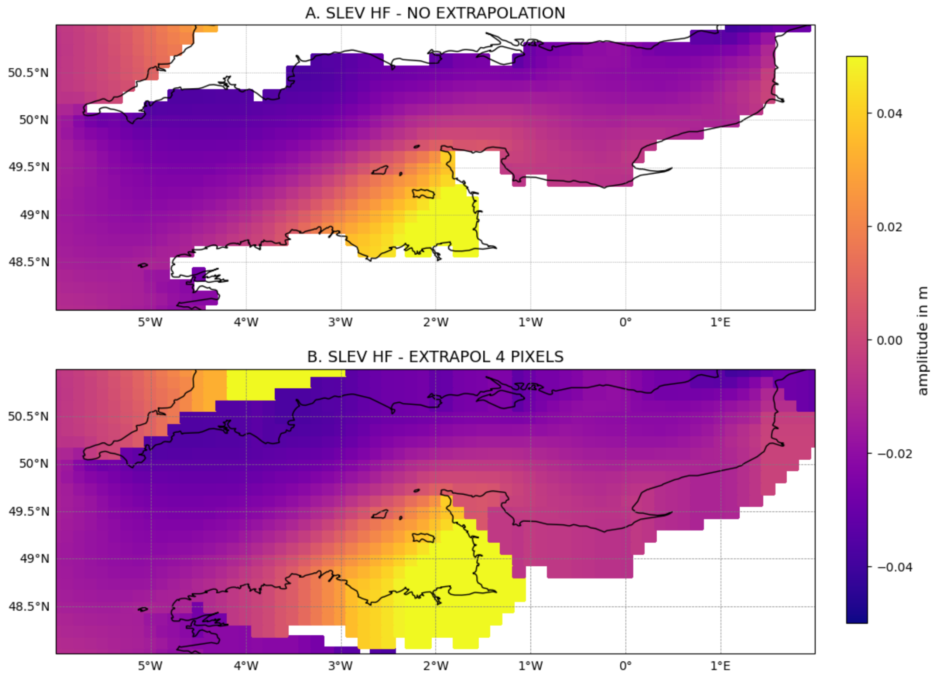

Figure 6: Amplitude of the SLEV-HF-ERA5 (m) on the cartesian grid (Top) and the extrapolated cartesian grid (Bottom) on the Channel.

Note that a specific mask file is provided to indicate which points of the cartesian grid come from the native grid or from the extrapolation procedure (cf Figure 7).

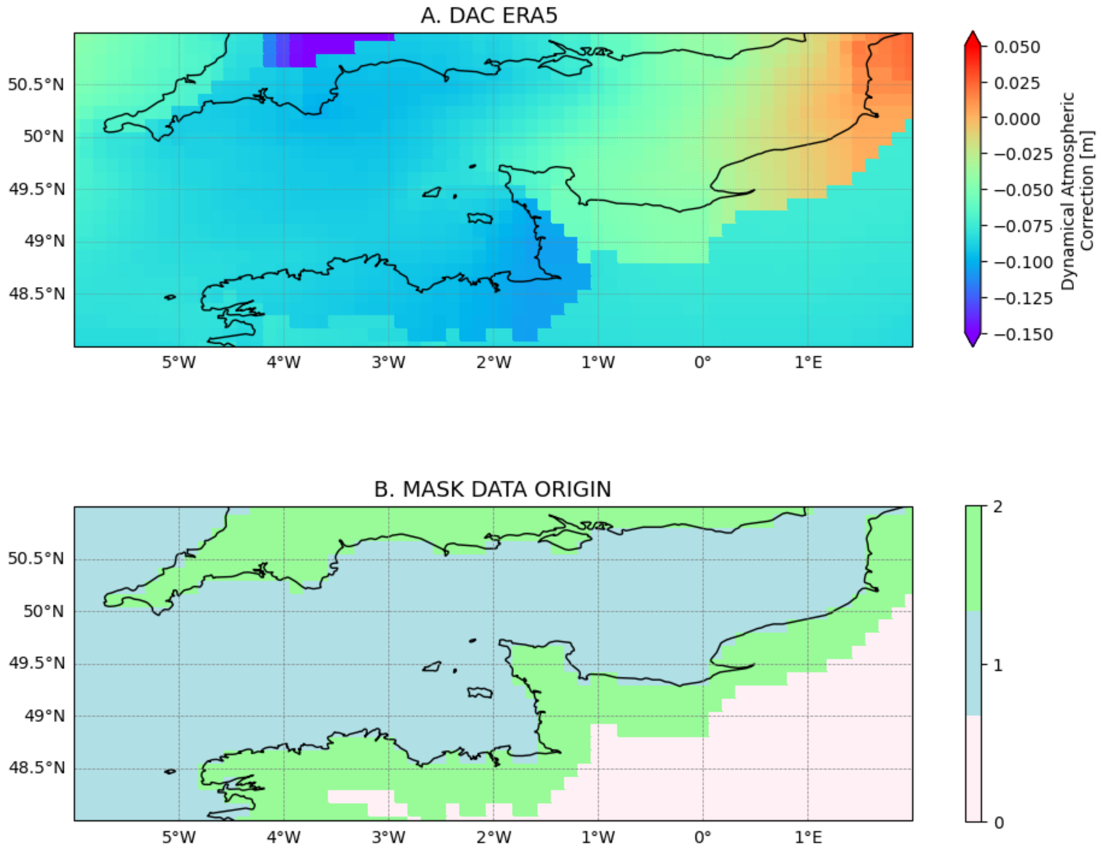

Figure 7: mask file provided for DAC-ERA5 grids. Values of the mask are : 0 = IB (continental areas) ; 1 = SLEV_HF + IB_LF (ocean areas) ; 2 = SLEV_HF_extrapol + IB_LF (transition land/sea = extrapolated area)

4.1.6. DAC on Earth surfaces

On Earth surfaces, the DAC is set to the IB value.

4.2. Assessment of the dataset performances

The new DAC-ERA5 dataset is compared to the DAC-ERA-Interim for oldest missions and to the operational DAC for more recent ones.

Results show a strong variance reduction of the altimeter crossovers differences when using the new DAC-ERA5 on continental shelves and also in deep ocean in southern high latitudes (blue areas on the maps below: Figure 8) : this indicates a significant improvement when using the DAC-ERA5.

A small variance raise is noted in the Mediterranean Sea : this is likely a problem in the mesh and/or the bathymetry field and it should be corrected within FES2022 project.

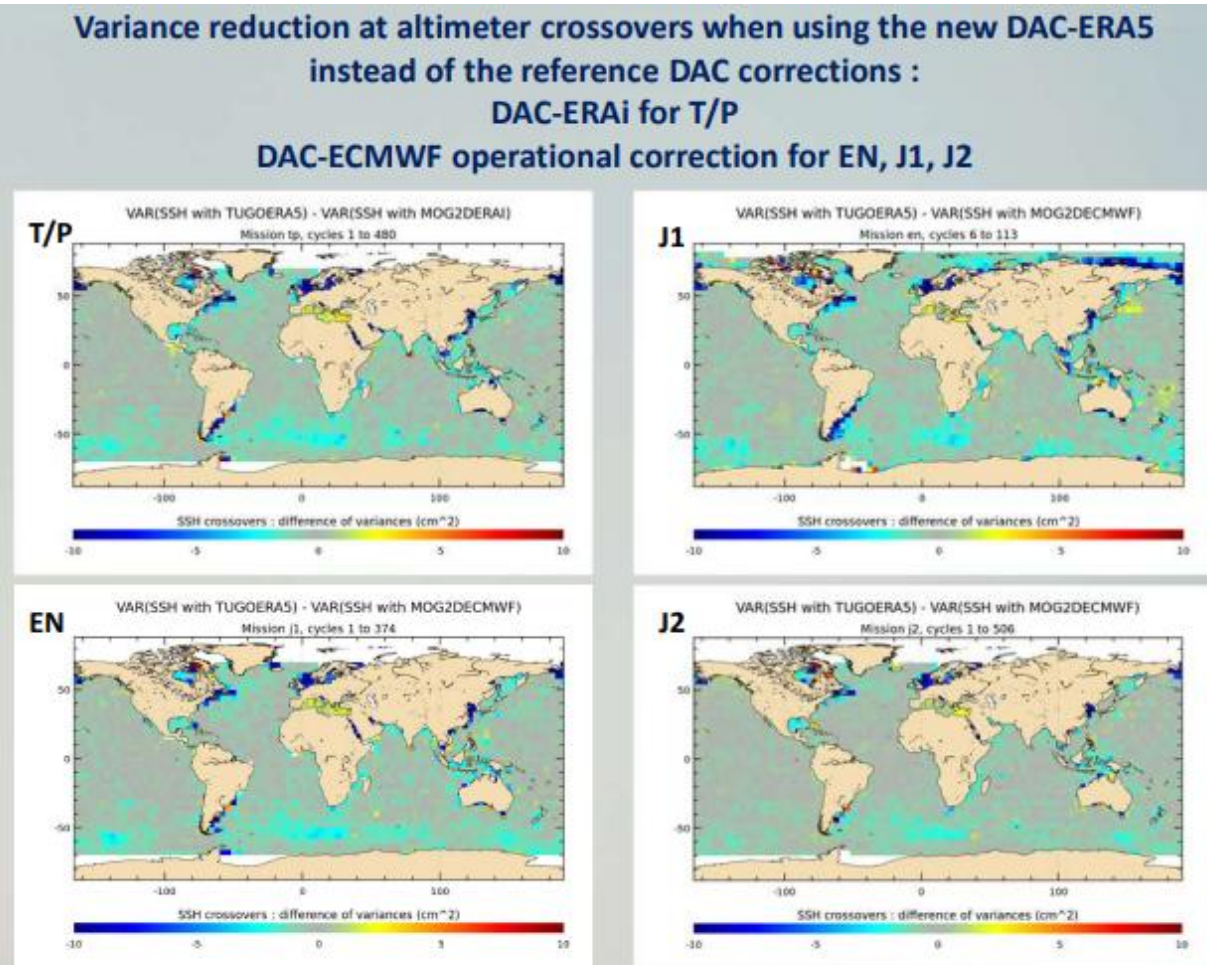

Figure 8 : maps of reduction of SSH crossovers variance for missions T/P, J1, EN and J2, when using the new DAC-ERA5 dataset instead of the reference solution (either DAC-ERA-Interim, or DAC-OPER), in cm². Blue regions indicate a significant variance reduction when using the new DAC-ERA5.

Figure 9 shows the temporal series of the mean variance reduction at altimeter crossovers on global ocean on the altimetric era, when comparing DAC-ERA5 with the reference DAC (DAC-ERA-interim or DAC-ECMWF = DAC-OPER). Comparison shows a mean variance reduction of ~1 cm², stable in time during the entire altimetric era, when using the new DAC-ERA5.

Even on most recent period (J3 and AL), the improvement remains visible showing the interest of the better bathymetry and the higher frequency forcing compared to the operational DAC.

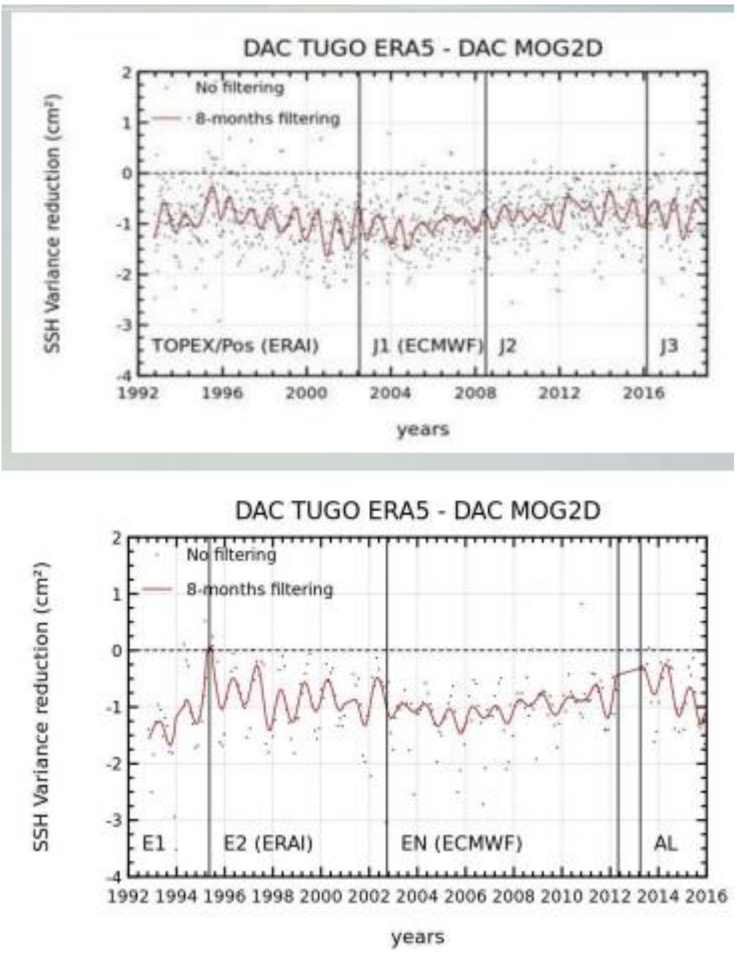

Figure 9: Temporal series of the mean variance reduction at altimeter crossovers on global ocean on the altimetric era, when comparing DAC-ERA5 with the reference DAC (DAC-ERA-interim or DAC-ECMWF = DAC-OPER). Two long-term altimeter series are considered: TP-J1-J2-J3 above and E1-E2-EN-AL below.

Figure 10 shows the mean SLA variance reduction as a function of coastal distance for T/P and J1 missions, when comparing DAC-ERA5 correction with the reference DAC.

DAC-ERA5 has a strong positive impact on T/P measurements, likely due to the better bathymetry used and to the better spatial resolution and better temporal resolution of ERA5 meteorological database compared to ERA-interim.

A positive impact is also noted compared to the operational DAC correction (DAC-ECMWF) on J1 measurements: although ERA5 has a weaker spatial resolution compared to operational ECMWF on this period, this improvement is likely explained by the 1-hour temporal sampling of ERA5 and the better bathymetry used in the T-UGO model.

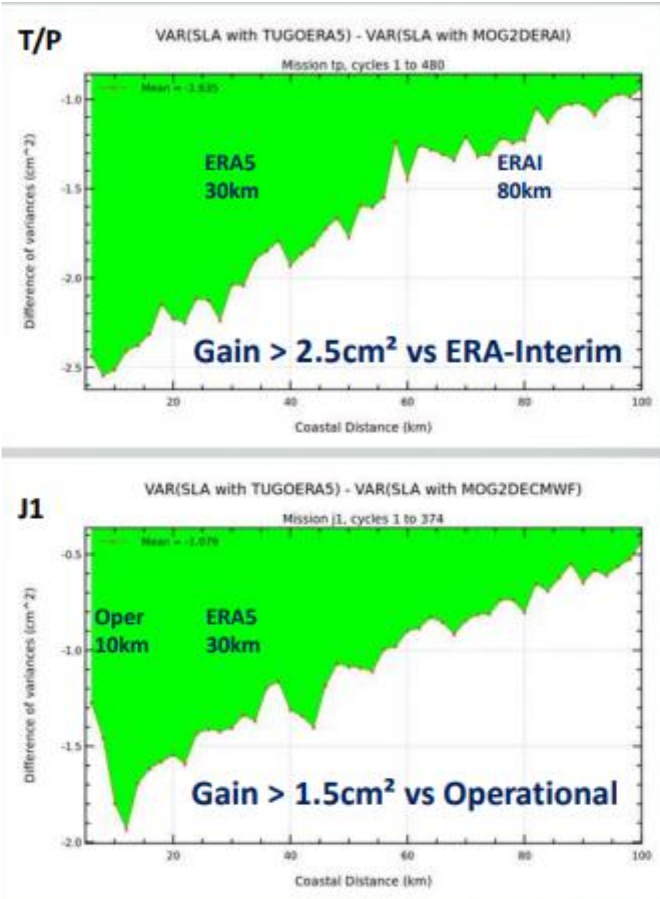

Figure 10: Mean SLA variance reduction as a function of coastal distance for T/P and J1 missions, when comparing DAC-ERA5 correction with the reference DAC (DAC-ERA-interim for T/P, DAC-ECMWF = DAC-OPER for J1)

Figure 11 shows the regional trend differences when using DAC-ERA5 instead of the reference DAC for several altimeter missions. A strong impact is noted for each mission on the regional trends:

- several mm/yr locally : this impact can be interpreted as an improvement thanks to the reduction of noise of the HF series (cf Figure 8 and Figure 9)
- regional trends differences observed are as important as the ones noted when changing DAC-ERA-interim vs operational DAC

When using DAC-ERA5, no impact is noted on global trends as it was already stated for the DAC-ERA-interim dataset (Carrere et al. 2016).

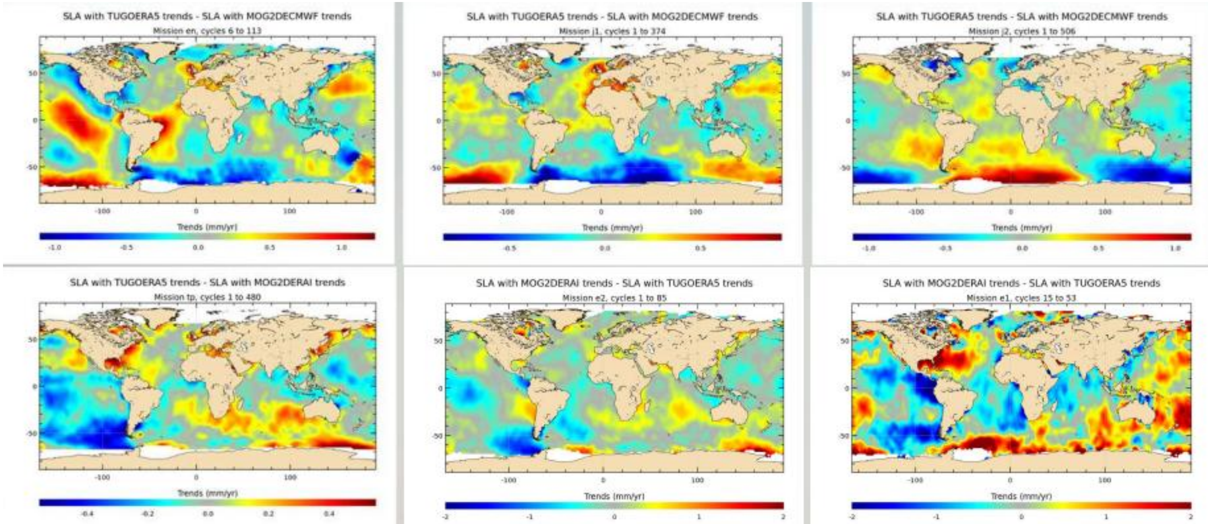

Figure 11: regional trends differences when using DAC-ERA5 instead of the reference DAC (DAC-ERA-interim for ERS1, ERS2, T/P and operational DAC for EN, J1, J2) for each altimeter mission.

5. Description of the DAC-ERA5 product

5.1. Product general content and specifications

DAC-ERA5 product is composed of hourly grids giving the DAC amplitude on global ocean.

The data are distributed on a regular cartesian grid with 1/8° (0.125°) resolution. Each file contains one variable named “dac”.

We also provide a mask file indicating if the pixel have been extrapolated or not.

5.2. Nomenclature of files

5.2.1. Gridded product: structure and semantic of provided NetCDF files

In addition to the conventions described above, the files are using a common structure and semantic:

Files **dac_ERA5_JJJJJ_HH.nc**
with :

- JJJJJ = CNES Julian day referenced to 1950
- HH = hour

5.3. NetCDF

The products are stored using the NetCDF CF format. NetCDF (network Common Data Form) is an interface for array-oriented data access and a library that provides an implementation of the interface. The NetCDF library also defines a machine-independent format for representing scientific data. Together, the interface, library, and format support the creation, access, and sharing of scientific data. The NetCDF software was developed at the Unidata Program Center in Boulder, Colorado. The NetCDF libraries define a machine-independent format for representing scientific data. Please see Unidata NetCDF pages for more information on the NetCDF software package: http://www.unidata.ucar.edu/packages/netcdf/

NetCDF data is:

- Self-Describing. A NetCDF file includes information about the data it contains.
- Architecture-independent. A NetCDF file is represented in a form that can be accessed by computers with different ways of storing integers, characters, and floating-point numbers.
- Direct-access. A small subset of a large dataset may be accessed efficiently, without first reading through all of the preceding data.
- Appendable. Data can be appended to a NetCDF dataset along one dimension without copying the dataset or redefining its structure. The structure of a NetCDF dataset can be changed, though this sometimes causes the dataset to be copied.
- Sharable. One writer and multiple readers may simultaneously access the same NetCDF file.

The NetCDF version provided here is version 4 “classic”.

5.4. Structure and semantic of NetCDF files

You will find hereafter the definitions of the variables defined in the DAC-ERA5 product. The variables are the same for the all types of files delivered.

Name of variable	Type	Content	Unit
latitude	double	Latitude value of measurements	degrees_north
longitude	double	Longitude value of measurements	degrees_east
dac	short	Dynamic atmospheric correction	m

Table 1. Overview of the DAC-ERA5 files

Name of variable	Type	Content	Unit
latitude	double	Latitude value of measurements	degrees_north
longitude	double	Longitude value of measurements	degrees_east
mask	short	0 = IB (continental areas) ; 1 = SLEV_HF + IB_LF (ocean areas) ; 2 = SLEV_HF_extrapol + IB_LF (transition land/sea = extrapolated area)	-

Table 2. Overview of the DAC-ERA5 mask file

6. How to download a product

6.1. Access

CNES AVISO FTP/SFTP access (with AVISO+ credentials):

- ftp://ftp-access.aviso.altimetry.fr:21
- sftp://ftp-access.aviso.altimetry.fr:2221
    - /auxiliary/dac/dac_forced_by_era5_meteo_model

CNES AVISO THREDDS Data Server access:

https://tds%40odatis-ocean.fr:odatis@tds-odatis.aviso.altimetry.fr/thredds/catalog/dataset-auxiliary-dynamic-atmospheric-correction-forced-by-era5-meteo-model/catalog.html

7. Bibliography

Carrere Loren, Marine Lievin , Quentin Dagneaux, Cécile Kocha , Florent Lyard, Damien Allain, Yannice Faugère , Gérald Dibarboure , Nicolas Picot : "Using ERA5 meteorological reanalysis to improve the Dynamic Atmospheric Correction for altimetry", presentation at OSTST meeting 2020 : https://ostst.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/DAC_ERA5_carrere_et_al.pdf

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Fu, L., 2003: Wind-Forced Intraseasonal Sea Level Variability of the Extratropical Oceans. J. Phys. Oceanogr., 33,436–449, https://doi.org/10.1175/1520-0485(2003)033<0436:WFISLV>2.0.CO;2.

Fukumori, I., R. Raghunath, and L.-L. Fu (1998), Nature of global large-scale sea level variability in relation to atmospheric forcing: A modeling study, J. Geophys. Res., 103(C3), 5493–5512, https://doi.org/10.1029/97JC02907 .

Kocha C. , M. Lievin, Y. Pageot, C. Rubin, V. Quet, F. Octau, M.I. Pujol, P. Prandi, S. Philipps, G. Dibarboure, I. Denis, C. Nogueira Loddo, T. Guinle, F. Bignalet-Cazalet : "Three decades of sea level multi-mission satellite data reprocessed to improve mesoscale quality while ensuring climate scale consistency", in preparation.

Lievin, M., C. Kocha, B. Courcol, S. Philipps, I. Denis, T. Guinle, C. Nogueira Loddo, G. Dibarboure, N. Picot, F. Bignalet Cazalet, 2020: REPROCESSING of SEA LEVEL L2P products for 28 years of altimetry missions. OSTST 2020 virtual meeting: https://ostst.aviso.altimetry.fr/fileadmin/user_upload/tx_ausyclsseminar/files/OSTST2020_Reprocessing_L2P_2020.pdf

Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., and Picot, N.: FES2014 global ocean tide atlas: design and performance, Ocean Sci., 17, 615–649, https://doi.org/10.5194/os-17-615-2021 , 2021.
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Ponte, R. M., and P. Gaspar (1999), Regional analysis of the inverted barometer effect over the global ocean using TOPEX/POSEIDON data and model results, J. Geophys. Res., 104(C7), 15587–15601, https://doi.org/10.1029/1999JC900113.

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Webb, D. J., and B. A. de Cuevas, 2003: The Region of Large Sea Surface Height Variability in the Southeast Pacific Ocean. J. Phys. Oceanogr., 33, 1044–1056, https://doi.org/10.1175/1520-0485(2003)033<1044:TROLSS>2.0.CO;2.

8. Appendix A. Product header

8.1. DAC-ERA5 file

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dimensions:
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	longitude = 2880 ;
variables:
	double latitude(latitude) ;
		latitude:long_name = "latitude coordinate" ;
		latitude:standard_name = "latitude" ;
		latitude:units = "degrees_north" ;
		latitude:valid_min = -90. ;
		latitude:valid_max = 90. ;
	double longitude(longitude) ;
		longitude:long_name = "longitude coordinate" ;
		longitude:standard_name = "longitude" ;
		longitude:units = "degrees_east" ;
		longitude:valid_min = 0. ;
		longitude:valid_max = 359.875 ;
	short dac(latitude, longitude) ;
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		dac:long_name = "Dynamic atmospheric correction" ;
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"sea_surface_height_amplitude_due_to_ocean_barotropic_response_to_air_pressure_and
_wind" ;
		dac:units = "m" ;
		dac:scale_factor = 0.0001 ;
		dac:add_offset = 0. ;
		dac:Date_CNES_JD = 26662.9583333333 ;
		dac:date = "2022-12-31 23:00:00 UTC" ;

// global attributes:
		:title = "DAC-ERA5 product" ;
```

```
            string :description = "DAC-ERA5 is based on a TUGO simulation forced by ERA5
meteorological reanalysis. DAC-ERA5 = TUGO HR barotropic model output (high frequencies)
combined with Inverted Barometer correction (low frequencies). The cutoff period used to
separate high and low frequencies is 20 days. Product is delivered with one hour time-step
on a 1/8° regular grid." ;
            :references =
"https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_DAC_ERA5.pdf" ;
            :Conventions = "CF-1.6" ;
            :institution = "CNES/CNRS-LEGOS/CLS" ;
            :history = "2025-07-09 10:18:04:creation" ;
            :doi = "10.24400/527896/a01-2025.006" ;
}
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8.2. Mask file

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            latitude:units = "degrees_north" ;
      double longitude(longitude) ;
            longitude:_FillValue = 9.96920996838687e+36 ;
            longitude:long_name = "Longitudes" ;
            longitude:units = "degrees_east" ;
      short mask(latitude, longitude) ;
            mask:_FillValue = -32767s ;
            mask:long_name = "Data Origin" ;
            mask:comment = "   0 = IB (continental areas) ;
                               1 = SLEV_HF + IB_LF (ocean areas);
                               2 = SLEV_HF_extrapol + IB_LF (transition land/sea)" ;
            mask:coordinates = "NbLongitudes NbLatitudes" ;

// global attributes:
            :title = "Origin of DAC ERA5 product data" ;
            :description = "Mask value describing the content of the DAC-ERA5 product
          depending on the surface. " ;
            :references =
"https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_DAC_ERA5.pdf" ;
            :Conventions = "CF-1.6" ;
```

```
        :institution = "CNES/CNRS-LEGOS/CLS" ;
        :history = "2025-06-20 08:16:22:creation" ;
        :doi = "10.24400/527896/a01-2025.006" ;
}
```