GUT WP8100 Standards and recommended models

January, 5th 2009

prepared by M.-H. Rio and O. Andersen

Table of content

1. Introduction

A recommendation from the 3rd GOCE User Workshop (see Proceedings SP-627) is that ESA initiate an activity to update and improve the Mean Sea Surface (MSS) modelling, with a special focus on the coastal regions as well as on the description of the error characteristics of their data. A proper and independent Mean Sea Surface model shall be created and distributed inside the GUT toolbox. This is needed for the computation of accurate Mean Dynamic Topography maps, knowing the geoid.

Moreover, all GUT auxiliary files, distributed with the toolbox, shall be selected from the state-of-the-art models available, updating the trade-off work already performed in GUTS.

However, the combined use of altimetric data (MSS, SLA) with a geoid model requires that we pay particular attention to a number of choices that are made in the computation of each individual dataset.

In this context, the objective of this sub-workpackage is to develop and recommend standards for processing altimetry and the derivation of MSS models. The standards will contain guidelines on selection of geodetic coordinate system, tidal system, IB-correction, averaging period, format, etc. The guidelines will also include recommendations for error estimation and contain procedures for transforming MSSs between different averaging periods. In addition, a list of available MSS models will be made. Furthermore, a list of available global up-to-date Digital Elevation Models (DEM) will be made with subsequent recommendation on which model to use in GUT.

2. Guidelines for Mean Sea Surface computation

An altimetric MSS is computed by averaging altimetric heights, preferably from different altimetric missions, over a **given time period.**

The MSS characteristics therefore directly depend on the standards and corrections applied to the individual altimetric heights.

Altimetric heights are defined relative to a **reference ellipsoid** and relative **to a tide system**. Furthermore, **geophysical and environmental corrections** are applied to the individual altimetric heights observations. In some cases, a choice of model or algorithm for the correction must be made. In the following section, we list all the different possibilities, in terms of tidal system, reference ellipsoid and altimetric corrections, that will impact the final MSS.

2.1. Reference ellipsoid issue

Both altimetric mean sea surface heights and geoid heights are given relative to a reference ellipsoid, which corresponds to a theoretical shape of the Earth. The characteristics of different, currently used, reference ellipsoids are given Table 1. Before subtracting a geoid from a MSSH, both fields have to be expressed relative to the same reference ellipsoid. If not, the impact on the resulting MDT is large: Figure 1 shows the height differences between the GRIM and Topex ellipsoids on a global grid.

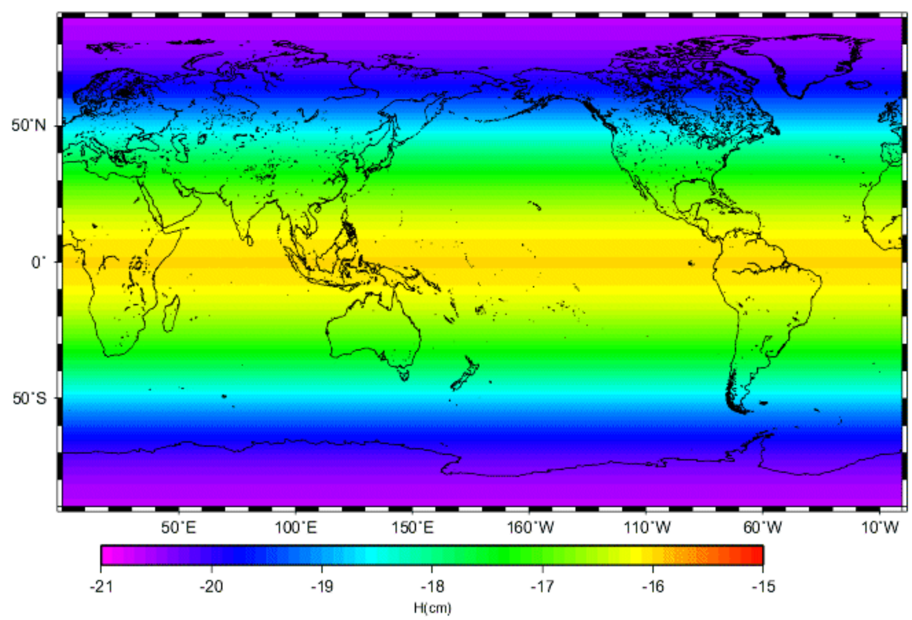


Figure 1: Height difference between the TOPEX and the GRIM ellipsoids.

Ellipsoid name	a (m)	1/f	Gm (m3/s)

"GRIM"	6378136.46	298.25765	398600.4369e9
"TOPEX"	6378136.3	298.257	398600.4415e9
"GRS80"	6378137.	298.257222101	398600.5e9
"WGS84" WGS84 rev 1	6378137. 6378137.	298.257223563 298.257223563	398600.5e9 398600.4418e9

Table 1: The different reference ellipsoids and their characteristics (semi grand axe a, flattening 1/f and coefficient Gm)

Altimetric Mean Sea Surfaces are most commonly computed relative to the TOPEX ellipsoid.

The GRACE geoid models provided by the GFZ are computed relative to the GRIM ellipsoid.

The **GOCE** geoid heights will be computed relative to the **WGS84** reference ellipsoid [DR 1].

Recommendations to users

The selection of a particular reference ellipsoid is not critical. The important criterion is, that the MSS and the geoid must be defined in the same system if these are to be used jointly to compute a Mean Dynamic Topography (MDT).

This means that before computing the ocean MDT by subtracting the GOCE geoid from an altimetric Mean Sea Surface, the user must check that the MSS is defined in the same system.

Recommendations for implementation of the toolbox

As conversion between reference systems can be done readily in spherical harmonic components, at the time of generation of a gridded product, it is recommended that the default behaviour of the toolbox is to convert the GOCE data to the TOPEX reference ellipsoid, to be consistent with the MSS auxiliary data.

The reference system used for each of the packaged auxiliary datasets must be available as metadata – either within the file or in a reference file.

The toolbox must allow for conversion of both spherical harmonic and gridded representations of data between reference ellipsoid.

2.2. Tide system issue

Geoid heights (and mean sea surface heights) also differ depending on what tidal system is implemented to deal with the permanent tide effects. In the **MEAN TIDE** system, the effects of the permanent tides are included in the definition of the geoid. In the **ZERO TIDE** system, the effects of the permanent tides are removed from the gravity field definition. In the **TIDE FREE or NON-TIDAL** system, not only the effects of the permanent tides are removed but the response of the Earth to that absence is also taken into account. Altimetric mean sea surfaces are usually expressed in the

MEAN TIDE system. The GRACE GGM02 geoids from the CSR are defined relative to the ZERO TIDE system. The GRACE EIGEN geoids from the GFZ are defined relative to the TIDE FREE system. When computing an ocean mean dynamic topography, the MSSH and the geoid first have to be computed in the same system. If not, the impact on the resulting MDT is large: for instance, Figure 2 shows the difference between the TIDE FREE and the MEAN TIDE reference systems.

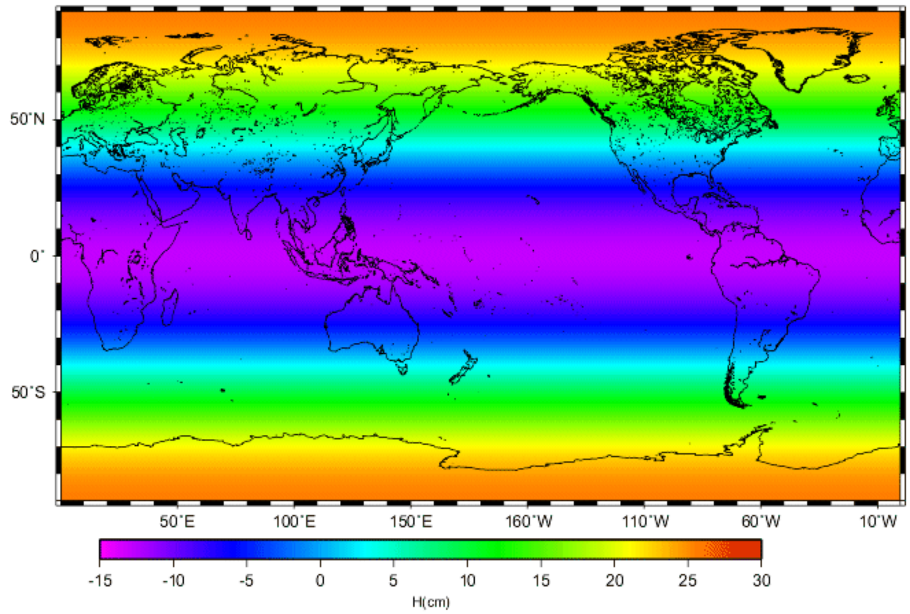


Figure 2: Height difference between the TIDE FREE and the MEAN TIDE reference systems

Recommendations to users

The choice of tide-system is not critical and the toolbox will enable conversion between the 3 tide-system options. However, it is important for ensure that the MSS and geoid are within the SAME tide system for studies of long-wavelength dynamic topography. The toolbox will ensure this happens when using the auxiliary data contained in the distribution, but users must ensure that tide system used in alternative data products (like GPS) is consistent,

Recommendations for implementation of the toolbox

As conversion between tide systems is done most readily in spherical harmonic components, at the time of generation of a gridded product, it is recommended that the default behaviour of the toolbox is to convert the GOCE geoid data to the mean-tide system to be consistent with the MSS data.

The tidal reference system used for each of the packaged auxiliary datasets must be available as metadata – either within the file or in a reference file.

The toolbox must allow for conversion of both spherical harmonic and gridded representations of data between the three tidal reference systems.

2.3. Time period issue:

Different MSS will have different averaging periods and consequently inter-annual ocean variability will be mapped differently into these. As for the tidal system and the reference ellipsoid, there is no reason to prefer any specific averaging period. In the GUT context, the objective is to compute a Mean Dynamic Topography, that will then be used to compute absolute dynamic topography data from altimetric anomalies using the equation:

h=MDT+SLA Eq1

The altimetric sea level anomalies (SLA) are anomalies of the sea level relative to a specific time period, and the period used may vary from one product to another. For instance, the altimetric SLA distributed by AVISO are computed relative to the 1993-1999 period. (Mean altimetric profiles covering the period 1993-1999 have been subtracted from the single SSH measurements). Similarly, the DNSC08 SLA are referenced to a 12 years averaging period (1993-2004)

This correction is generally of minor importance, but the user needs to be aware of the existence of the effect (Figure 3)

However, a simple procedure exists that allows transformation of MSS models between different time periods.

Error! Objects cannot be created from editing field codes.

To change the reference period of an altimetric MSS from P2 to P1, altimetric anomalies relative to the P2 period are needed.

For instance, let's consider the altimetric Sea Level Anomalies distributed by AVISO. They are referenced to the period 1993-1999, like the CLS01 MSS. To compute the CLS01 MSS over a different averaging period, let's say 1993-2004, just average the AVISO SLA over 1993-2004 and add it to the CLS01 initial field. The "correction" is displayed on Figure 3.

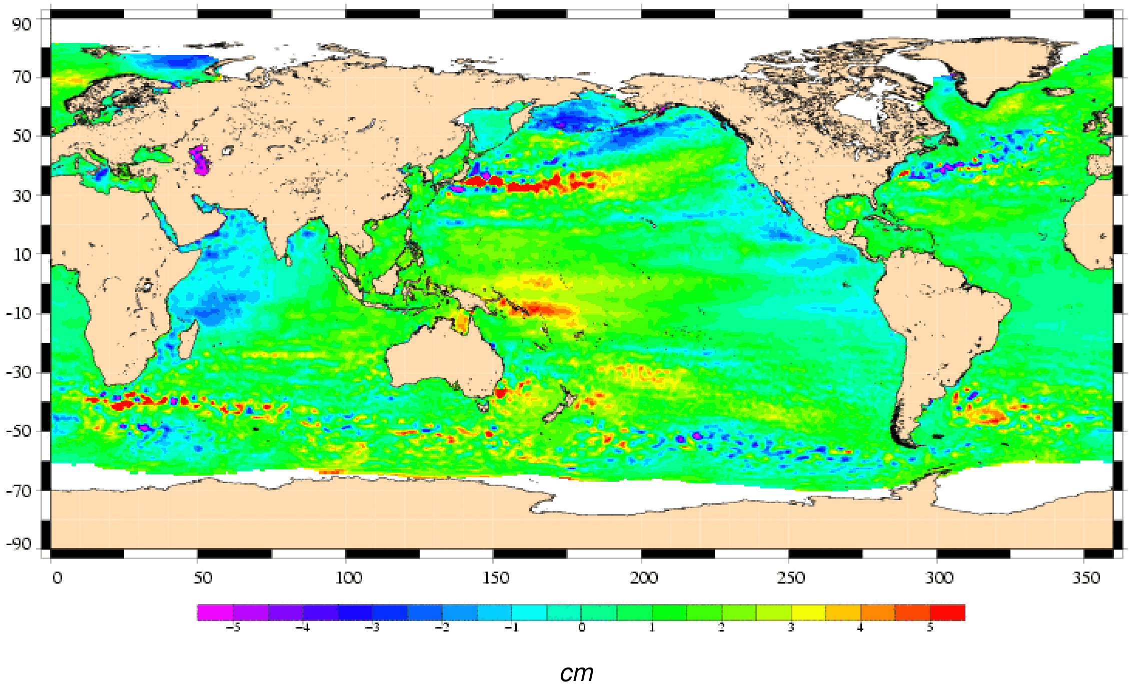


Figure 3: Average over the 1993-2004 period of SLA computed relative to the 1993-1999 period. Adding this field to the CLS01 MSS enable to change the reference period of the CLS01 MSS from 1993-1999 to 1993-2004.

Recommendations to users

The selection of a particular averaging period for the MSS is not critical. The important criterion is that the MSS used to generate the SLAs must be defined over the same averaging period as the MDT.

This means that before computing the absolute dynamic topography by adding an altimetric SLA to a MDT, the user must check that the SLA are defined relative to the same averaging period as used for the MDT. If not, the time period of the MSS must be changed and a consistent MDT computed.

Recommendations for implementation of the toolbox

The averaging period of packaged MSS and SLA auxiliary datasets should be consistent, and consistent with packaged MDT auxiliary files.

The averaging period used for each of the packaged auxiliary MSS, SLA & MDT datasets must be available as metadata – either within the files or in a reference file.

The toolbox must allow for conversion between averaging period by use of simple gridded field averaging.

2.4. Altimetric correction issue

2.4.1. Overview of the altimetric corrections

Before subtracting the altimetric range from the satellite's orbit to compute altimetric heights, a number of corrections have to be applied in order to take into account instrumental and geophysical effects that affect the range computation.

The following geophysical corrections are computed:

Ocean tides: Corrections for sea surface height variations due to the attraction of the Sun and Moon. Different tide models exist (FES, GOT) that is used to correct from this effect.

In the following section, different tide model versions will be mentioned: ***FES99, FES04*** *(*DR 3*),* ***GOT00.***, ***GOT99***, ***GOT4.7*** *(*DR 4*)*

Solid earth tides: Corrections for solid earth variations due to the attraction of the Sun and Moon. Calculated by models. [DR 5, DR 6]

Pole tides: Corrections for variations due to the attraction of the Sun and Moon. Calculated by models. [DR 7]

Tidal loading: Corrections for height variations due to changes in tide-induced forces acting on the Earth's surface.

Ionosphere: Correction for the path delay in the radar return signal due to the atmosphere's electron content. It is calculated by combining radar altimeter measurements acquired at two separate frequencies (C-band and K_u-band for Topex and Jason-1, K_u-band and S-band for Envisat). An alternative is to use outputs from ionospheric models as the Bent model (DR 8), the GIM model (DR 9) or the IRI model (DR 10)

In the following section, ***GIM*** *and* ***IRI*** *will refer to the GIM and IRI model corrections while* ***ALTIMETER*** *will refer to the correction based on altimetry.*

Wet troposphere: Correction for the path delay in the radar return signal due to liquid water in the atmosphere. It is calculated from radiometer measurements and/or meteorological models.

In the following section, ***RADIOMETER*** *will refer to the wet tropospheric correction based on the radiometer measurements while* ***NCEP*** *will refer to the wet troposphere correction based on the NCEP model and* ***ECMWF*** *will refer to the wet troposphere correction based on the ECMWF model.*

Dry troposphere: Correction for the path delay in the radar return signal due to the atmosphere. It is calculated from meteorological models as ECMWF or NCEP.

In the following section, ***NCEP*** *will refer to the dry troposphere correction based on the NCEP model and* ***ECMWF*** *will refer to the dry troposphere correction based on the ECMWF model.*

Electromagnetic bias: Correction for bias in measurements introduced by varying reflectivity of wave crests and troughs. It is calculated from models, parametric (BEM4,

DR 11) or non parametric (DR 12, DR 13)

In the following section, BEM4 will refer to the parametric model from (

DR 11*) while NPARAM will refer to the non-parametric model from (*DR 13*)*

Atmospheric Correction

Static: Correction for variations in sea surface height assuming a static response (**Inverse barometer**) of the ocean to atmospheric forcing, and neglecting wind effects (atmospheric loading). Pressure anomalies P' are calculated using pressure estimates from meteorological models.

Different methods can be used to compute the pressure anomaly:

- P'=Pressure-Pref where Pref is a constant (taken as 1013.3 mbar if the average over the full globe is done, or 1011mbar if the average is only done over the oceans)

- P'=Pressure-$\overline{P}$ where $\overline{P}$ is the spatial average (over the ocean) of the instantaneous pressure map (every 6 hours). It has been shown (DR 16) that the use of $\overline{P}$ instead of Pref leads to significant improvement for the IB correction.

Dynamic: Correction for high frequency variations in sea surface height that is aliased in the altimetric measurements. This correction is based on ocean models as MOG2D (barotropic model: assumes a dynamic response of the ocean to atmospheric forcing (wind and pressure)). Full baroclinic+barotropic models can also be used.

In the following section, different Atmospheric Correction will be referred to: ***IB****, standing for Inverse Barometer where* $\overline{P}$ is used to compute pressure anomalies, or ***IBref*** *when Pref is used to compute pressure anomalies and* ***MOG2D-IB****, referring to a combination between IB at long wavelengths and MOG2D high resolution model at short wavelengths (periods smaller than 20 days)*

For all these corrections, as well as for the satellite's orbit computation, different solutions exist; some of them have been given in the above list. Standards are regularly decided and updated by the international scientific community. These standards are decided by the OSTST (Ocean Surface Topography Science Team) for the Topex and Jason missions and by the QWG (Quality Working Group) for the ERS and Envisat missions

2.4.2. Recommendation to users

For oceanographic applications, the MSS and the SLA are jointly used: The MDT computed from MSS minus Geoid is added to altimetric anomalies (Level-3 products) to compute absolute altimetric heights. It is therefore recommended that the standards applied to the MSS are the same as those used to compute the altimetric anomalies. This means that before computing the absolute dynamic topography by adding an altimetric SLA to a MDT, the user must check that the SLA was calculated using the same correction set as was used for the MSS. If not, merging the fields may provide erroneous results, caused by difference in corrections rather than ocean dynamic topography.

In that context, we provide in the following section:

- a quantitative, exhaustive study of the impact of choosing different standards for MSS computation.(sections 3.1 and 3.2)

- a description of the standards used for GUT altimetric products computation (section 3.3)

3. Choosing standard corrections for MSS computation

3.1. Characterization of the different altimetric corrections

3.1.1. Spatial characterization of the different altimetric corrections

The aim of this section is to characterize each altimetric correction introduced previously, from a spatial point of view (what is the intensity and the geographical patterns of each correction?)

Method

To characterize the spatial distribution, we show for each correction:

- A global map of the correction mean computed over 1 year of the Jason 1 mission (2004 : cycles 73 to 109).
- A global map of the correction variance computed over 1 year of the Jason 1 mission (2004 : cycles 73 to 109).

Results

- Ionospheric correction from altimetry

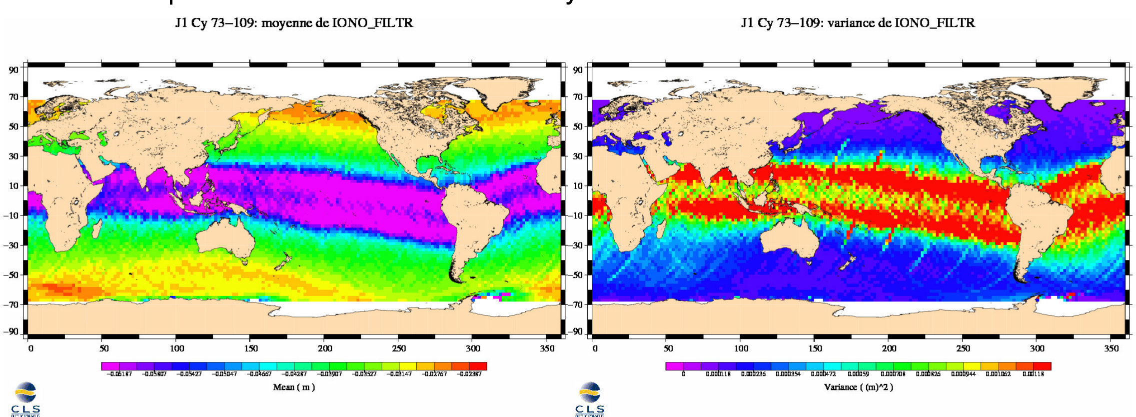


Figure 4: Spatial (top) analysis of the ionospheric correction

The signal depends strongly on latitude. It ranges from -6 cm in the tropics (with a 12 cm² variance) to -2.5 cm at high latitudes (1 cm² variance)

- Dry troposphere correction from ECMWF model

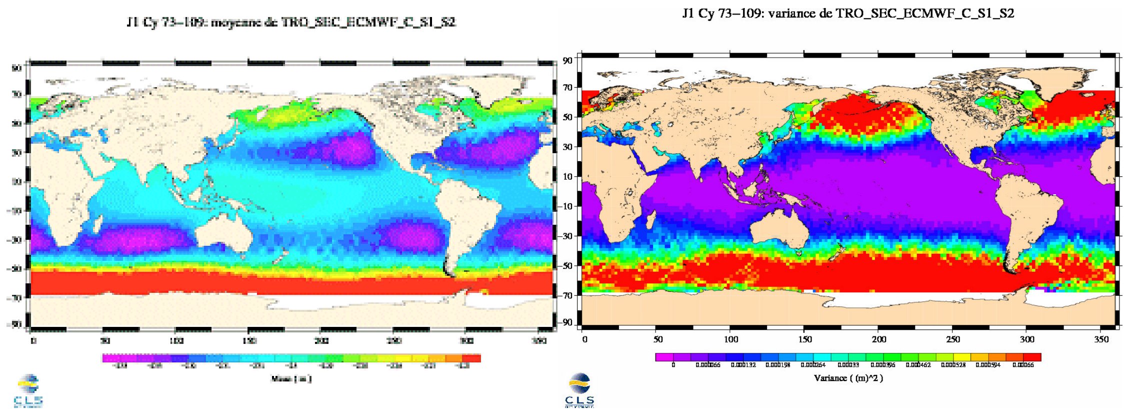


Figure 5: Spatial (top) analysis of the dry troposphere correction

The spatial distribution of the dry troposphere correction computed from the ECMWF model features a latitudinal dependency, with highest values (-2.33m and a variance of 0.5 cm²) in the subtropical gyres and smallest values at high latitudes (> -2.27m and a variance > 6 cm²)

- Wet troposphere correction from radiometer

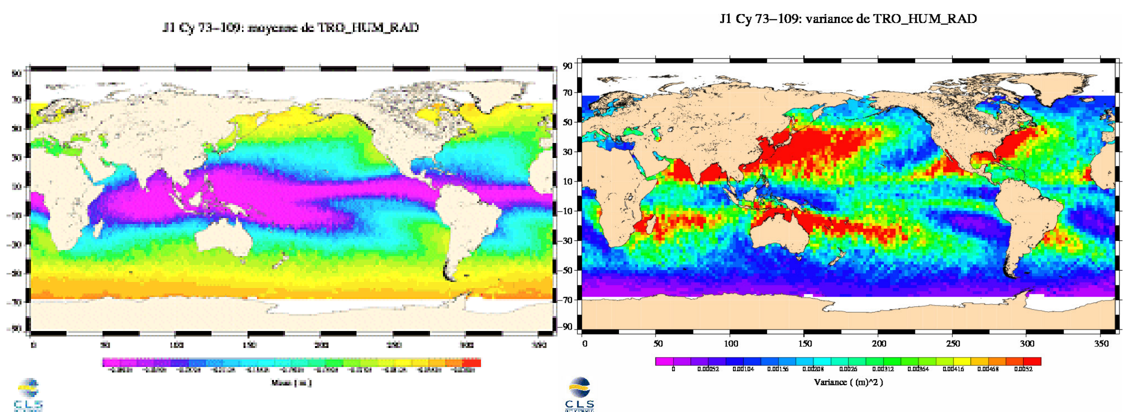


Figure 6: Spatial (top) analysis of the wet troposphere correction

Once again, the mean signal over 1 year is strongly dependent on latitude, with highest values in the equatorial band (-30cm) and smallest values in the Antarctic circumpolar current (-5cm).

The strongest variability is observed at mid latitudes (> 50 cm²)

- Atmospheric Correction (MOG2D-IB)

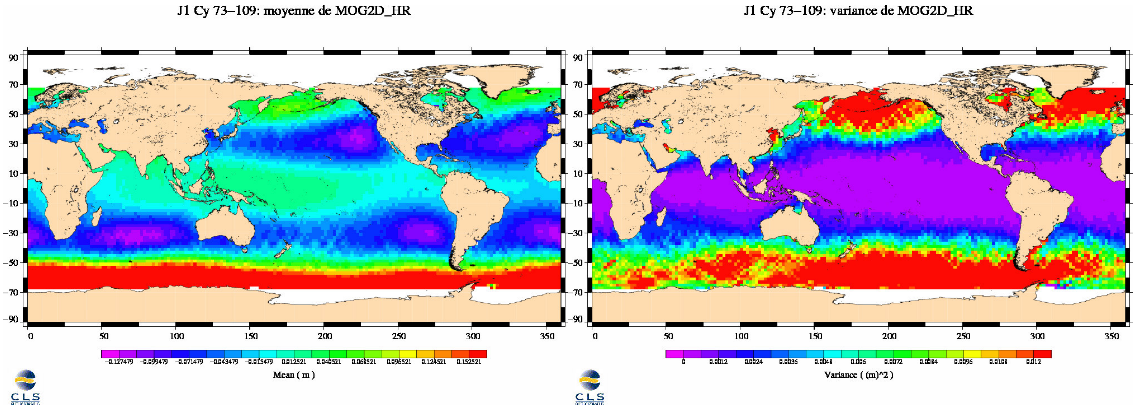


Figure 7: Spatial (top) analysis of the Atmospheric correction

The spatial distribution of the mean and variance of the MOG2D-IB correction is quite similar to the spatial pattern of the dry troposphere correction (Figure 5) but with different amplitudes: Mean values range from -10 cm (Variance around 10 cm^2) at mid latitudes to 15 cm at high latitudes (variance greater than 120 cm^2).

- Tide correction from GOT00.2

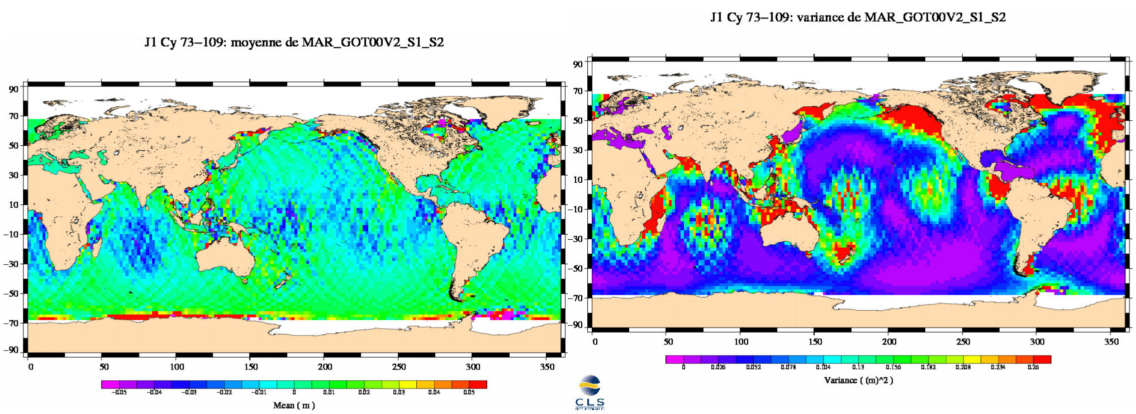


Figure 8: Spatial (top) analysis of the Tide correction

The mean of the tide correction over 1 year of data ranges between roughly -5 and 5 cm. The spatial distribution of the variance is very characteristic of the ocean tides.

- Sea State Bias correction from non parametric model

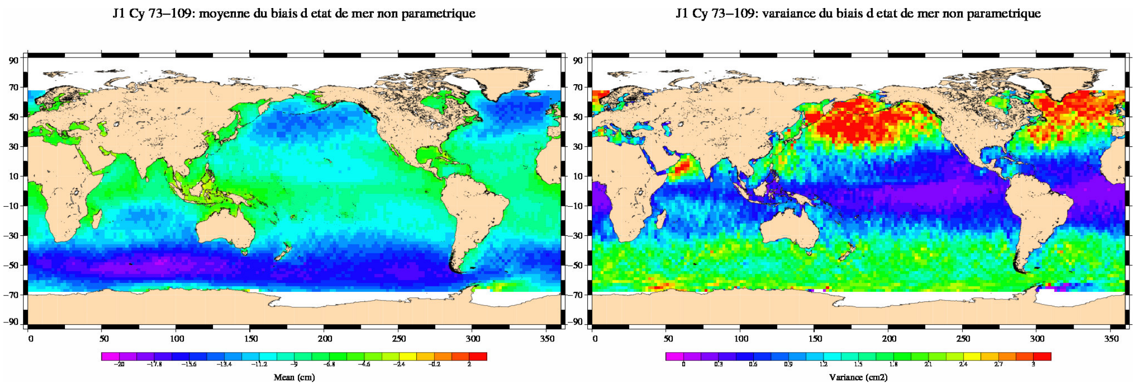


Figure 9 : Spatial (top) analysis of the non parametric SSB correction

The spatial pattern of one year of SSB correction average features smallest values at low and mid latitudes (from 5 to 10 cm with a variance of up to 1.5 cm²) and highest values at high latitudes (up to -20 cm with variability greater than 3 cm² in the Northern hemisphere).

3.1.2. Stability of the corrections with time - investigating any potential trends

The above chosen set of range and geophysical corrections for the satellite altimetry observations were subsequently analysed for possible trend with time as well as offsets between satellite missions. For this investigation all corrections for the TOPEX, JASON-1, ERS2 and ENVISAT were averaged repeat by repeat for the period 1992-2007. For the ERS-2 and ENVISAT the repeat period is 35 days where as for the TOPEX and JASON-1 the repeat period is 9.9 days.

In the computation of the global value for each repeat the different density of observations as a function of latitude was taken into account in order not to weight the much higher number of observations at high latitude higher than the lower number of observations at low latitude.

For each correction a trend was estimated using the combined TOPEX and JASON 1 time series of 17 years from September 1992 until September 2008.

The time series of the global averaged value of each range and geophysical correction is shown in the figures 19-23. Each figure shown the mean value and the standard deviation of the correction as a function of each repeat No investigation were made for the ocean tide correction as this is not assumed to generate any trend with time.

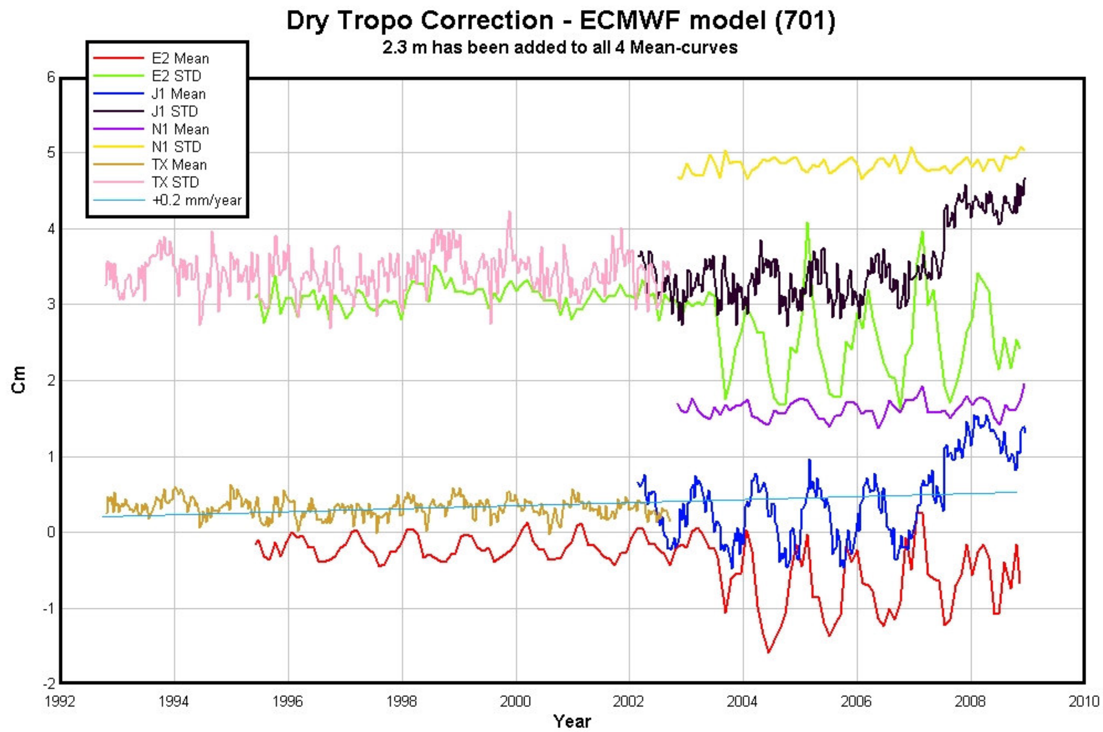


Figure 10: Temporal evolvement of the ECMWF Dry troposphere corrections (include trend for T/P-Jason1).

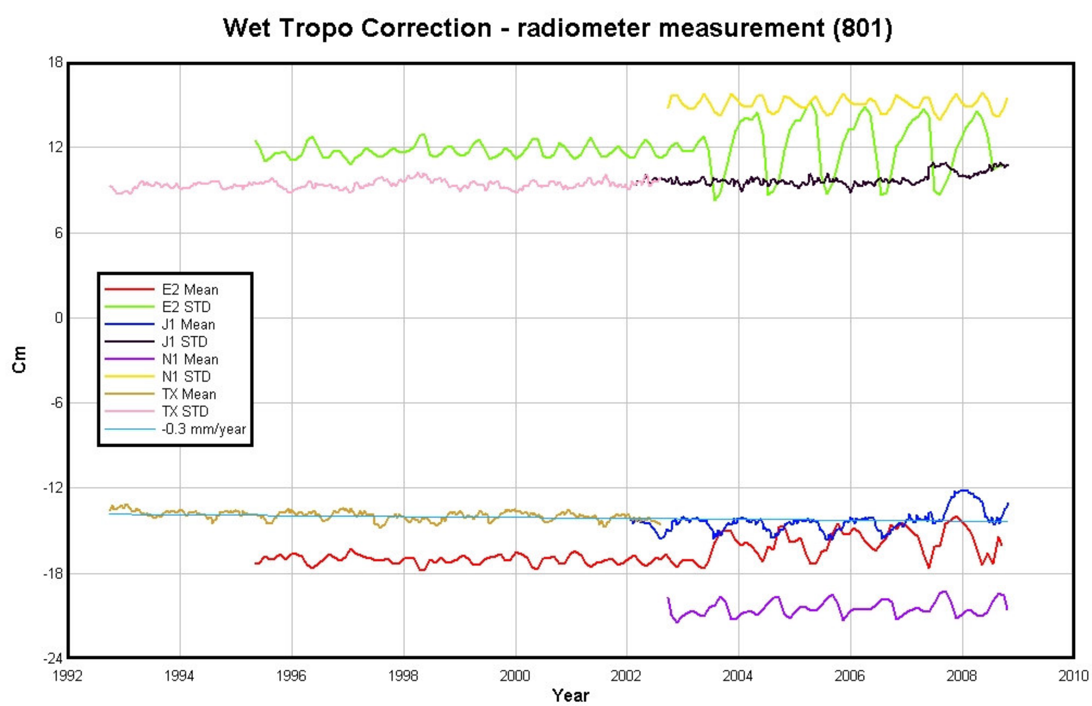


Figure 11: Temporal evolvement of the wet troposphere corrections (include trend for T/P-

Jason1).

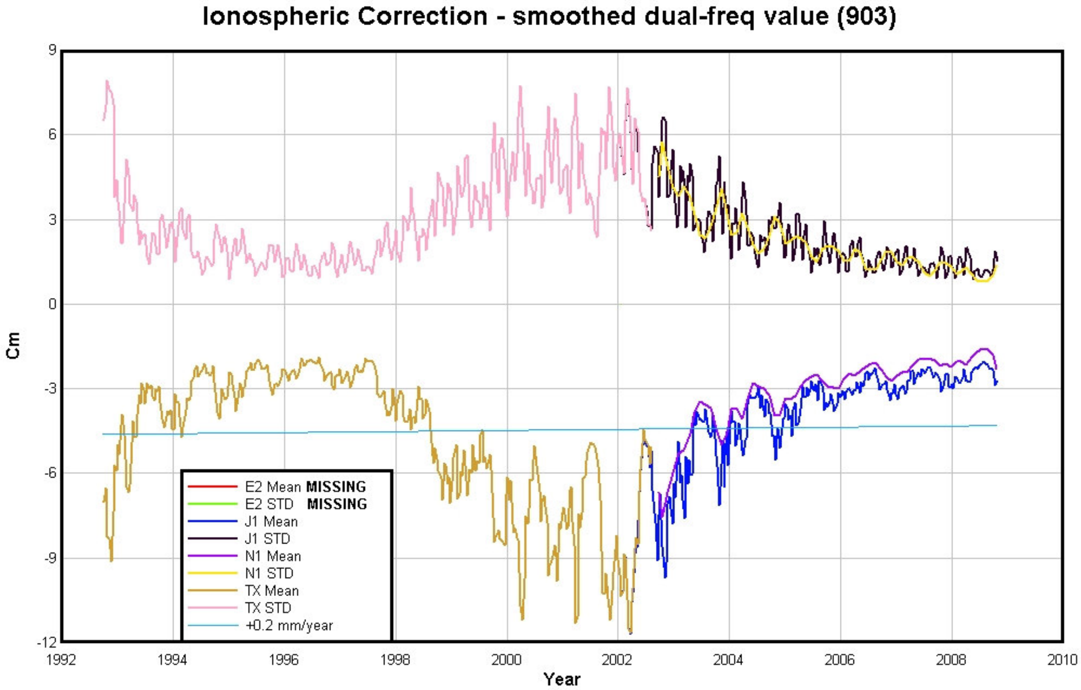


Figure 12: Temporal evolvement of the ionosphere range corrections (include trend for T/P-Jason1).

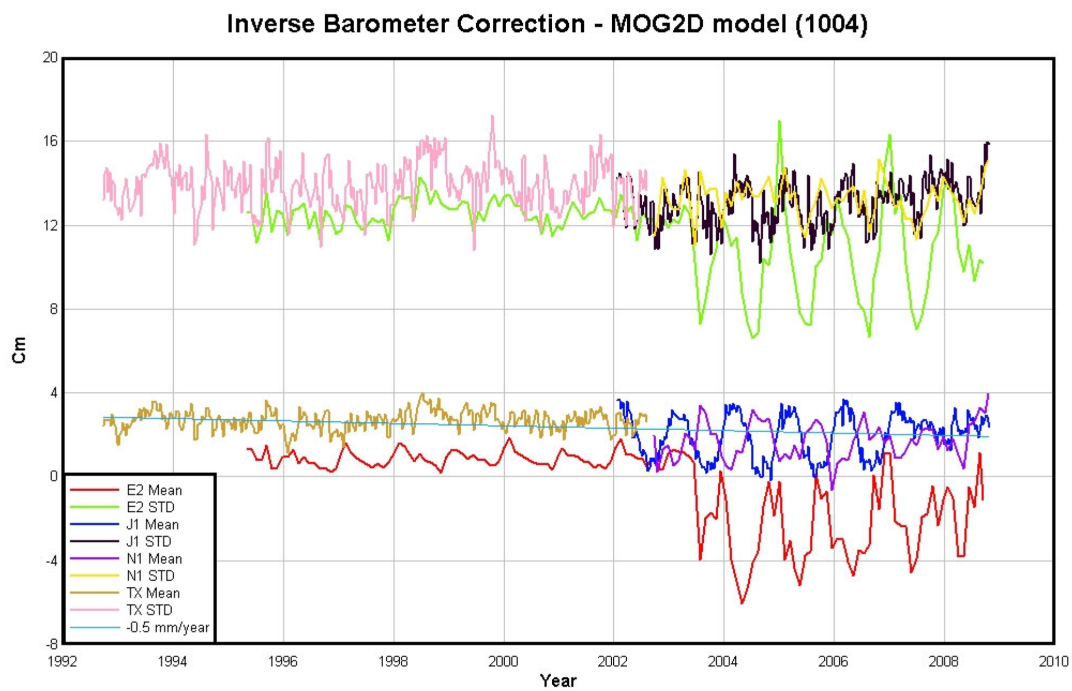


Figure 13: Temporal evolvement of the corrections MOG2D-IB Dynamic Atmosphere correction

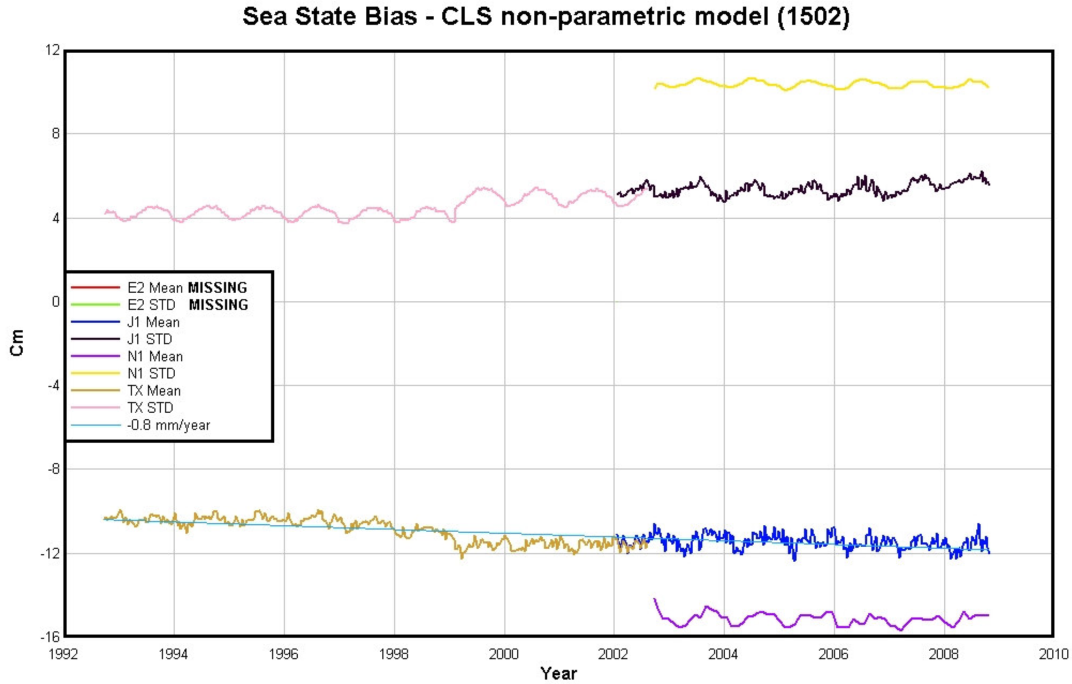


Figure 14: Temporal evolvement of CLS non parametric SSB correction (include trend for T/P-Jason1).

The Ionosphere correction shows very large variation with time due to the correlation with the solar cycle. This also means that depending on the length of the time scale used for the averaging period this will give a different contribution to both the mean value, but also to the trend estimate from the data.

Several of the model corrections seem to have some kind of (small) discrepancy when applied to JASON-1 versus TOPEX. This is very interesting as the two altimeters should in principle be identical.

Several of the model corrections show some trend over time which is not in-significant. This is not necessarily due to geophysical changes: For example, we can see a jump in the CLS non-parametric SSB correction after 1999. This is due to the instrumental drift of TOPEX-A (clearly visible on the Surface Wave Height parameter). Due to this drift, the instrument was switched to TOPEX-B. Without the 1999 jump the trend is nearly in-significant.

3.2. Impact of using different standards for MSS computation

In this section, we investigate the impact of using different corrections on multi-years average, with the final objective of characterizing the impact for MSS computation of using different standards.

We first investigate this point on global scales (section 3.2.1) and then further consider the impacts observed depending on the distance to the coast (section 3.2.2).

3.2.1. Impact on global scale

Method

This is done comparing different mean profiles for which alternative corrections are applied. The mean profiles considered are the following:

- 5 years (2003-2007) mean profiles for Jason 1 (cycles between 36 and 220)
- 5 years (2003-2007) mean profiles for Envisat (cycles from 13 to 64)
- 7 years mean profiles (1993-1999) for TP (cycles from 12 to 268).
- 6 years mean profiles (1996-2001) for ERS-2
- 6 years mean profiles (1996-2001) for TP*

* The European satellites ERS and ENVISAT have 35 days repeat which is considerably longer than the 9,9 days repeat of the French American Satellites TOPEX/POSEIDON and JASON-1. Such difference in sampling will have a profound effect on the average due to the smaller amount of samples for the ERS+ENVISAT

satellites and the exactly 35-days repeat which is an integer number of solar days and hence the solar tides will be phase locked in the orbit for this satellite.

Therefore it was needed to carry out the analysis for both TOPEX and ERS-2 for an identical time span. The timespan of 1996-2001 was used for the computation and a total of 62 repeats of the ERS2 data and 221 repeats of TOPEX were used to determine the 6 year mean.

Results:

Figure 15 to Figure 34 show for each correction tested the difference between the two mean profiles. For the 5 years Jason and ENVISAT mean profiles as well as for the 7 years TP mean profiles, we also show the difference between the variance computed at each point of the mean profile. The variance difference corresponds to the maximum variance gain that we can get between two versions of a single correction. The correction version that allows to get the minimum variance is theoretically the best. Attention must be paid however when the correction applied is correlated to the oceanic signal, as for the SSB correction for instance. In that case, a variance reduction may signify that realistic oceanic signal has been removed that was not supposed to.

Impacts of using one correction instead of another are synthesized in **Table 2**. The impact on multi-years mean of using different altimetric corrections does not exceed some centimetres, for an amplitude of the MSS signal ranging between + and – 100m. However, we highlight that the use of particular corrections compared to others allow to reduce the variance along the mean profiles, and hence most probably, the errors. An important point is that the best correction to apply may depend on the area. It is for instance the case for the wet tropospheric correction: better results can be expected in coastal areas when using a model-based correction rather than the radiometer signal.

Mis-sion	Test	P	Impact on mean	Impact on mean accuracy
Orbit				
J1	GDRC VS GDRB	23	+/-1 cm Geographical bias btw Pacific + North Atl / Indian + South Atl	Weak local improvements and degradations
EN	ESOC VS CNES	24	+/-2 cm depending on basins. Global 0.1 cm bias	Global improvement (+6 cm^2) with CNES orbit
TP	GSFC00 VS CNES	25	+/- 3 cm depending on basins. Global 0.7cm bias	Weak local improvements and degradations
	GSFC05 VS GFSC00	26	+/- 0.3 cm depending on hemisphere - No bias	Weak local improvements and degradations
Iono				
J1	GIM VS ALTIMETER	27	+/-1 cm depending on latitude. Global 0.1 cm bias	Weak global improvement with ALTIMETER
EN	GIM VS ALTIMETER	28	0 to +2 cm depending on latitude. Global 0.8 cm bias	Weak global improvement with ALTIMETER
ERS 2	GIM VS IRI	29	-1.7 to 0.3 cm depending on latitude.	

TP	ALTIMETER VS IRI	30	-1.5 to 0.1 cm depending on latitude	
WET TROPO				
J1	ECMWF VS RADIOMETER	33	Open ocean: +/- 0.5 cm depending on latitude. in Coastal areas up to 2 cm. No bias	Global improvement (from 5 to 20% of variance) with Radiometer
EN	ECMWF VS RADIOMETER	37	Open ocean: +/- 0.5 cm depending on latitude. in Coastal areas up to 2 cm. Global 0.6 cm bias	Global improvement (from 5 to 20% of variance) with Radiometer
	NCEP VS ECMWF	39	+/- 3 cm btw wet and dry areas. Global -0.8 cm bias	Significant improvement with ECMWF (+5 cm^2) mostly in wet areas (>20cm^2)
ERS 2	RADIOMETER VS ECMWF	35	-1.4 to 1.8 cm depending on latitude	
TP	RADIOMETER VS ECMWF	36	-1.2 to 1.6 cm depending on latitude	
DRY TROPO				
ERS 2	ECMWF VS NCEP	31	+-0.2 cm depending on latitude and oceans	
TP	ECMWF VS NCEP	32	+-0.2 cm depending on latitude and oceans	
DAC				
TP	IB VS DAC-HR	40	+/- 1 cm locally. No global bias	Global improvement: (+ 9 cm^2) with DAC-HR. Stronger in coastal and strong wind variability areas
ERS 2	IBref vs MOG2D_IB	41	1.2 to 2.8 cm Global bias due to the static response not included in MOG2D An interesting global pattern of highs and lows.which corresponds to the S2 constituent in the Atmosphere which is included in the MOG 2D but not in the inverse barometer	
TP	IBref VS MOG2D_IB	42	2 to 2.8 cms locally Global bias due to the static response not included in MOG2D	
TIDES				
J1	FES04 VS GOT00.2	43	> 2 cm locally in coastal areas. No bias	Weak global improvement with GOT near the coasts
EN	FES04 VS GOT00.2	44	> 2 cm locally in coastal areas. No bias	Weak global improvement with GOT near the coasts Improvements with FES at high latitudes
TP	FES04 VS GOT00.2	47	> 2 cm locally in coastal areas. No bias	Weak global improvement with GOT near the coasts
	GOT00.2 VS GOT99	48	> 0.5 cm locally in coastal areas. No bias	Slight global improvement with GOT00 near the coasts
ERS 2	FES04-GOT4.7	45	+-2cm	

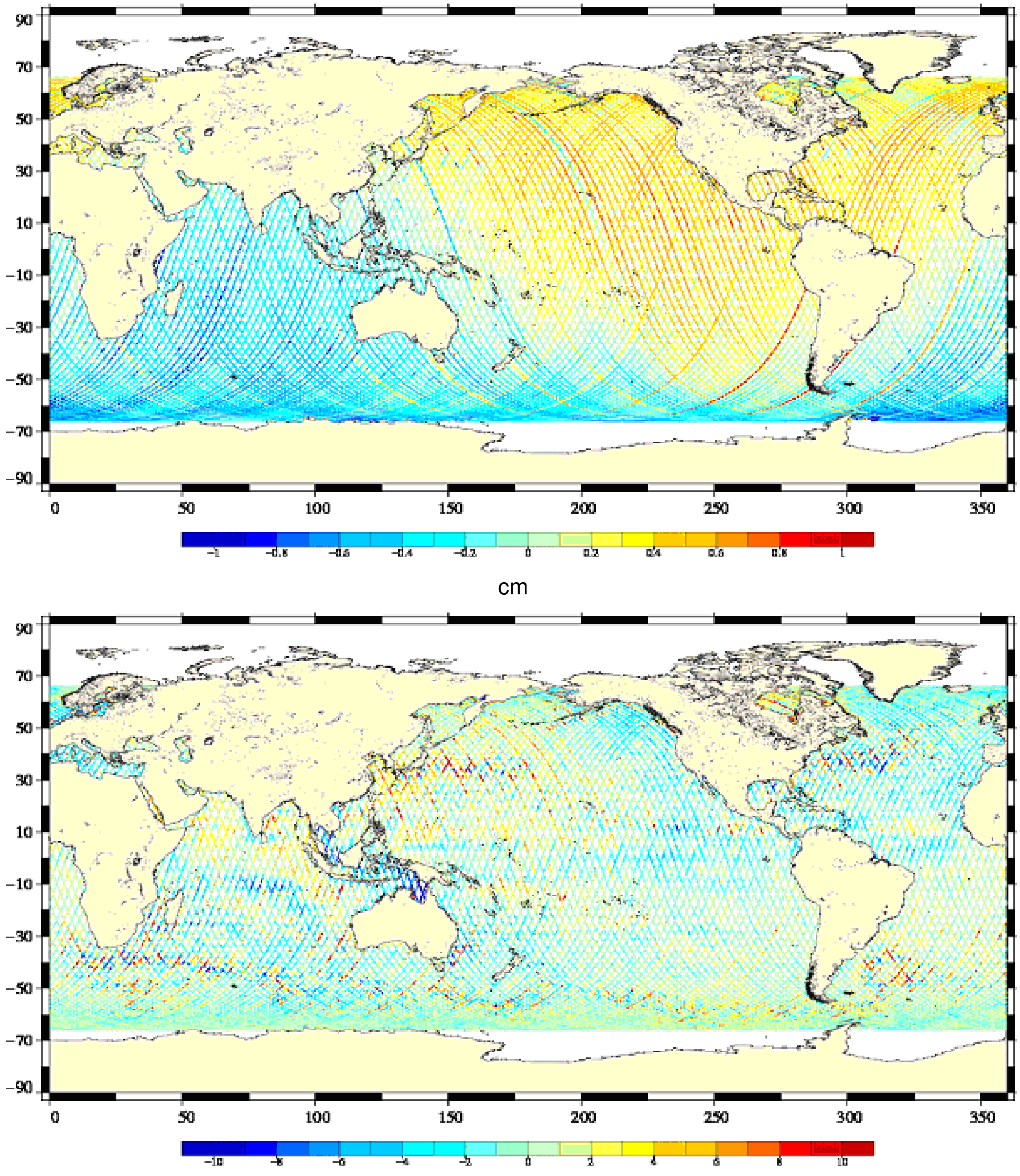
TP	FES04-GOT4.7	46	+-0.2 cm	
SSB				
EN	BM4 VS NPARAM	49	+/- 3 cm Global 2.6 cm bias	Inhomogeneous impact
TP	BM4 VS NPARAM	51	+/-0.5 cm Global 2.4 cm bias	Weak improvement with NPARAM
TP	BM4 VS NPARAM	53	1.6 to 2.4 cm Global 2 cm bias	

Table 2: Tests applied on the different mission mean profiles

Figures

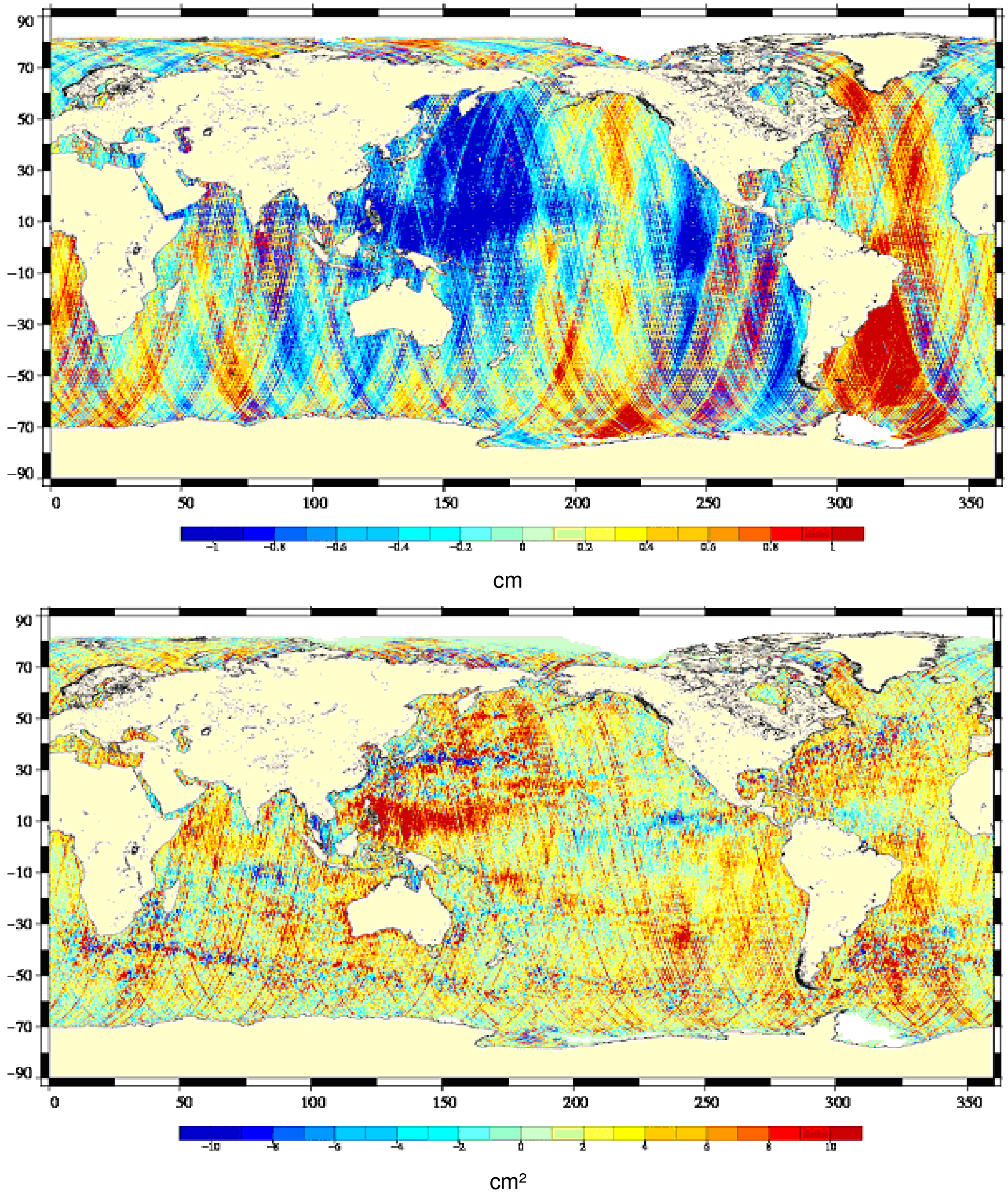
Orbit impact

Figure 15 : Jason-1 mean profile, GDRC VS GDRB Mean (top) and variance (bottom) profile differences.



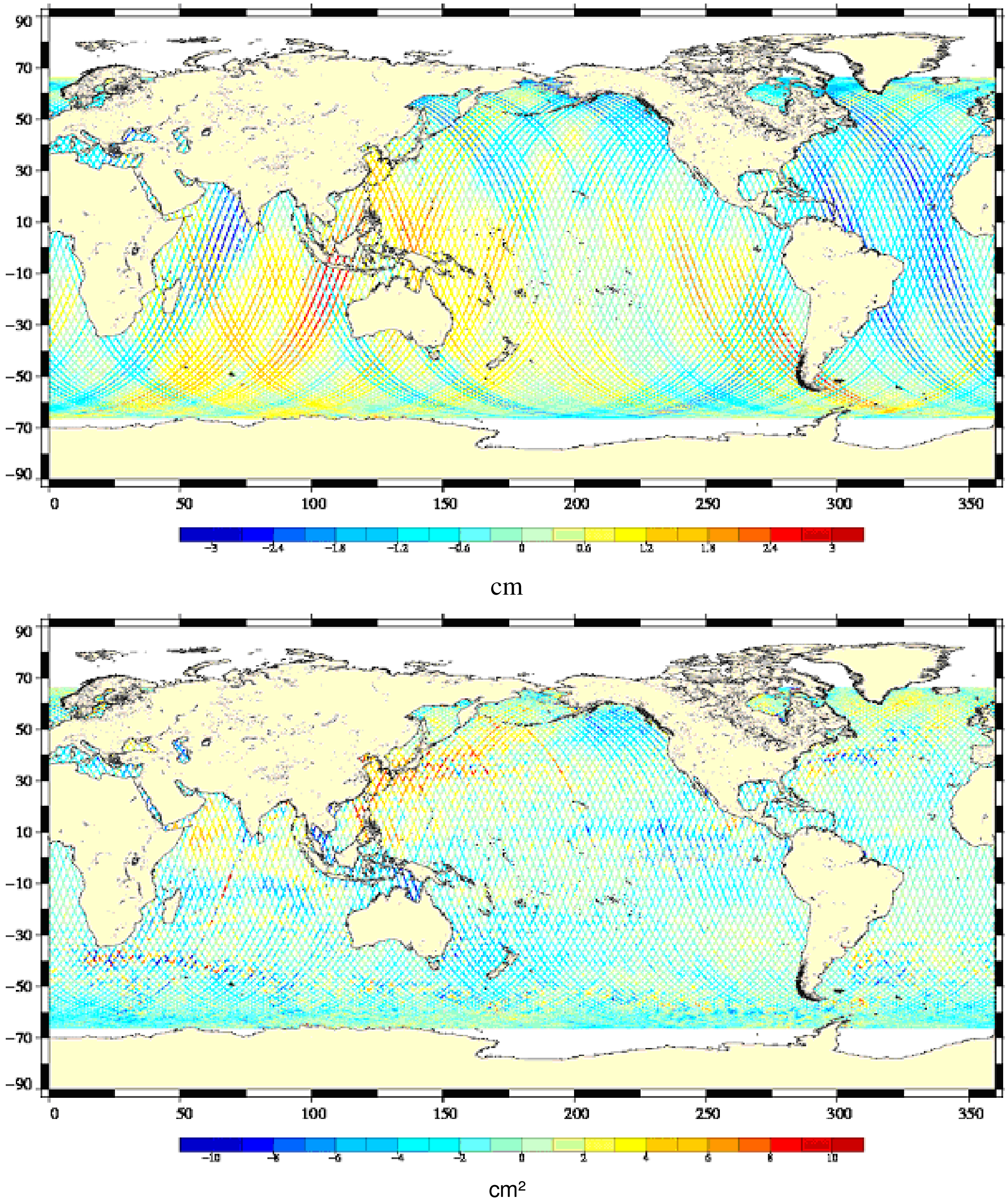
Back to **Table 2**

Figure 16 : ENVISAT, ESOC VS GDRB : Mean (top) and variance (bottom) profile differences.



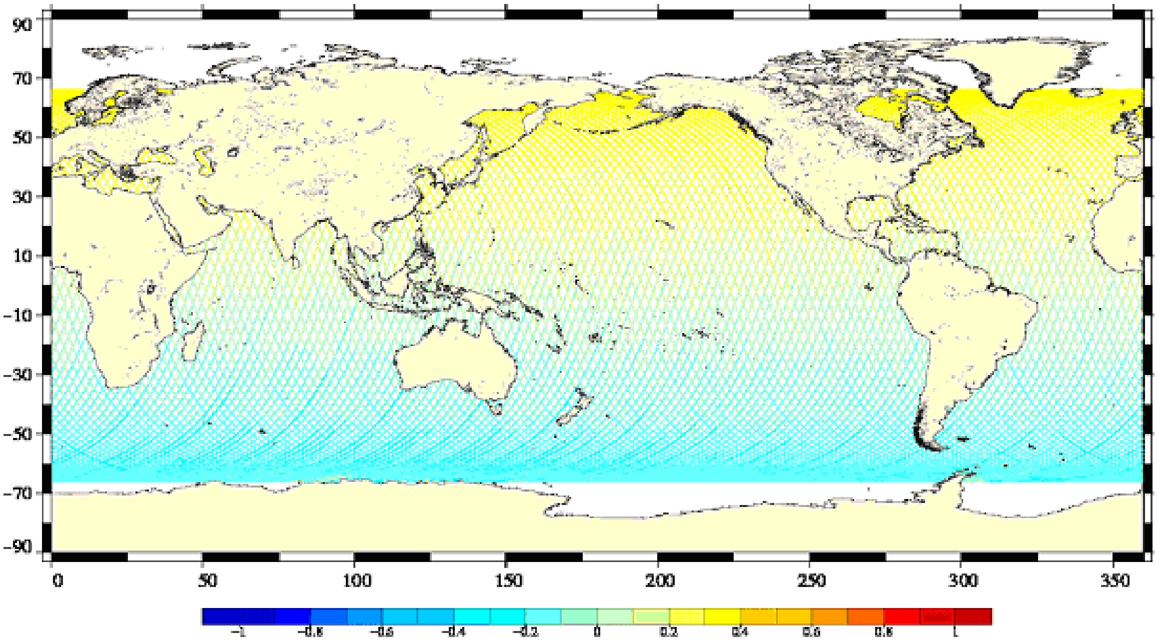
Back to **Table 2**

Figure 17 : TOPEX, GSFC00 VS GDRB : Mean (top) and variance (bottom) profile differences.

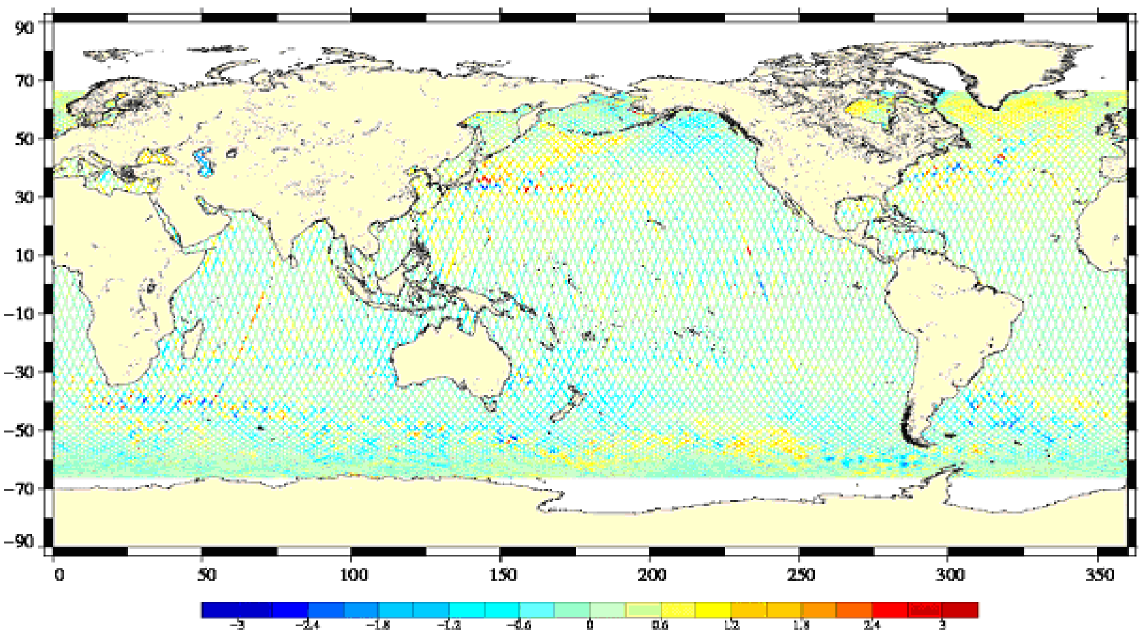


Back to **Table 2**

Figure 18 : TOPEX, GSFC05 VS GSFC00: Mean (top) and variance (bottom) profile differences.



cm

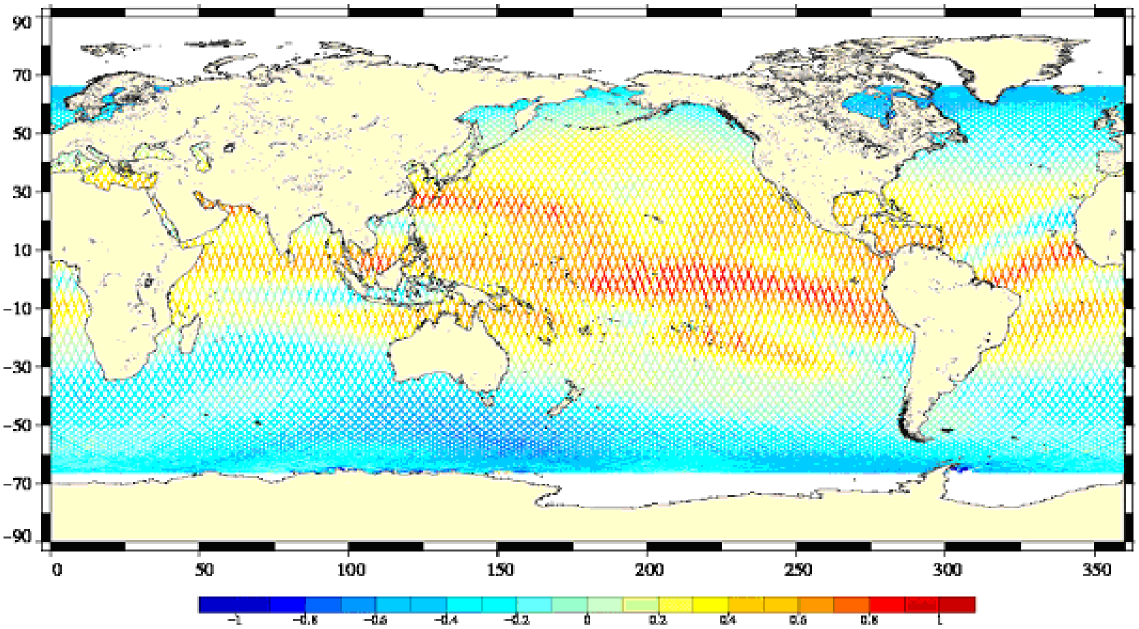


cm²

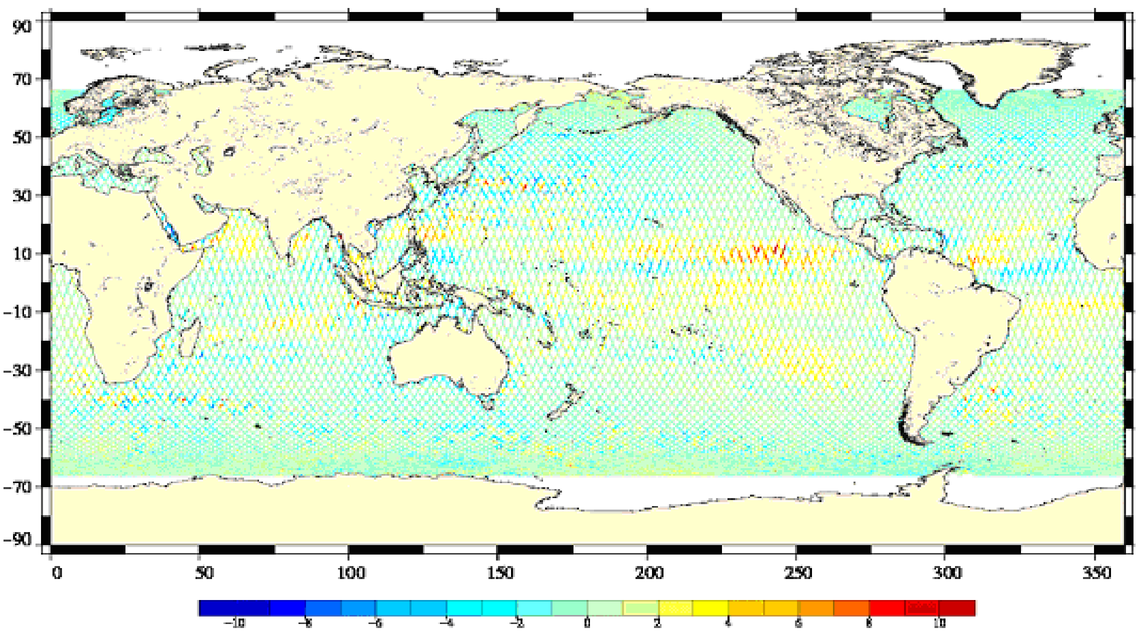
Back to **Table 2**

Ionospheric correction

Figure 19 : JASON1, GIM VS ALTIMETER : Mean (top) and variance (bottom) profile differences.



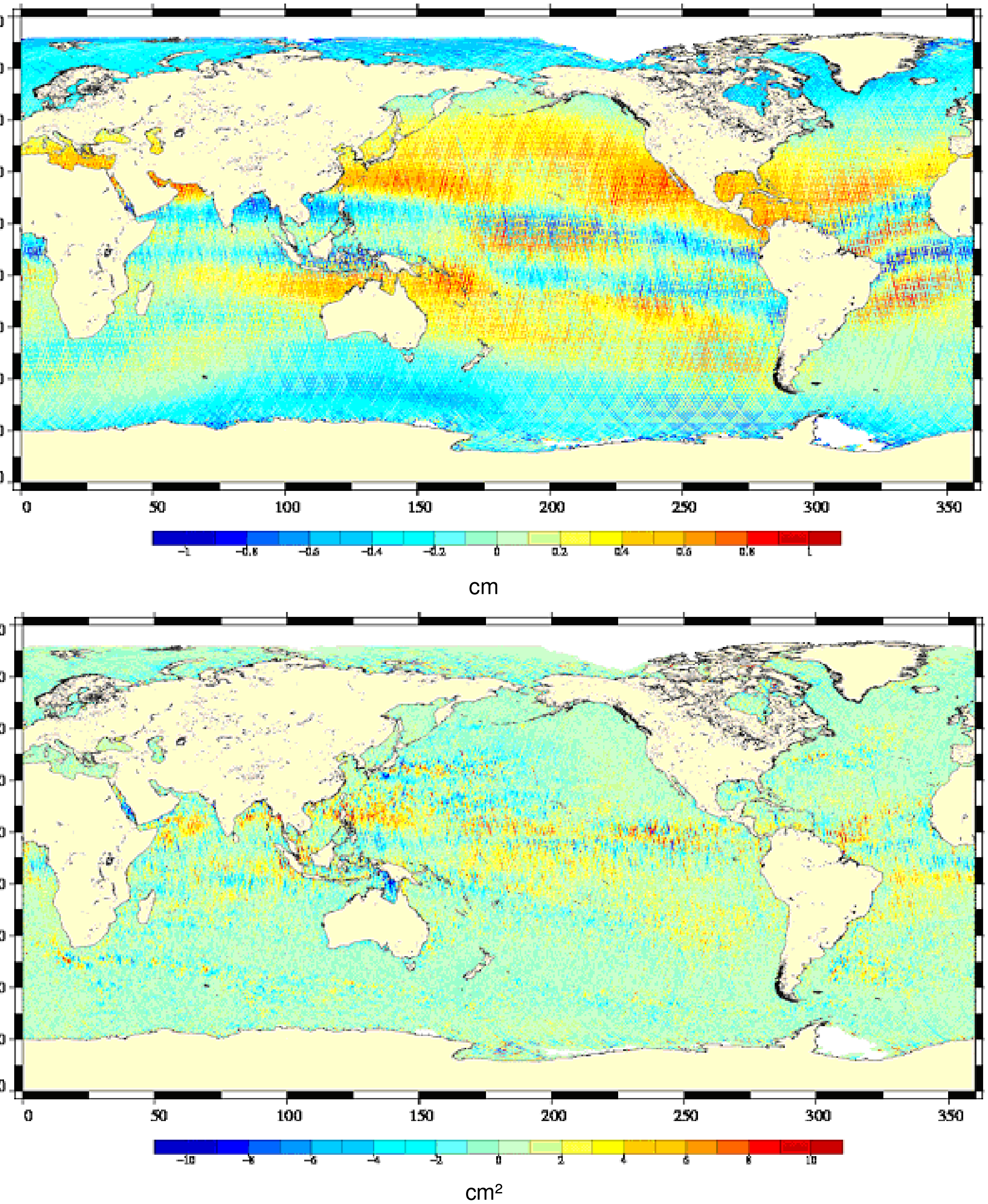
cm



cm²

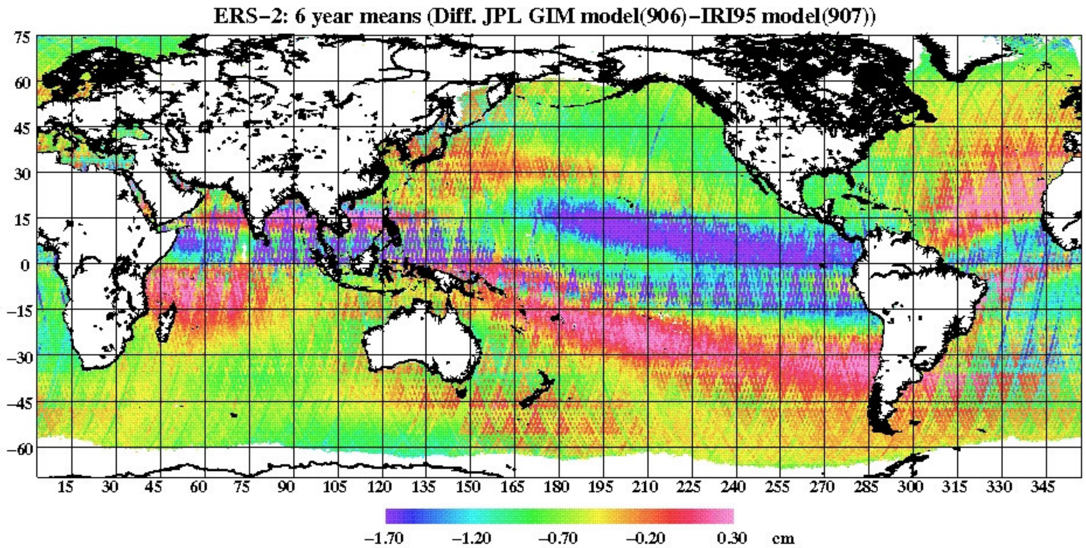
Back to **Table 2**

Figure 20 : ENVISAT, GIM VS ALTIMETER: Mean (top) and variance (bottom) profile differences.



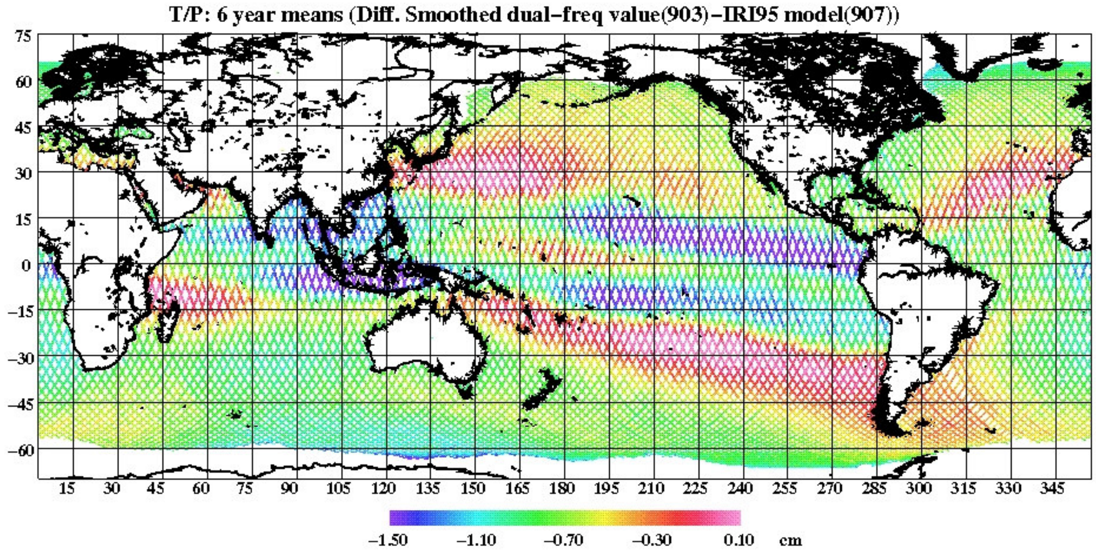
Back to **Table 2**

Figure 21: 6 year means difference between ionosphere corrections for ERS-2



Back to **Table 2**

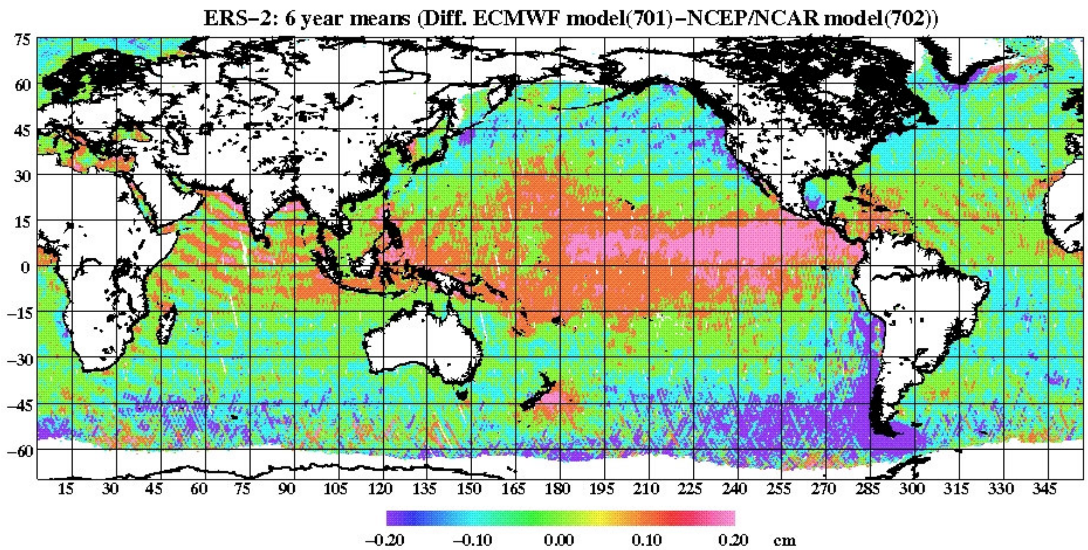
Figure 22: 6 year means difference between Ionosphere corrections for T/P



Back to **Table 2**

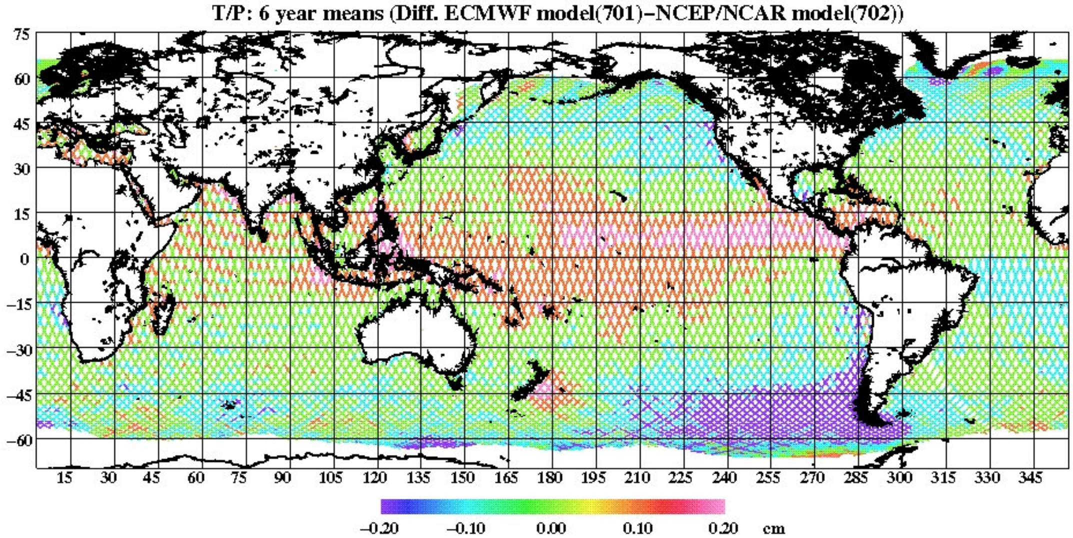
Dry Tropospheric correction

Figure 23:. 6 year means difference between dry troposphere corrections for ERS-2



Back to **Table 2**

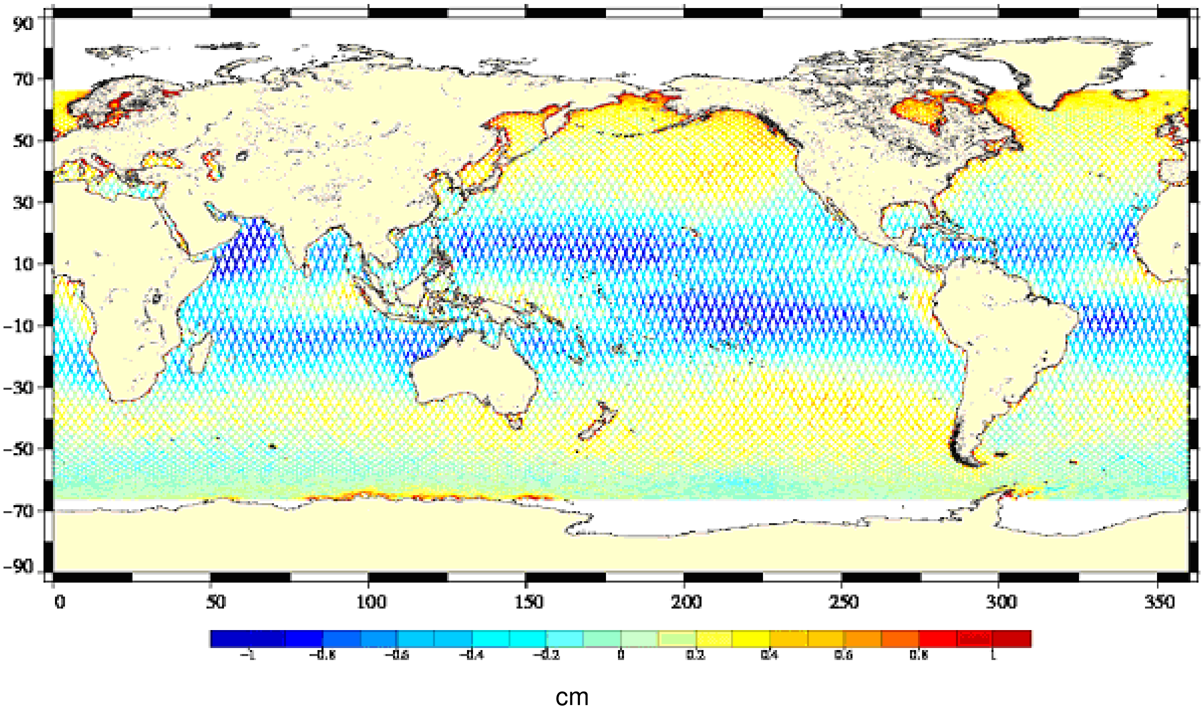
Figure 24:. 6 year means difference between dry troposphere corrections for TP

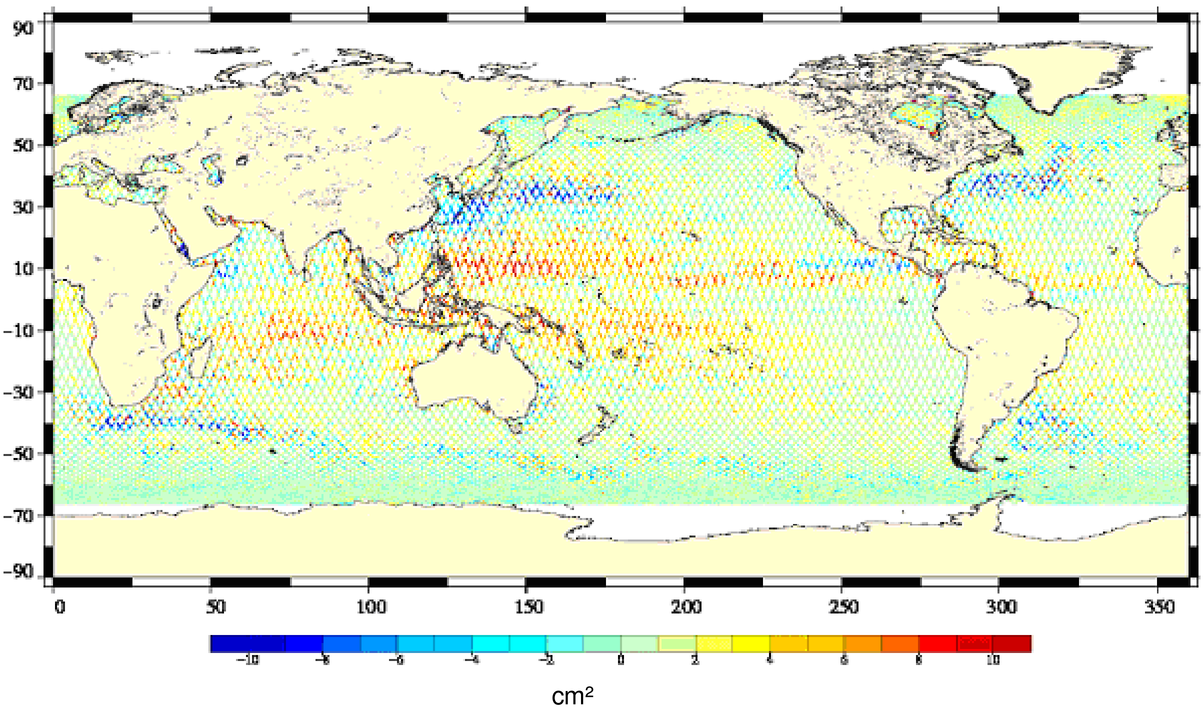


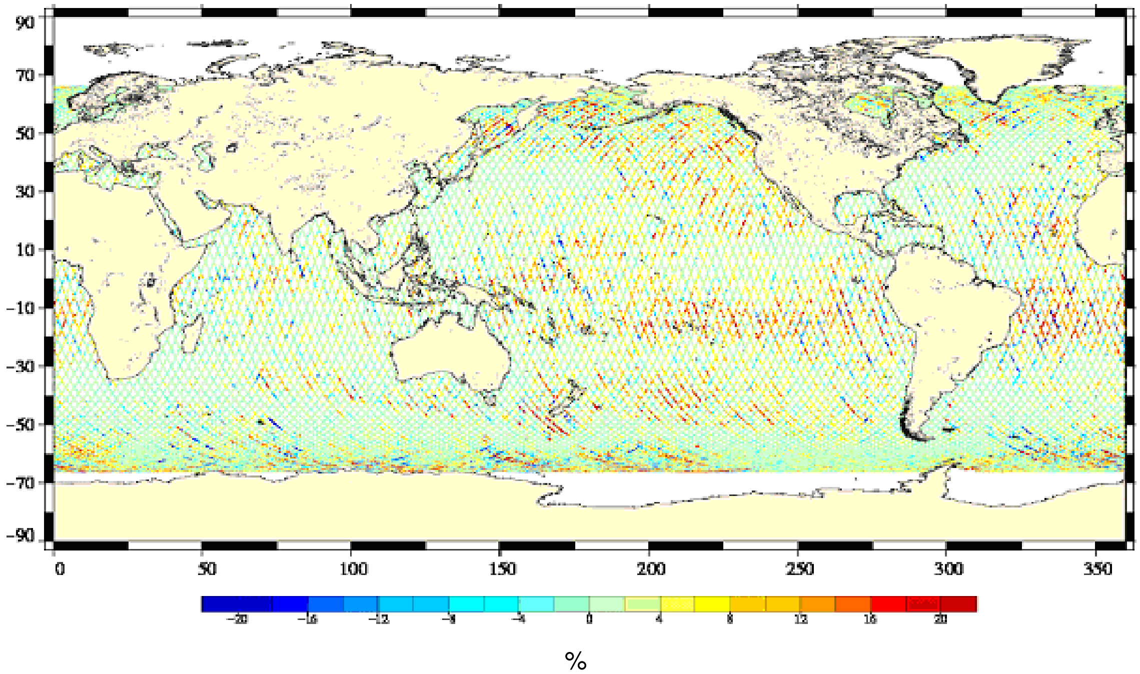
Back to **Table 2**

Wet Tropospheric correction

Figure 25: JASON1, ECMWF VS RADIOMETER: Mean (top), variance (middle and bottom (in % of variance)) profile differences.

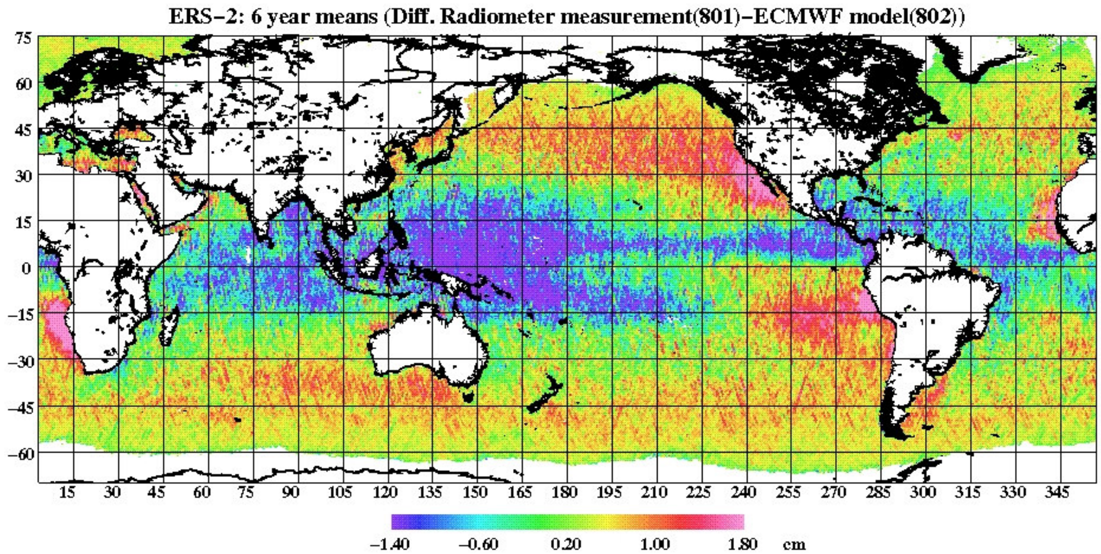






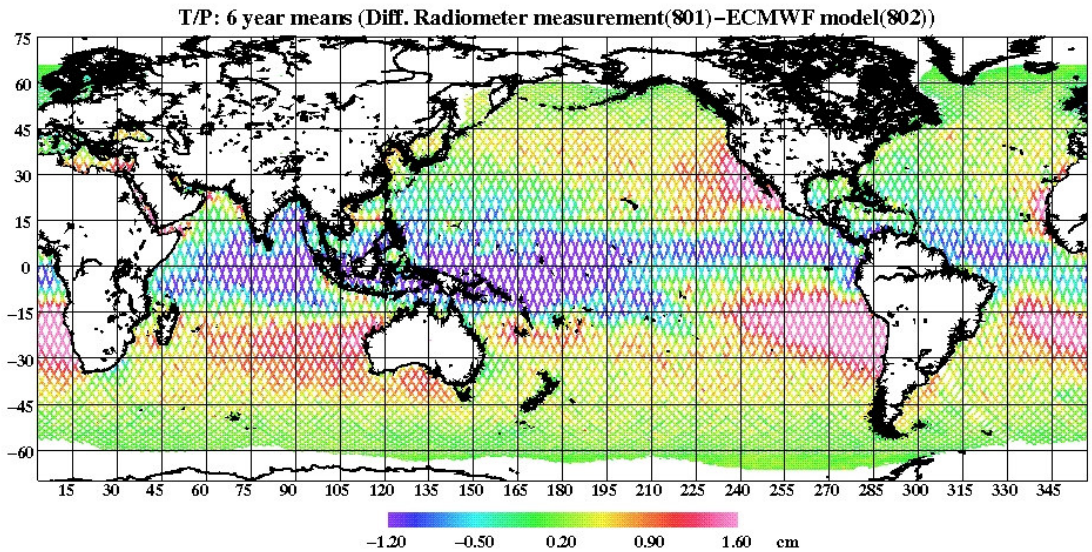
Back to **Table 2**

Figure 26: 6 year means difference between wet troposphere corrections for ERS-2



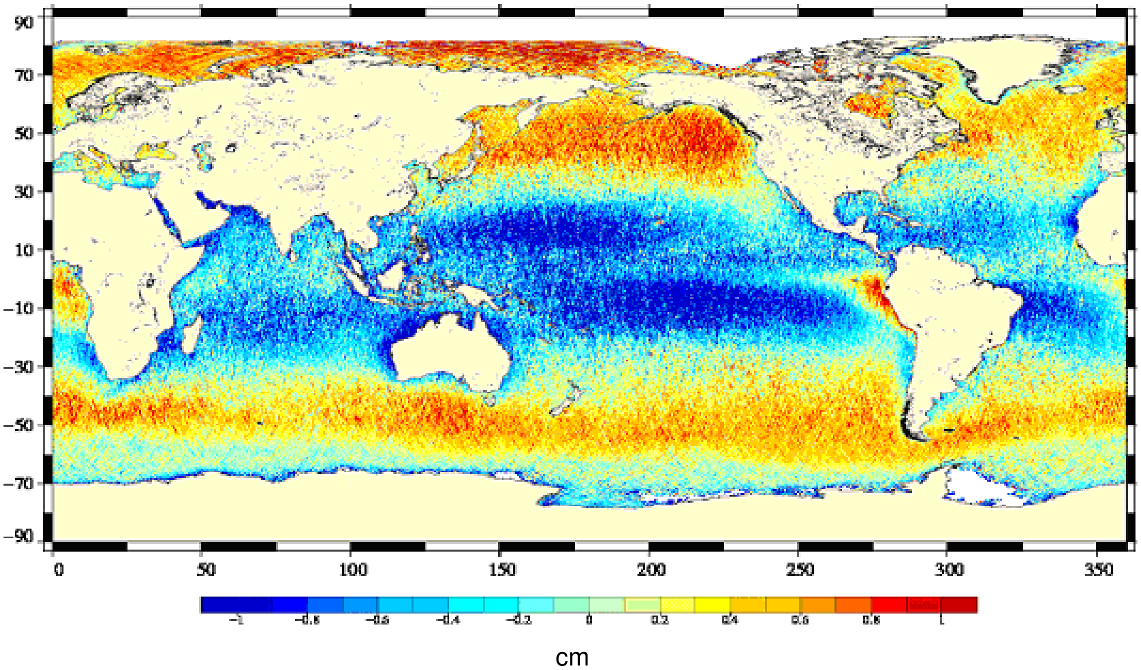
Back to **Table 2**

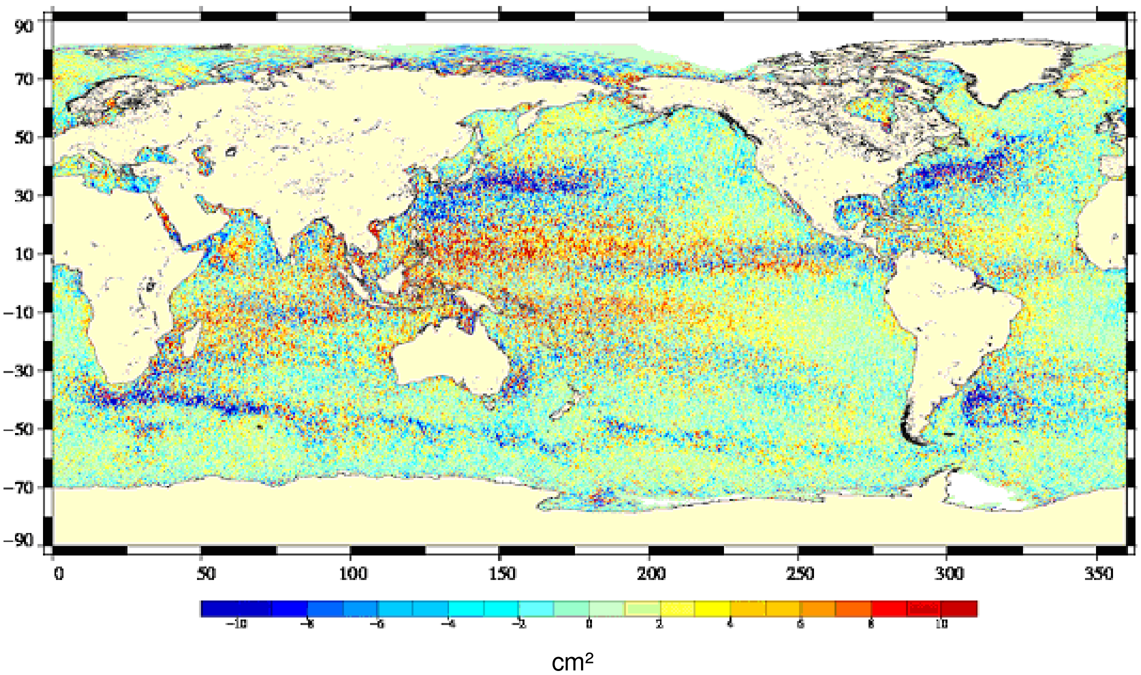
Figure 27: 6 year means difference between wet troposphere corrections for TP

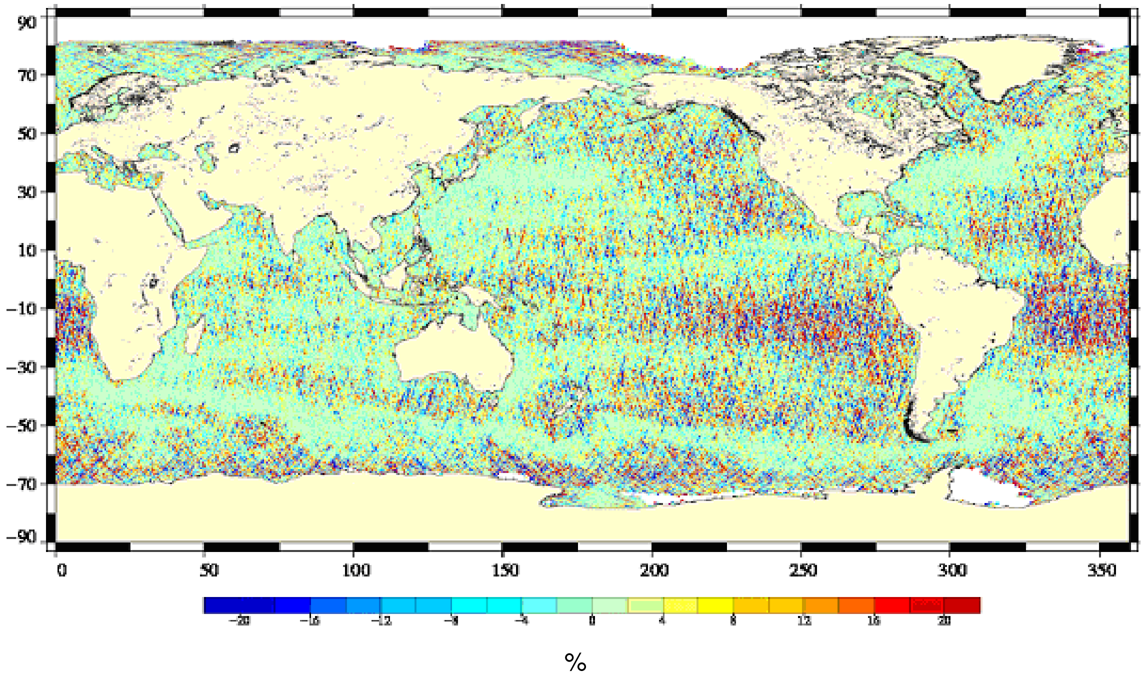


Back to **Table 2**

Figure 28 : ENVISAT ECMWF VS RADIOMETER : Mean (top), variance (middle and bottom (in % of variance)) profile differences.

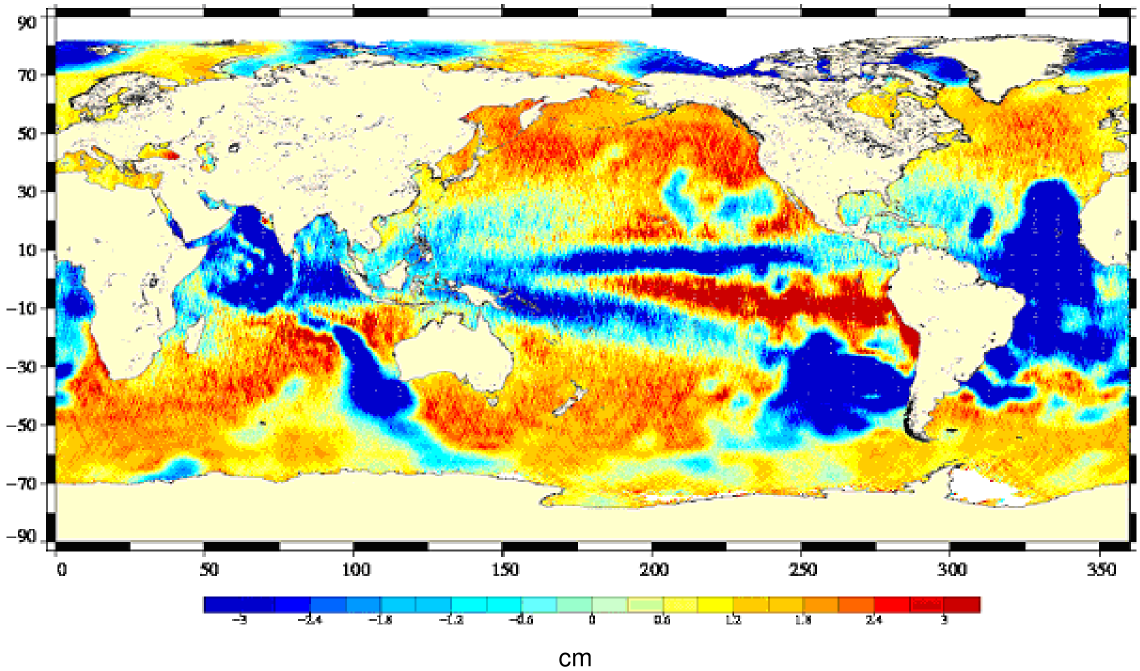


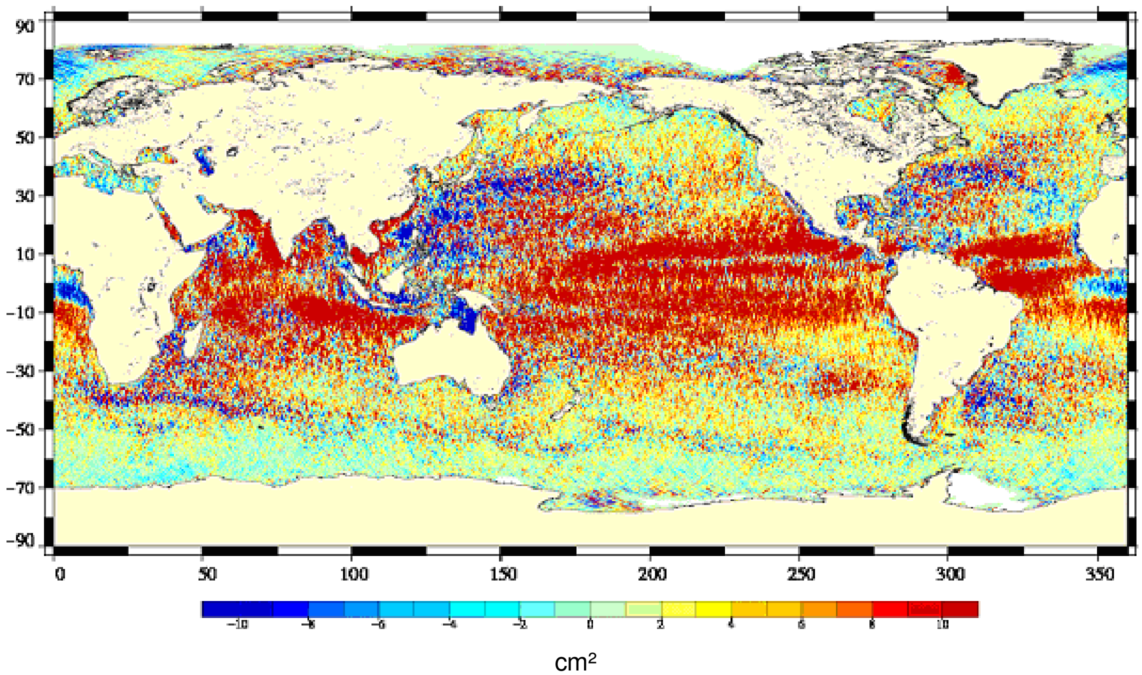




Back to **Table 2**

Figure 29 : ENVISAT: NCEP VS ECMWF: Mean (top), variance (bottom) profile differences.

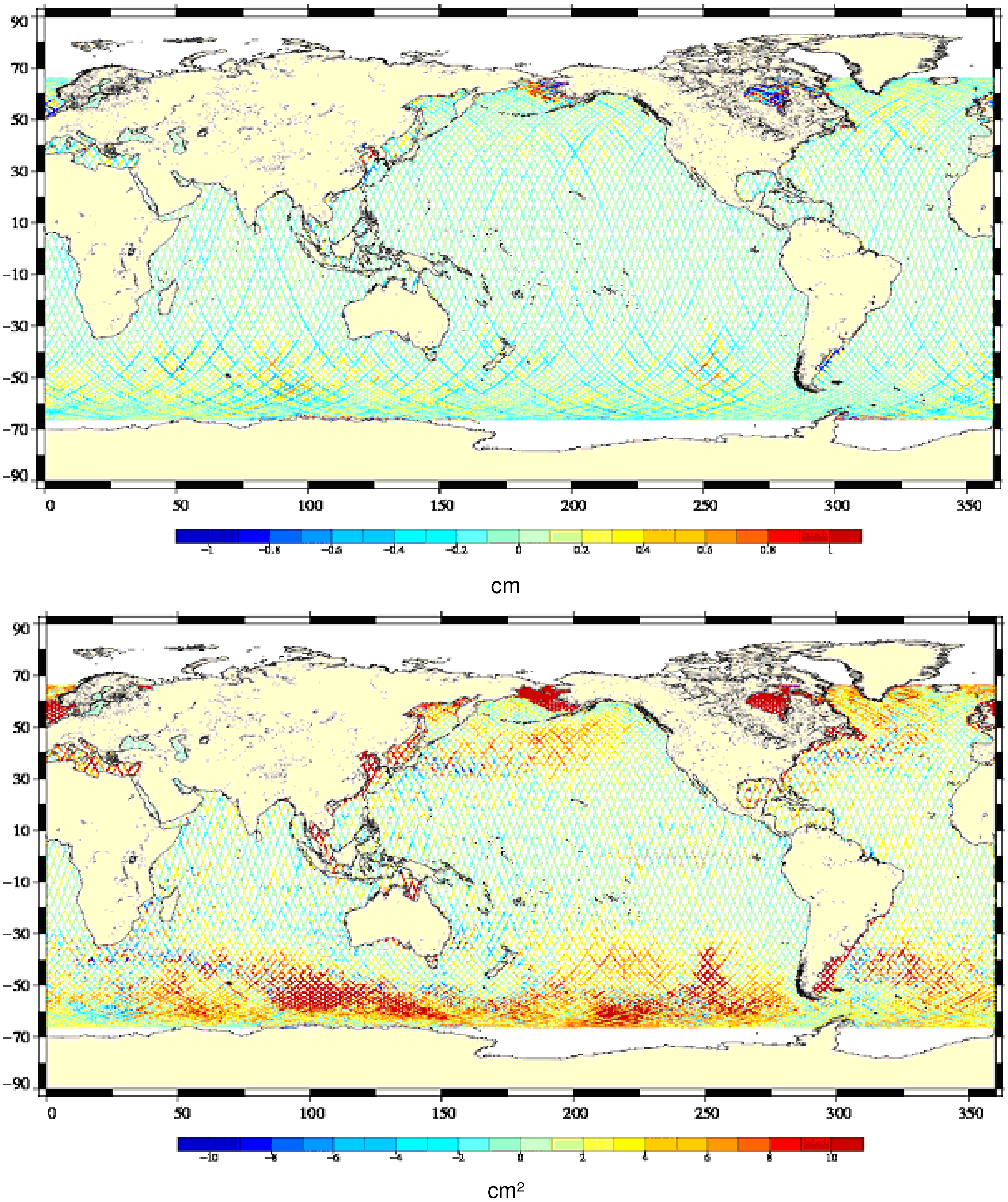




Back to **Table 2**

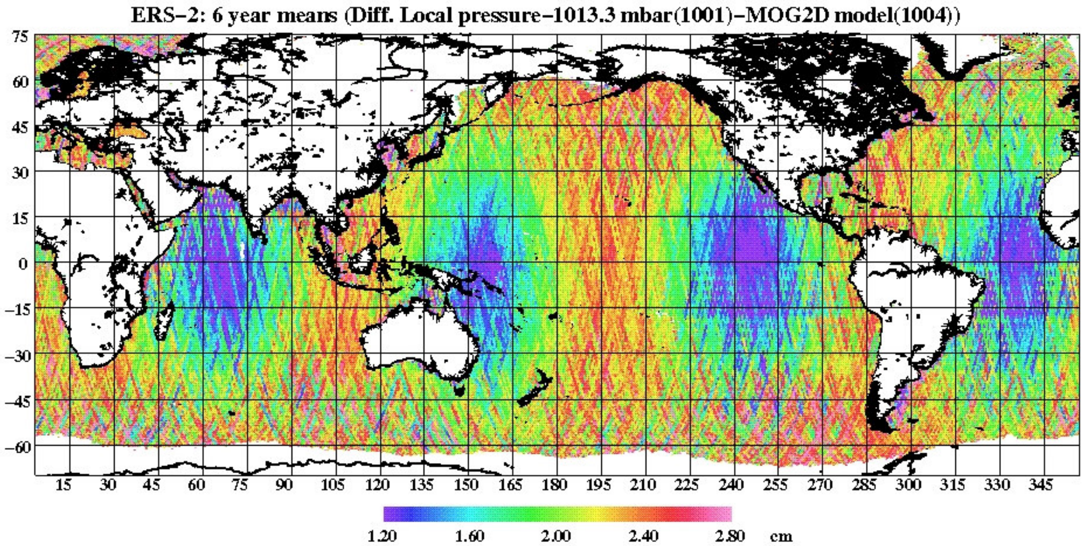
Static/Dynamic Atmospheric Correction

Figure 30 : TOPEX Inverse Barometer VS MOG2D-IB: Mean (top), variance (bottom) profile differences.



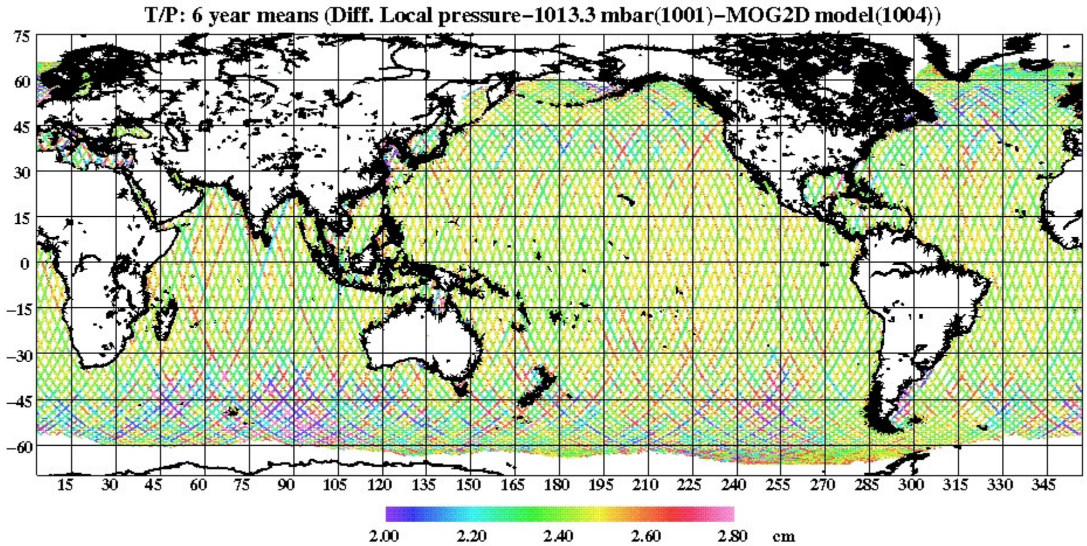
Back to **Table 2**

Figure 31: 6 year means difference between IBref and MOG2D_IB for ERS-2



Back to **Table 2**

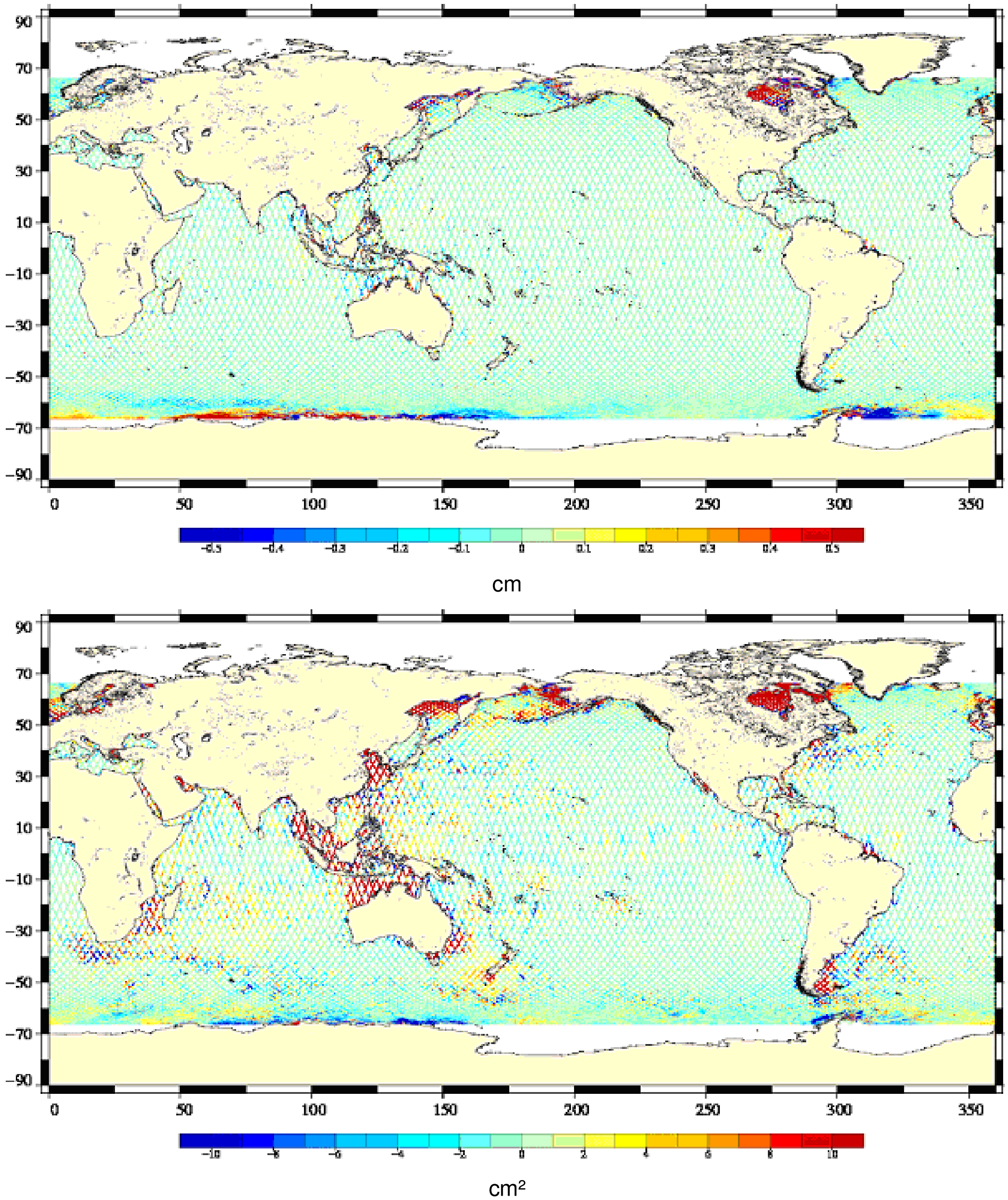
Figure 32: 6 year means difference between IBref and MOG2D_IB for TP



Back to **Table 2**

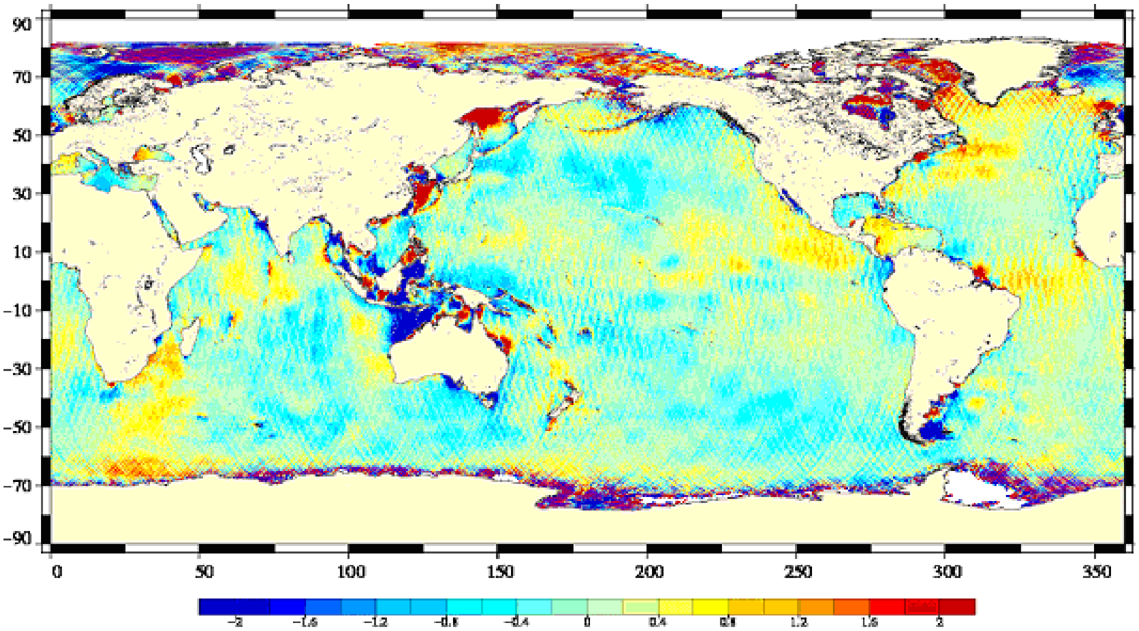
Tide correction

Figure 33 : JASON1, FES04 VS GOT00V2: Mean (top), variance (bottom) profile differences.

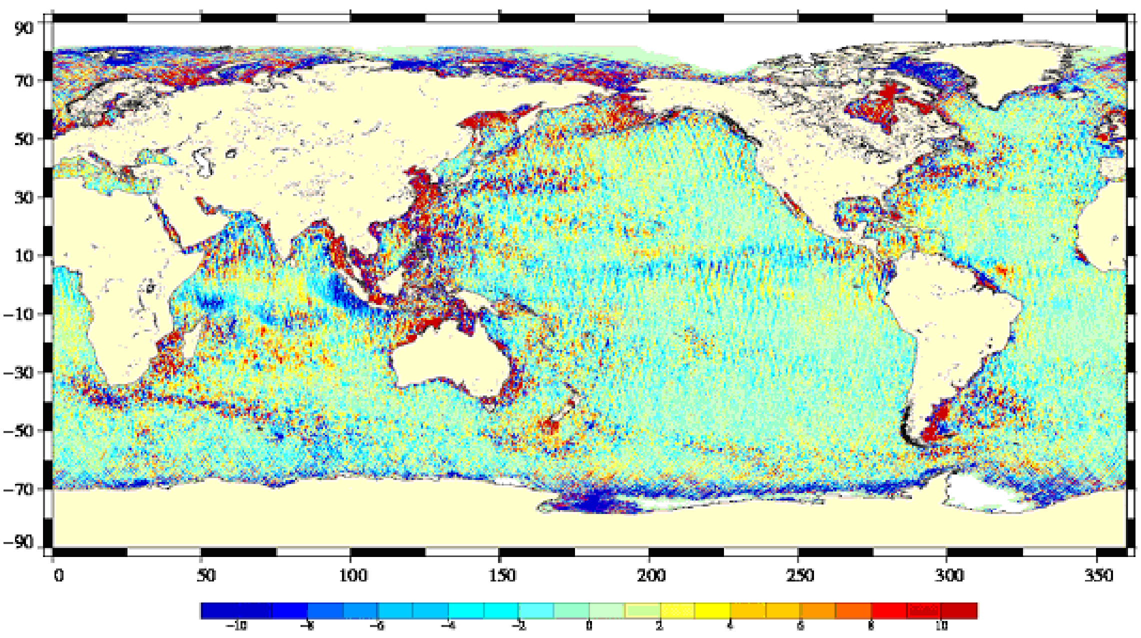


Back to **Table 2**

Figure 34 : ENVISAT, FES04 VS GOT00V2: Mean (top), variance (bottom) profile differences.



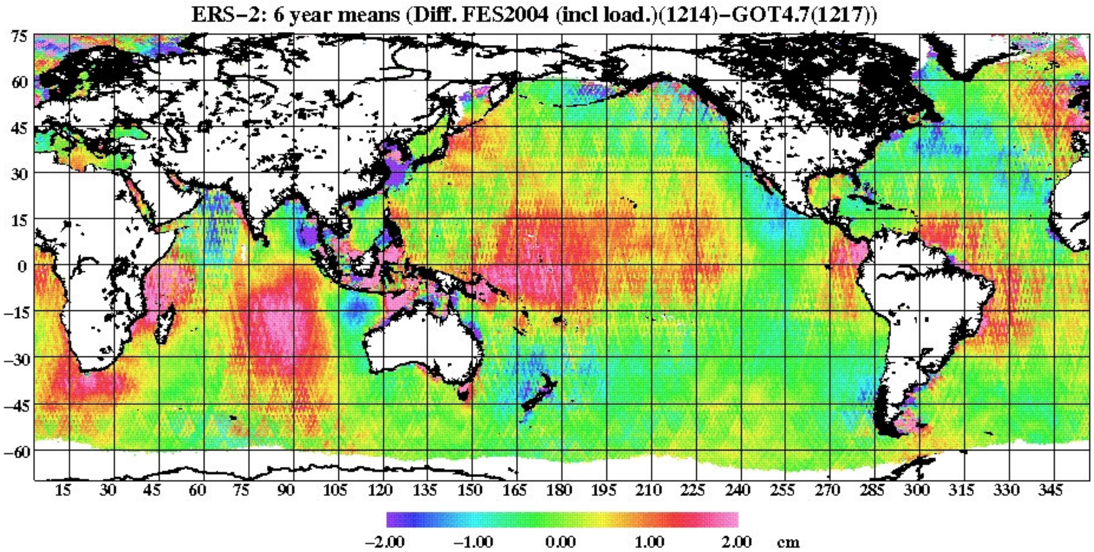
cm



cm²

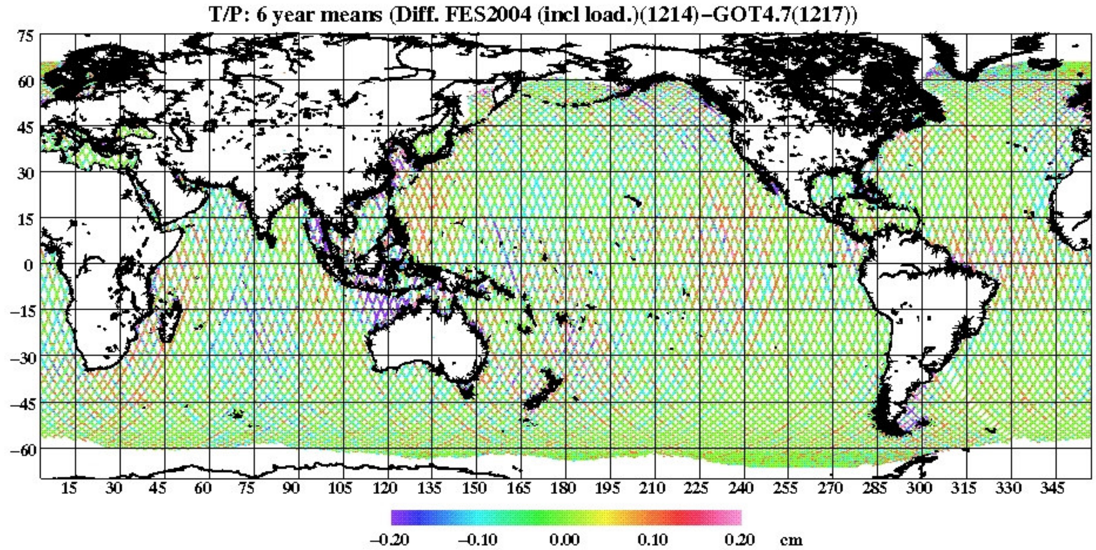
Back to **Table 2**

Figure 35: 6 year means difference between ocean tide corrections for ERS-2



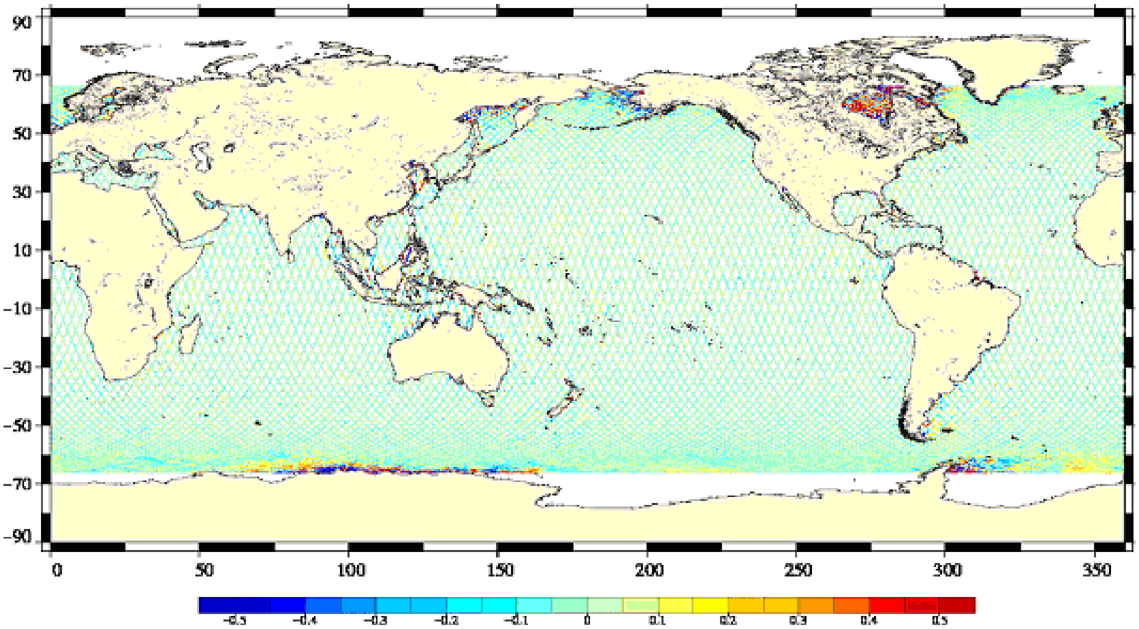
Back to **Table 2**

Figure 36: 6 year means difference between ocean tide corrections for T/P

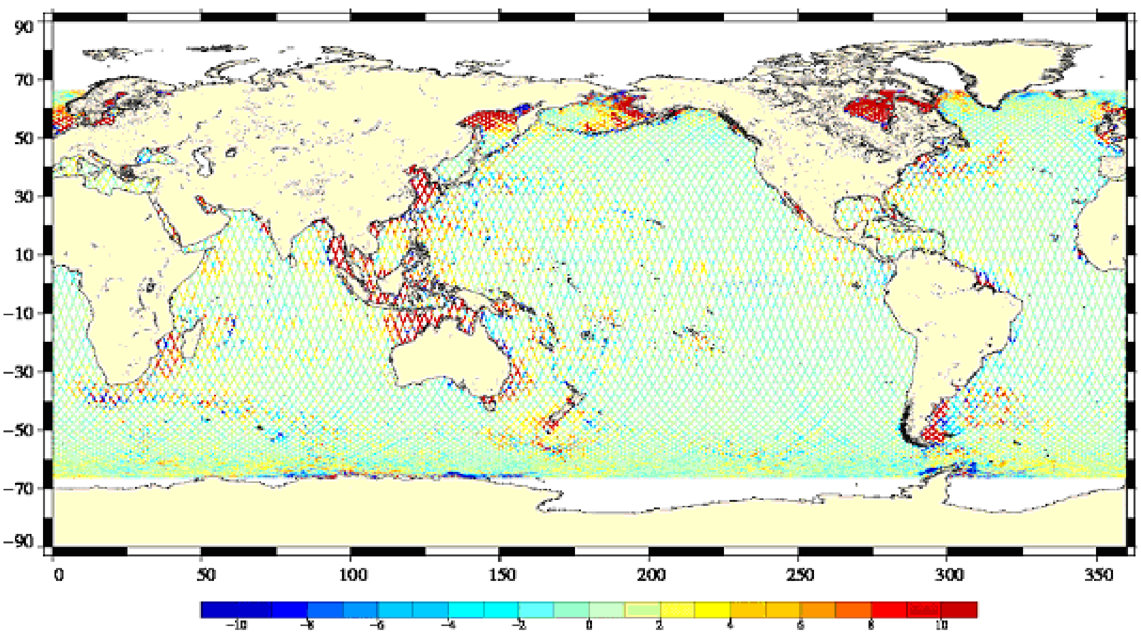


Back to **Table 2**

Figure 37 : TOPEX, FES04 VS GOT00V2, Mean (top), variance (bottom) profile differences.



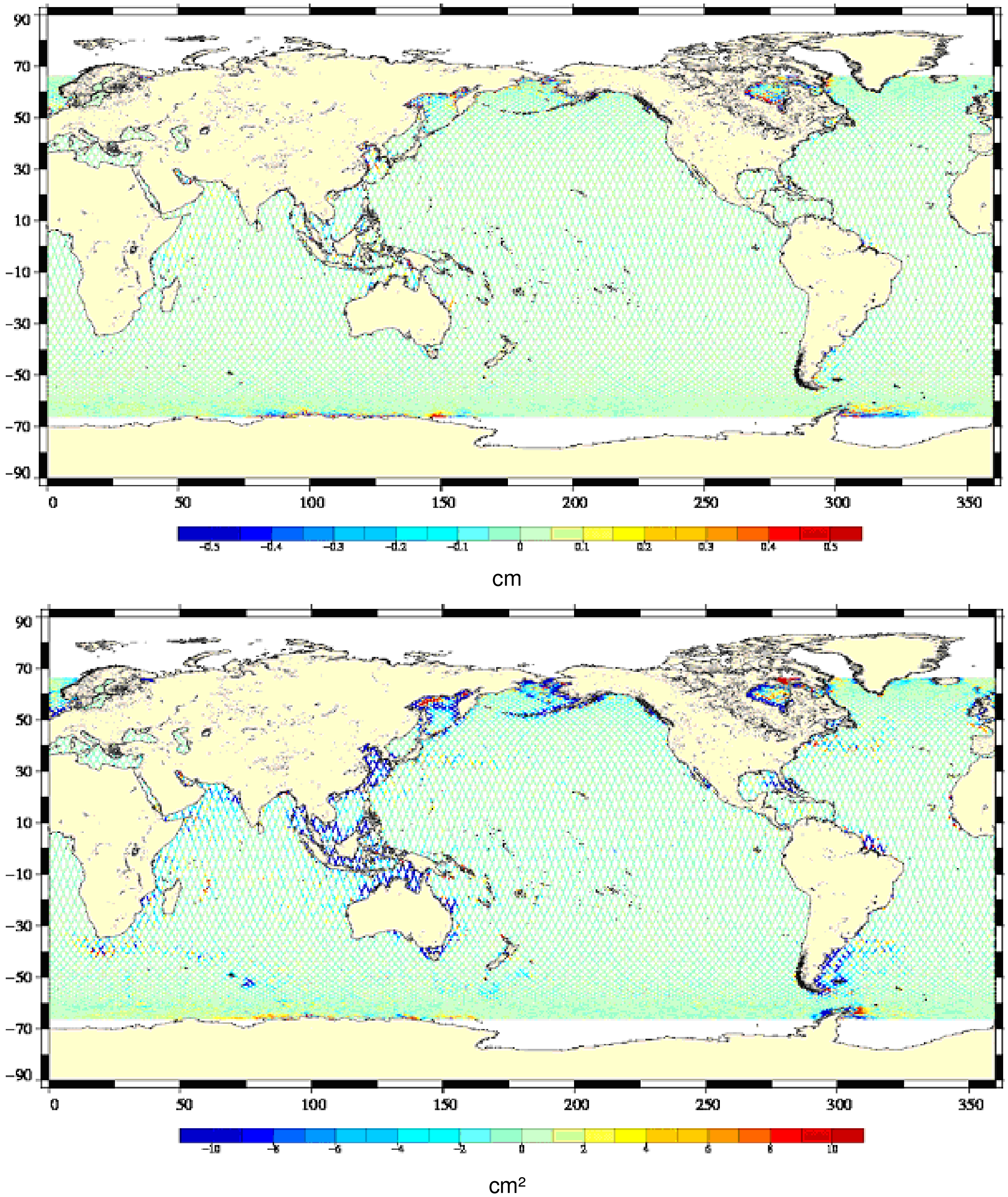
cm



cm^2

Back to **Table 2**

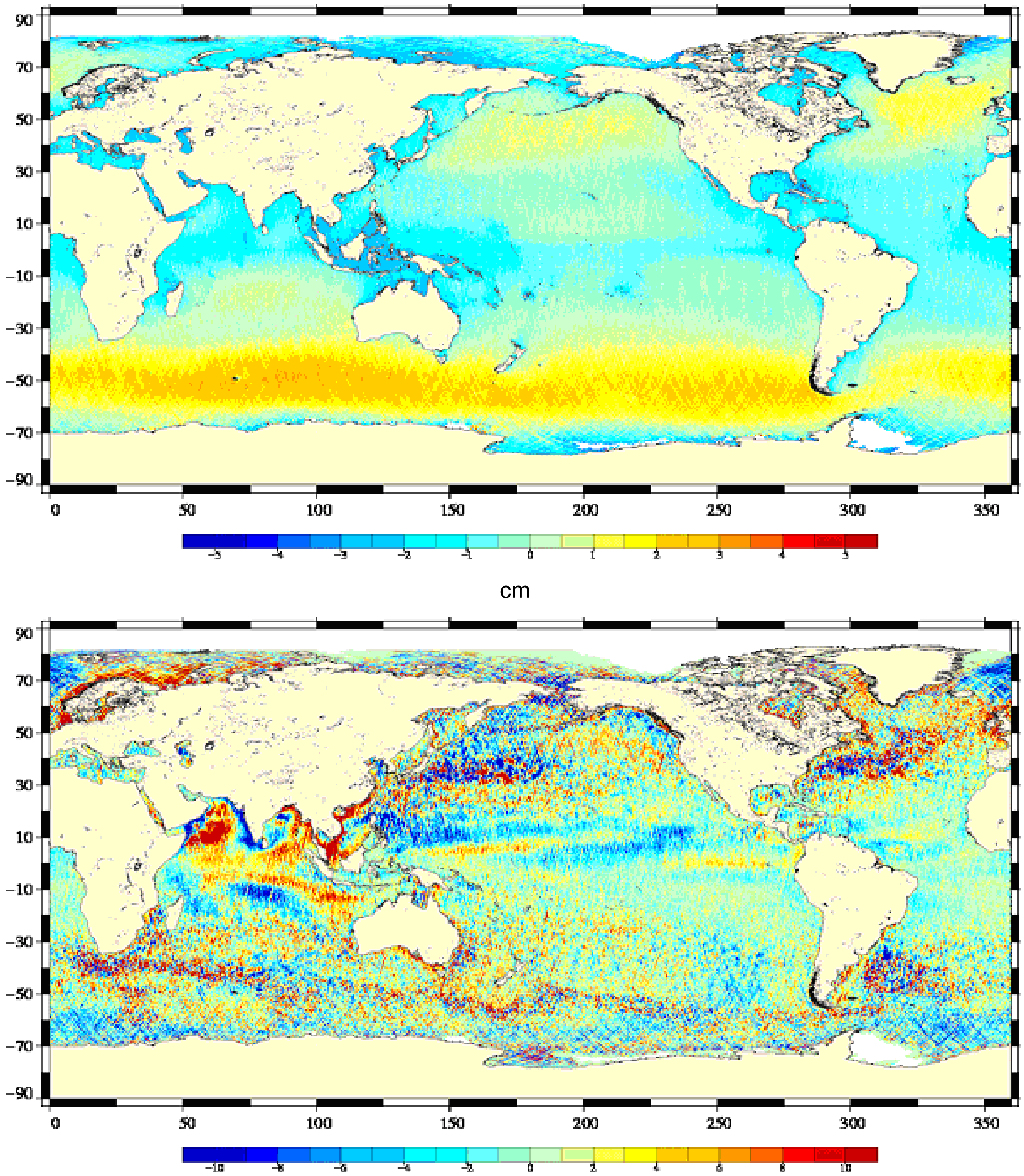
Figure 38 : TOPEX, GOT00V2 VS GOT99, Mean (top), variance (bottom) profile differences.

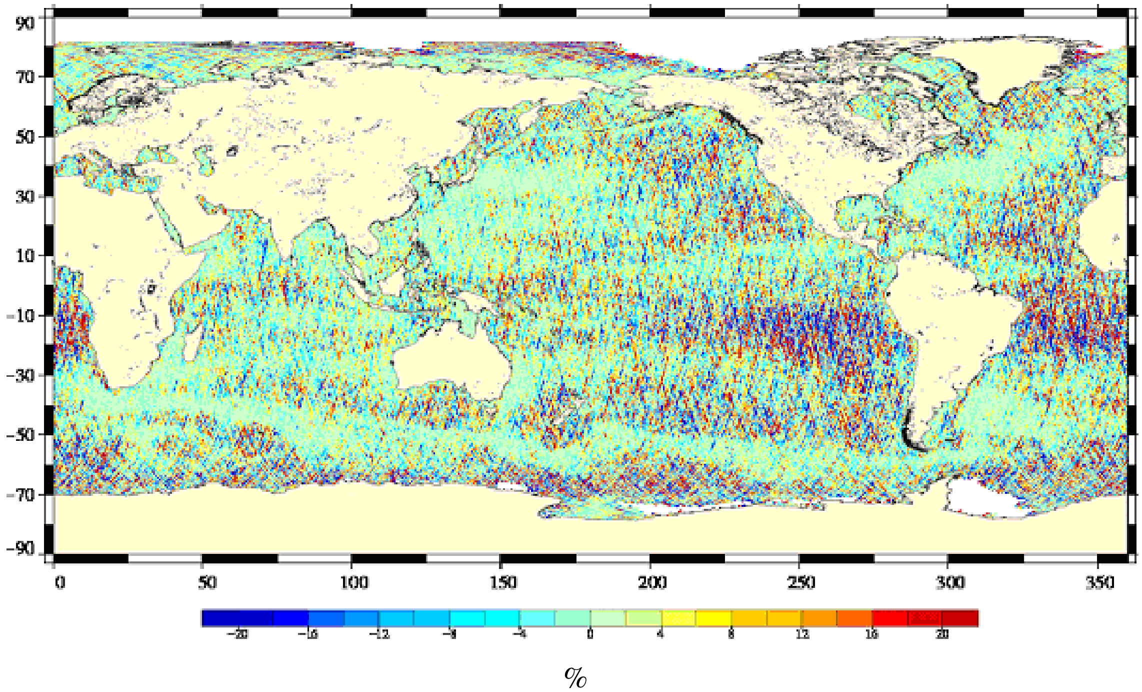


Back to **Table 2**

SSB correction:

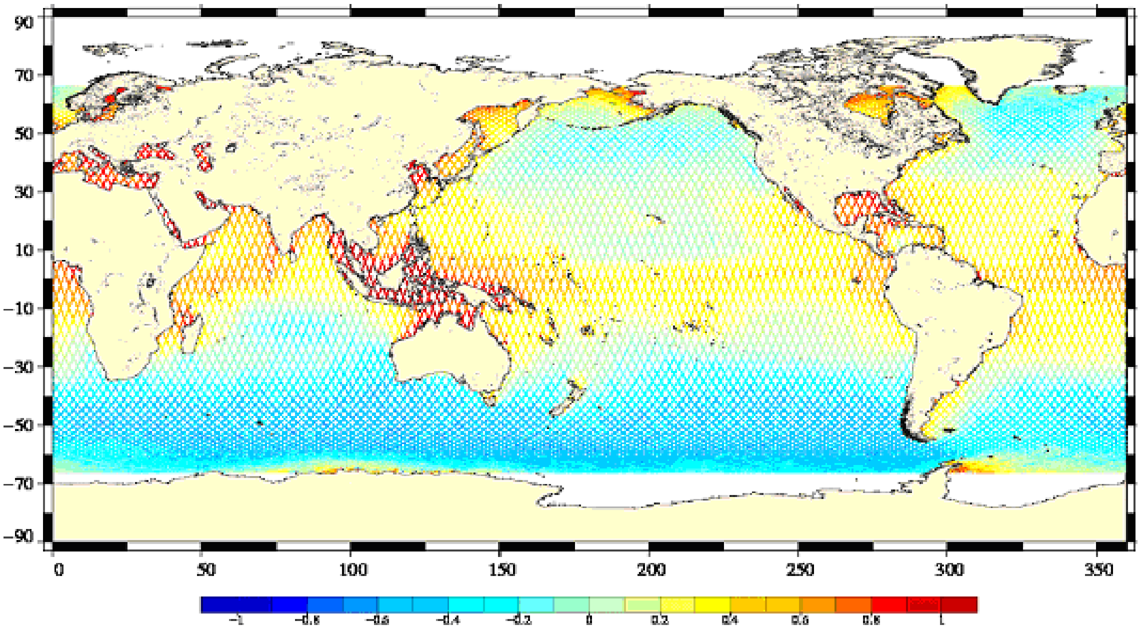
Figure 39 : ENVISAT, BM4 VS NPARAM : Mean (top), variance (bottom) profile differences.

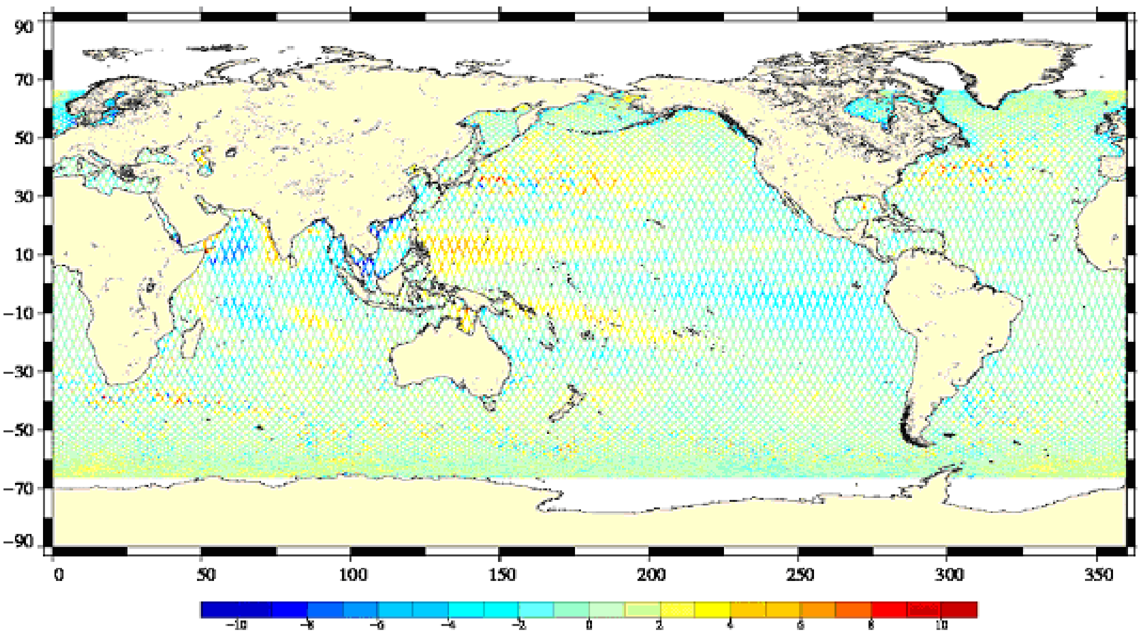


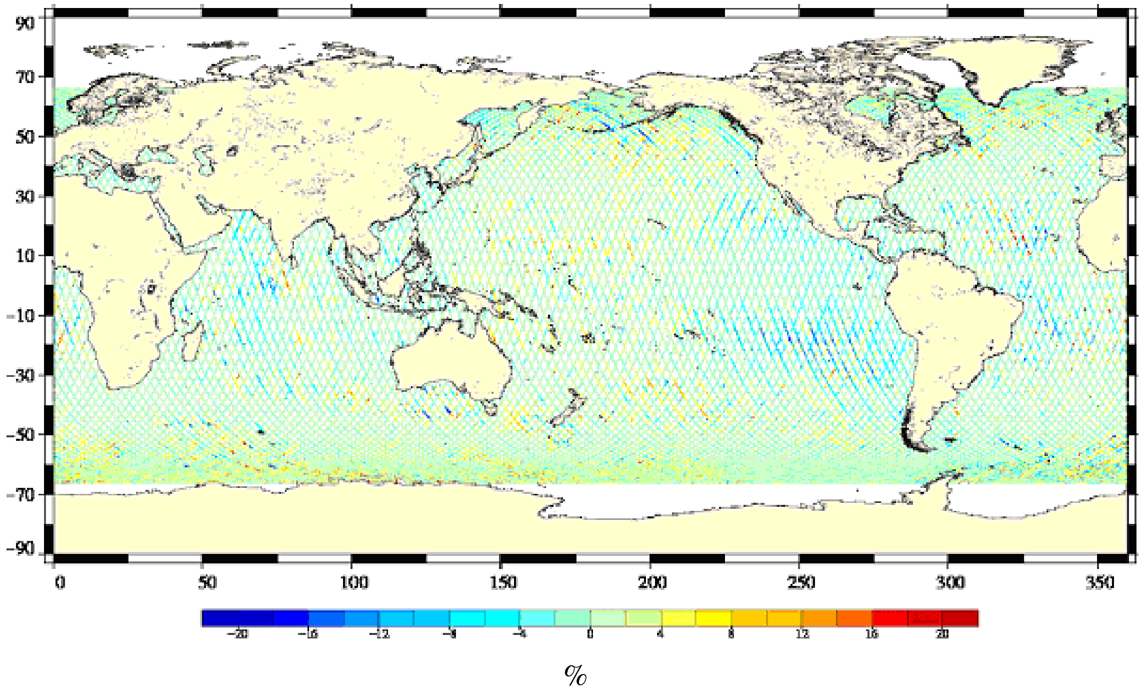


Back to **Table 2**

Figure 40 : TOPEX, BM4 VS NPARAM: Mean (top), variance (bottom) profile differences.

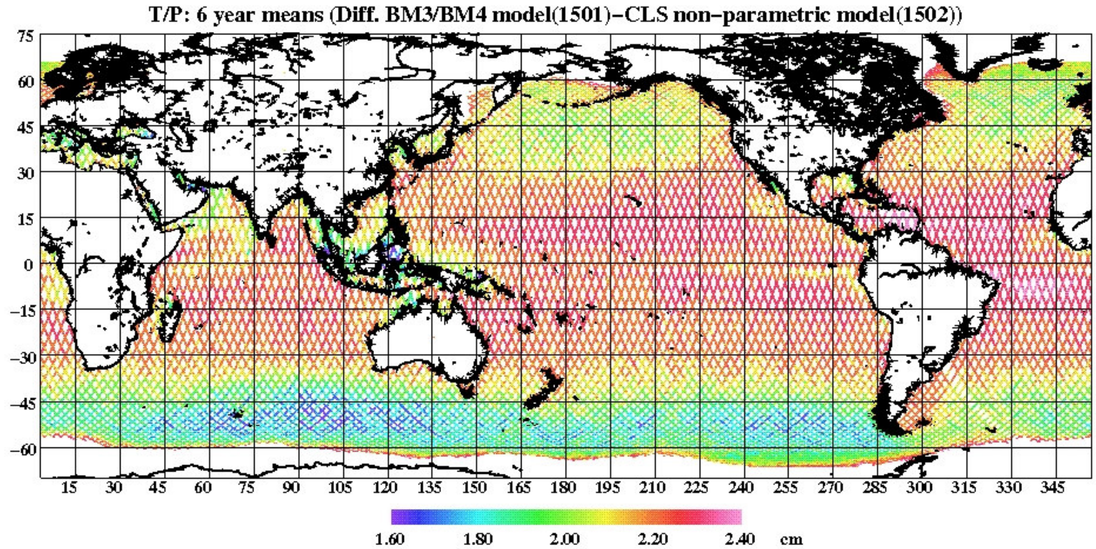






Back to **Table 2**

Figure 41:6 year means difference between SSB corrections for T/P



Back to **Table 2**

Global Impact on TOPEX 7 year (1993-1999) mean profile

Figure 42 : Sum of the difference maps computed between two TP mean profiles for which different versions of the orbit, the SSB, the DAC and the tides are used.

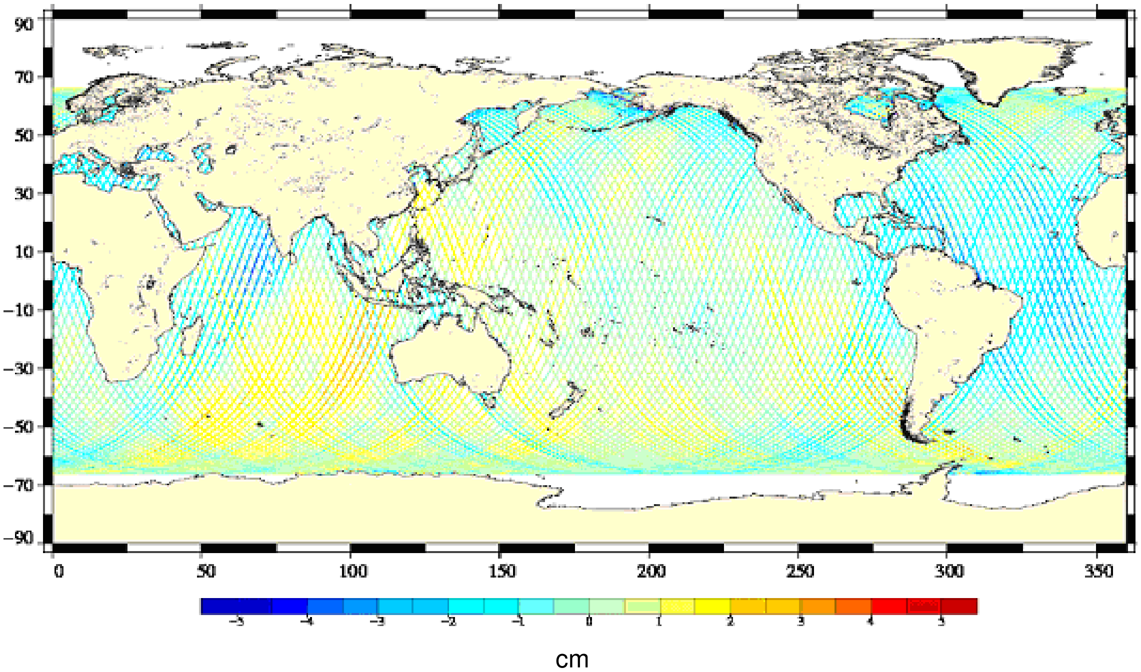
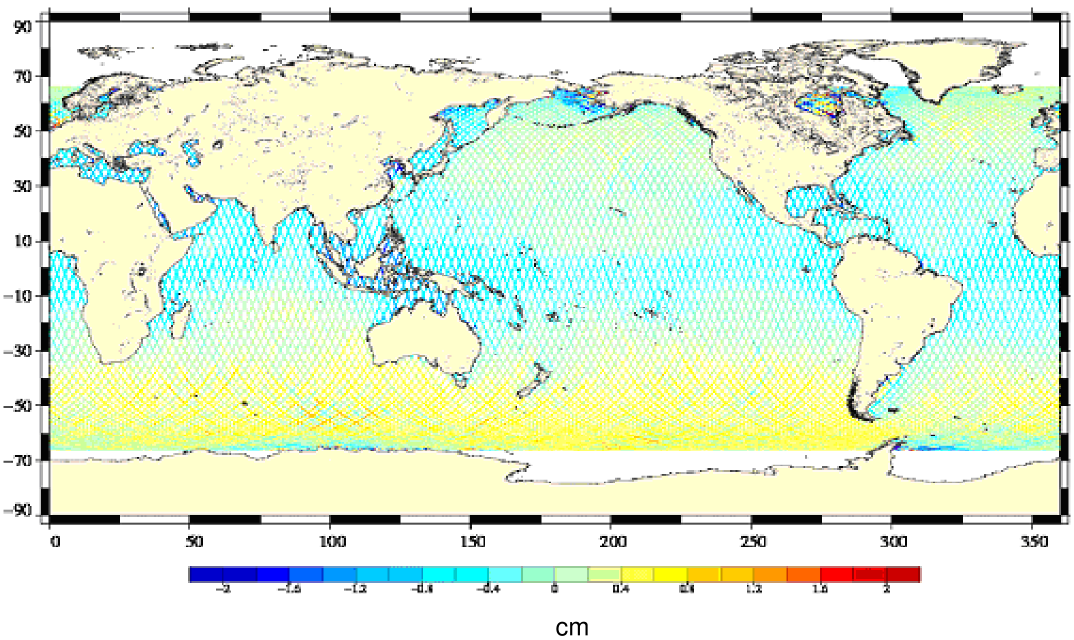


Figure 43 : Sum of the difference maps computed between two TP mean profiles for which different versions of the SSB, the DAC and the tides are used.



3.2.2. Impact in coastal areas

In the shallow part of the ocean we are expecting larger differences between one correction and another. In order to identify which models are generally the best to reduce the sea surface height variations of the altimeter signal, we carried out a comparison between the various models and their performance as a function of distance to the coast.

A global set of six years of all sea surface height observations from the Envisat was used as this satellite provide data considerably closer to the coast than both TOPEX and JASON-1. All ENVISAT sea surface height observations were then distributed in 2 km intervals according to the closest distance to shore in any direction. In **Figure 44** to **Figure 49**, the reduction of the standard deviation sea surface height for each range and geophysical correction is shown.

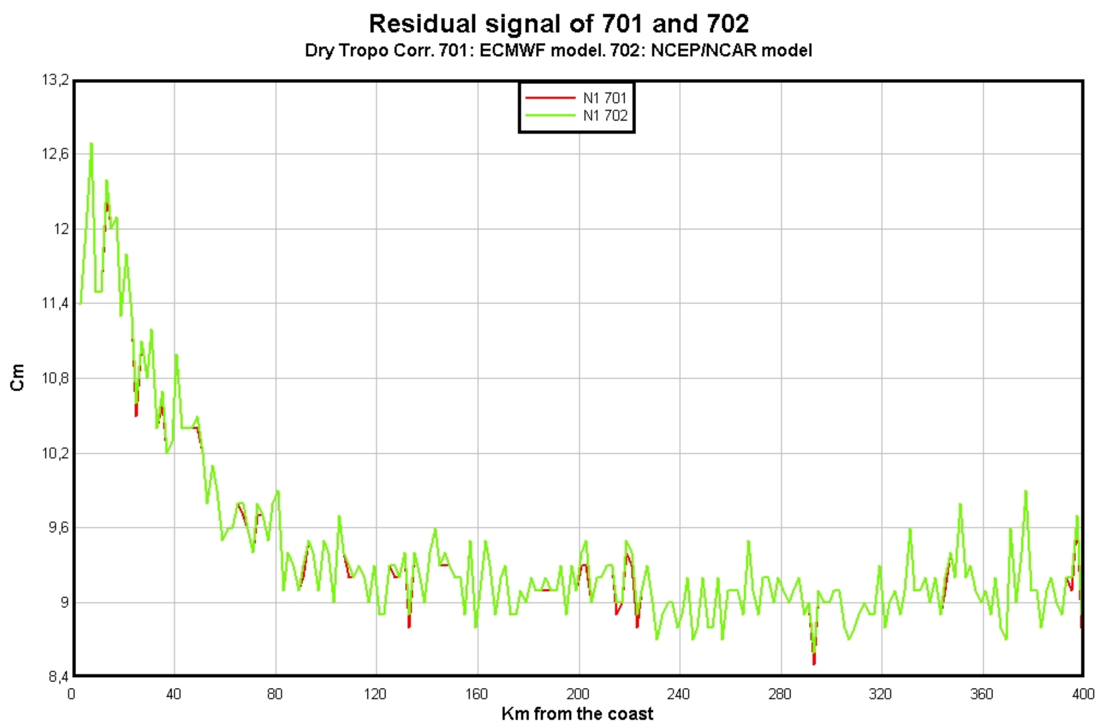


Figure 44: Residual sea surface height signal after The Dry Troposphere correction from ECMWF and NCEP

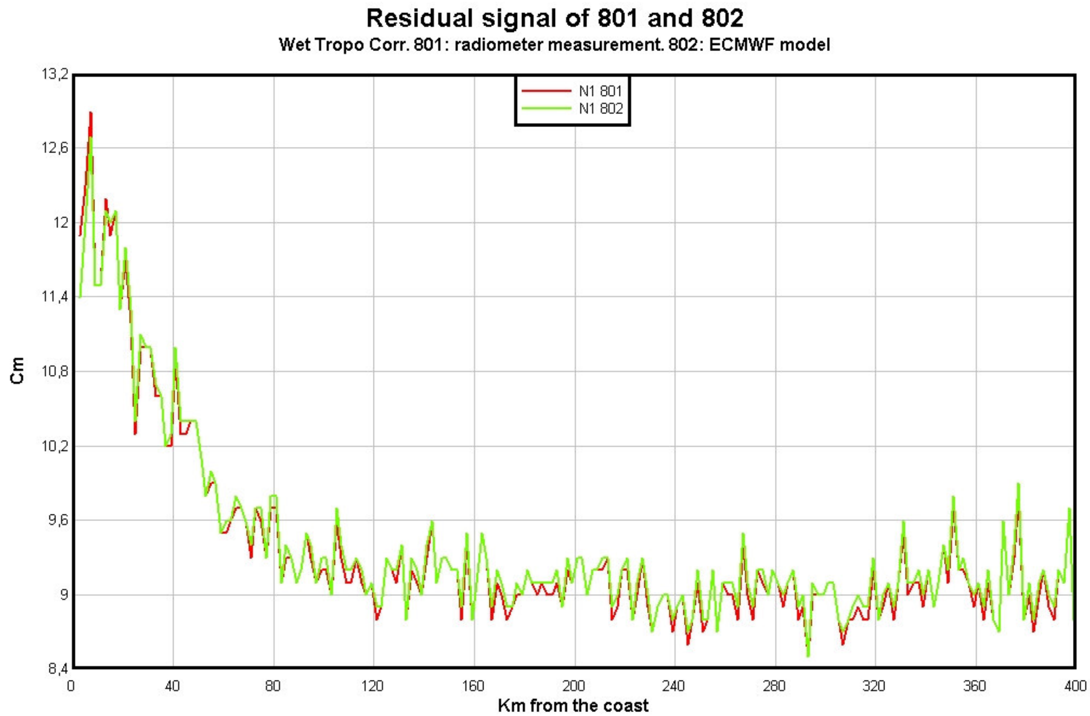


Figure 45:. The Wet Troposphere correction from Radiometer and ECMWF

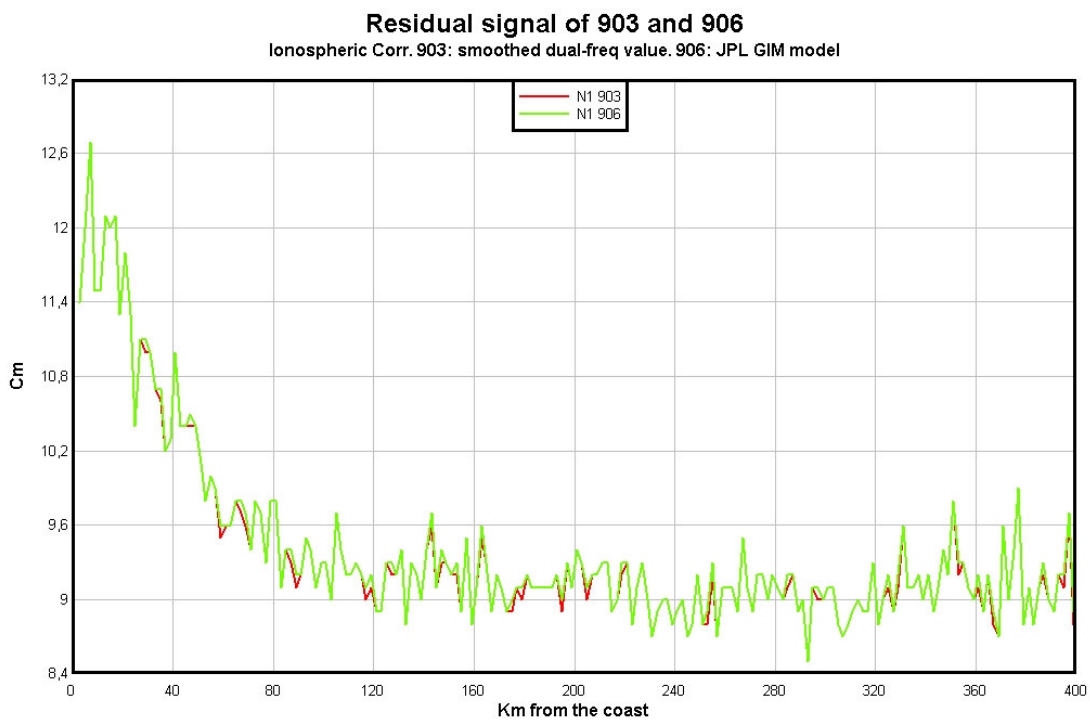


Figure 46: The Ionosphere Correction from Smoothed Dual-freq Value and JPL GIM model

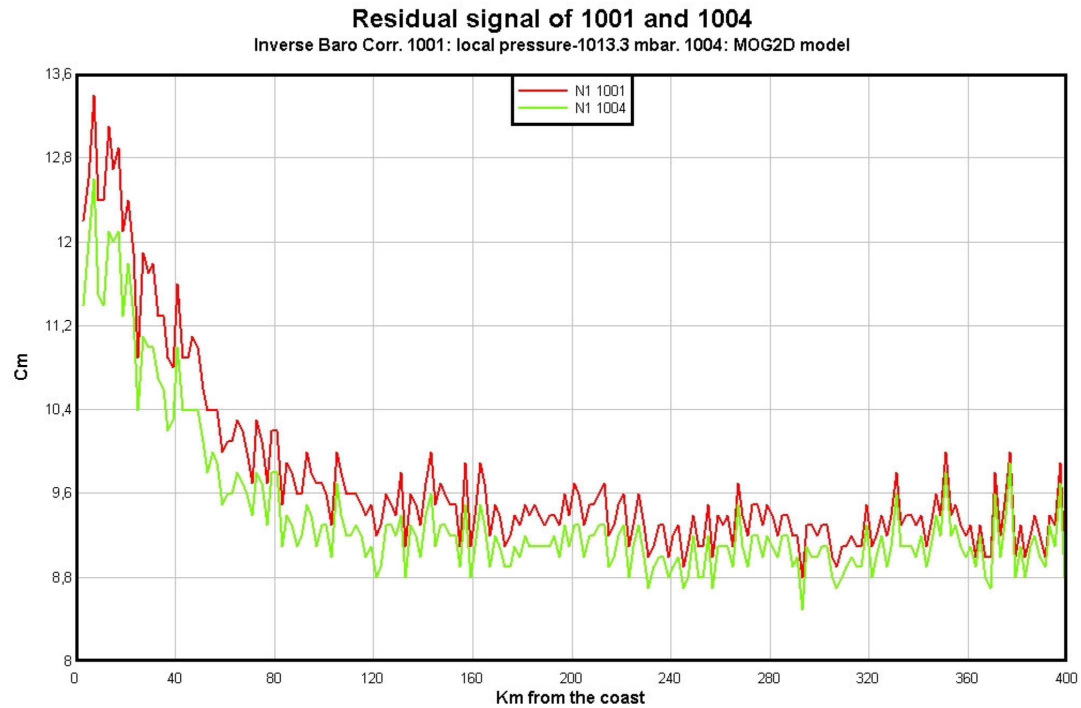


Figure 47:. Inverse Barometer Correction from Local Pressure and MOG2D_IB model

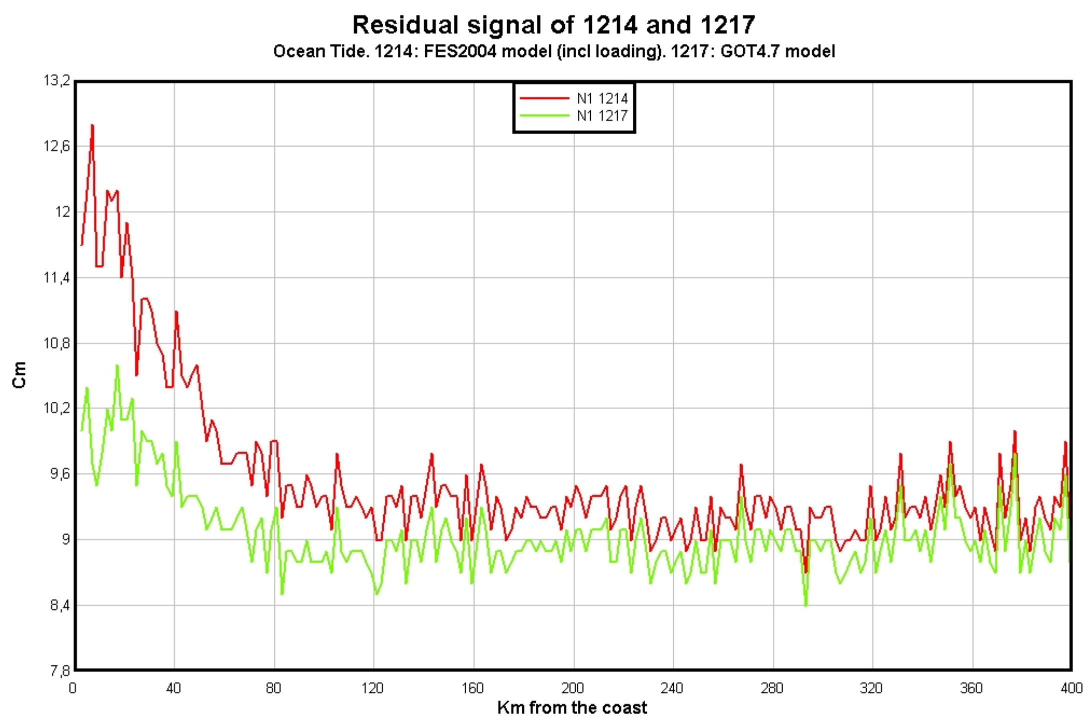


Figure 48: Ocean Tide from FES2004 model and GOT4.7 model

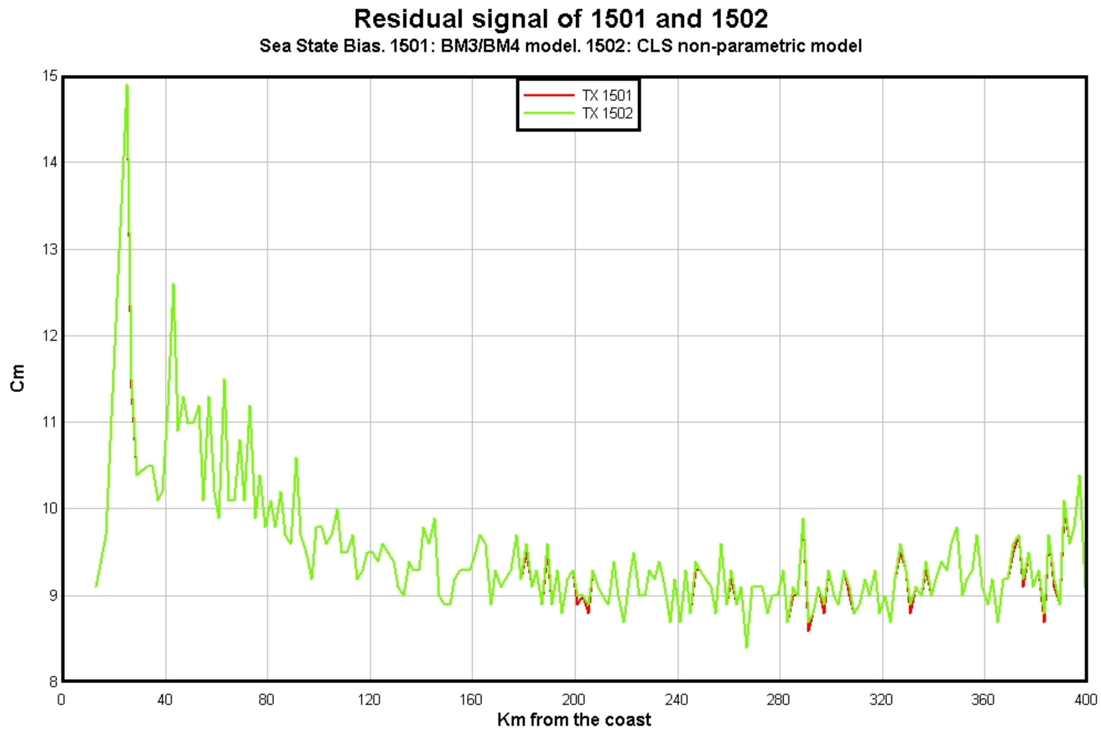


Figure 49: Sea State Bias Correction

The investigation shows that for the 400 km proximity to the shore there is not considerably difference between the range corrections applied. There does however, seem to be larger differences in the Geophysical corrections applied. This is particularly so with the dynamic atmosphere correction MOG 2D, which is reducing considerably more sea surface height variability than the older and simpler IB correction. The same can be said about the more recent ocean tide model GOT4.7 which reduces considerably more sea surface height variability in the coastal zone than the now “older” FES2004 ocean + loading tide model.

3.3. Recommended standards for MSS computation

Based on the previous analysis, we end up with a set of recommended corrections to apply on altimetric measurements that we will further use as standards for the GUT MSS computation. These are:

Ionospheric correction:	ALTIMETER
Dry tropospheric correction:	ECMWF
Wet tropospheric correction:	RADIOMETER / ECMWF
DAC:	MOG2D-IB
TIDES:	GOT
SSB:	NPARAM

These standards differ from the standards that had been used for the computation of the two most recent global MSS available CLS01 (DR 14) and DNSC08 (DR 15) and that are given in **Error! Reference source not found.** We will therefore compute for the GUT specific regional MSS based on the new corrections. The new standards that will be used to compute these two regional GUT MSS are also given in **Error! Reference source not found.**.

Standards	AVISO SLA	MSS CLS01	GUT MSS (Ibiroos)	MSS DNSC08	GUT MSS (Northwestern Shelf) and SLA
Reference period	1993-1999	1993-1999	1993-1999	1993-2004	
Reference ellipsoid	-	TP	TP	-	TP
Tide system	-	Mean tide	Mean tide	-	Mean tide
Altimetric corrections					
Sea State Biais	NPARAM	BM4	NPARAM	BM4	NPARAM
Orbite	Depending on mission	ORB_POE_ N (NASA)	ORB_GSFC_ITRF2005	NASA GGM02/ITRF2000	EIGEN-GL04C orbits
Ionosphère	ALTIMETRIC	ALTIMETRIC	ALTIMETRIC	ALTIMETRIC	ALTIMETRIC
Dynamical Atmospheric Correction	MOG2D_IB	IB	MOG2D_IB	IB	MOG2D_IB
Wet Troposphere	Radiometer	Radiometer	Radiometer	Radiometer	ECMWF
Dry Troposphere	ECMWF	ECMWF	ECMWF	ECMWF	ECMWF
Tides	GOT 00.2	GOT 99	GOT 00.2	GOT 00.2	GOT 4.7

Table 3: Standards used for the GUT altimetric products (SLA and MSS)

In order to quantify the global impact of these corrections on the new MSS computation, we computed the differences between two TOPEX mean profiles (1993-1999) the first one being based on the old (CLS01) standards and the second one on the new standards for the orbit, the SSB, the DAC and the tide corrections.

The obtained map is shown on Figure 42. The signal amplitude ranges between +/-2cm, reaching locally +/-5cm. A global 2.5 cm bias is measured. The similarity between Figure 42 and Figure 17 suggests that the orbit signal dominates the profiles differences. This is confirmed by Figure 43, where the same analysis than Figure 42 is done, except that the same orbit is used in the two cases. We hence obtain a weaker amplitude signal (<+/- 2 cm) that varies with latitude and distance to the coast.

3.4. Impact for MSS error estimation

3.4.1. Formal errors

The DNSC08 and CLS01 MSS are computed together with associated formal errors. Figure 50 shows the formal error of the MSS computed by CLS for the GOCINA project.

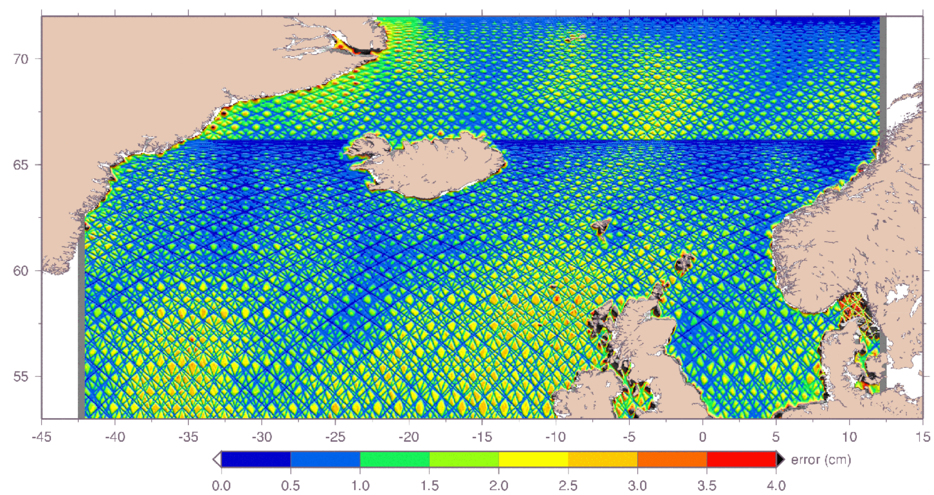


Figure 50: Formal error computed for the CLS GOCINA MSS

However, formal errors strictly depend 1) on the error budget allocated to the input data (along-track mean altimetric profiles) 2) on the a-priori knowledge of statistical covariance characteristics of the MSS.

At the present time, errors allocated to the altimetric mean profiles do not take into account the errors on the different geophysical and instrumental corrections applied on the altimetric range. The obtained formal error is mainly an under-estimate of the real MSS error.

3.4.2. Comparison of different MSS solutions

An efficient way to “calibrate” the formal errors, that are often underestimated, is to compare different MSS fields.

We show hereafter comparison results between two regional MSS computed in the framework of the GOCINA project as well as comparison results between two global MSS.

Comparison of the GOCINA MSS

This was done for instance in the framework of the GOCINA project: Figure 51 shows the difference on the GOCINA area between two MSS fields computed by CLS and DNSC.

This exercise will also be done later on in this project comparing the 2 regional GUT MSSs computed in WP8200.

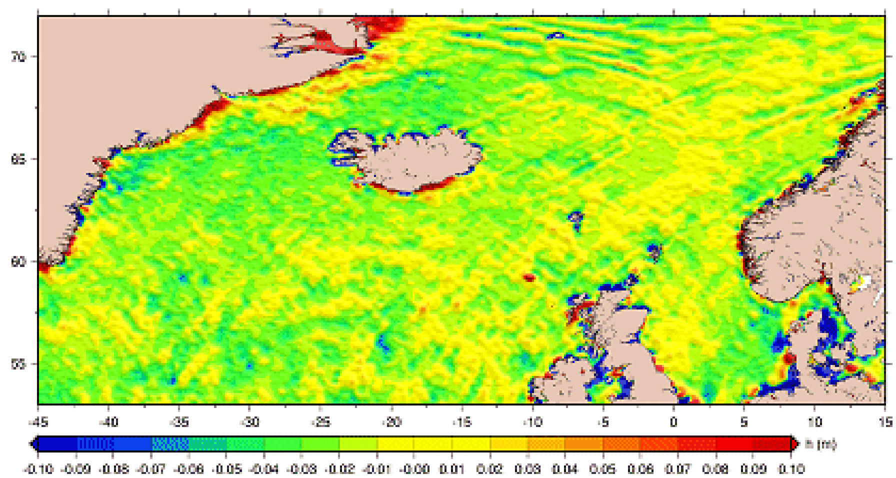


Figure 51: Regional differences between the CLS and GOCINA KMS04 MSS

Comparison of two global MSS

The presently two most widely used global MSS models are the DNSC08MSS and the CLS01 MSS model. The CLS01 MSS model is based on seven years of satellite altimetry covering the period 1993-2000 and the DNSC08MSS is based on 12 years of data. Furthermore, different standards have been applied in the computation of these two fields (see **Error! Reference source not found.**) that have a signature on the mean. Figure 52 shows the difference between the two global solutions.

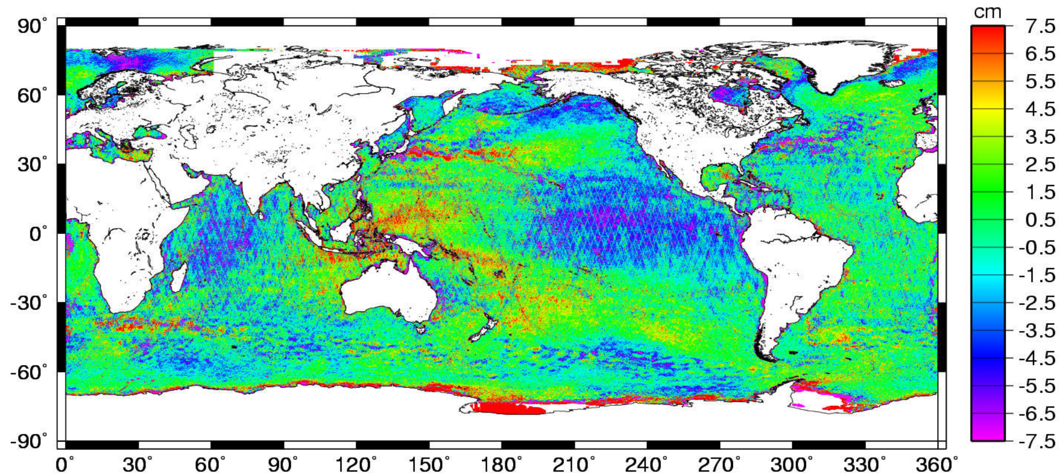


Figure 52. The difference between DNSC08 and CLS01 Mean Sea surfaces (IB corrected). An offset of 2 cm due to different IB correction between the two MSS have been removed. Figure courtesy of S. Holmes and N. Pavlis

A closer inspection of the difference between these two models reveals several important fact contributing to the difference:

- In CLS01, The T/P and ERS SSH are corrected using an inverse barometer correction with a ocean mean average pressure of (~1011 mbar), instead of a constant value of 1013 mbar (computed over oceans+land) used for DNSC08MSS. This generates a ~2 cm bias on the mean profiles which consequently, appears as a constant height bias between the two MSS.
- Large scale differences of the order of +/- 5 cm from east to west in the Pacific Ocean reflect inter-annual ocean variability that will be averaged out differently. DNSC08 is averaged over 12 years (1993-2004) whereas the CLS01 MSS is referenced to the 7-year (1993-99) period (see expected impact on Figure 3). The east-west dipole in the Pacific Ocean is largely caused by the 1997-1998 El Nino dominating the 7 years CLS01 period more than the 12 year period for DNSC08MSS.
- Altimetric related striation originating from a combination of different range corrections (particularly visible in the central Pacific Ocean) which is presumably thought to be related to, different range correction applied to the two MSS models.

Recommendations to users

Estimating the error on the altimetric MSS, SLA and MDT is a complex issue that definitively requires more dedicated studies. The 'true' error is tricky to estimate since different error sources have to be taken into account:

- altimeter and radiometer instrumental errors

- errors on the different models entering in the altimeter processing chain An estimate of this error can be inferred from impact studies like what has been done in section 2.4

- method (combination and cartography) errors...

Moreover, some of these errors may be correlated.

In order to better understand the accuracy of all these products, the user need not to focus only on the formal errors provided with the products but rather adopt a multi-angles approach

Recommendations for implementation of the toolbox

Formal errors of the different MSS provided within GUT shall also be available in the GUT toolbox.

4. List of recommended GUT products

4.1. Altimetric Data

4.1.1. List of altimetric SLA products

Altimetric anomalies have been identified as auxiliary products for the GUT toolbox.

Altimetric Level-3 SLA are produced and distributed by two main data centers:

- AVISO for all altimetric missions (ERS-ENVISAT-TOPEX-JASON-GFO): Data distributed by Aviso have been validated and inter-calibrated for all missions. Monomission along-track data as well as multi-mission gridded products are available

- PO-DAAC for the TOPEX and Jason missions. In that case, mono-mission along-track data are available.

In these two cases, regular updated standards from the OSTST and QWG recommendations are applied for the SLA computation (DR 17, DR 18, DR 19).

In addition to these two operational data centres, the RADS (Radar Altimeter Database System) is DEOS' (Delft Institute for Earth-Oriented Space Research) effort in establishing a harmonised, validated and cross-calibrated sea level data base from satellite altimeter data It produces and distributes data from all altimetric missions. These are mono-mission along-track Level-2 products but the user has access to a number of possible corrections that he can download to create his own SLA field. **Table 4** shows the most recent range and geophysical corrections in the RADS data base used for the computation of recent MSS.

	Corrections
Dry Troposphere	ECMWF (Model) NCEP (Model)
Wet Troposphere	Radiometer (onboard) ECMWF (Model)
Ionosphere	Smoothed Dual Frequency Radiometer IRI 2007 (model)
Dynamic Atmosphere Correction	IB (Model, Local pressure) MOG 2D_IB Model
Tides	FES 2004 (Model) GOT 4.7 (Model)
Sea State Bias	BM4 (model) CLS NPARAM-GDRC (model)

Table 4: The two most recent range and geophysical corrections in the RADS data base used for the computation of recent MSS.

4.1.2. List of altimetric MSS products

Several global altimetric MSS are currently available as the CLS01 MSS and the DNSC08 MSS. Their characteristics are given **Error! Reference source not found.**. In addition to these global fields, regional solutions are computed in the framework of the GUT project, following the standards agreed on in the present workpackage. The first one will cover the Ibiroos area while the second one will cover the European North Western Shelf. Their characteristics are also given **Error! Reference source not found.**.

4.1.3. Recommendation to users

As stated in section 2.4, it is highly recommended to use consistent SLA and MSS products. Consequently, two different sets of consistent altimetric products (SLA and MSS) are provided inside the GUT toolbox.

The first one, computed at CLS, consists in one year of SLA grids as well as a regional MSS computed for the Ibiroos area in the framework of GUT. These altimetric products use the corrections described in **Error! Reference source not found.**. The SLA products are gridded maps of intercalibrated, multimissions altimetric anomalies. One year of weekly data is provided within GUT.

The second set of altimetric data, computed at DNSC, consists of SLA data computed using the RADS service as well as a regional MSS computed for the Northwestern shelves area in the framework of GUT. The standards used are described in **Error! Reference source not found.** The SLA products are along-track mono-mission data.

Also, two additional, global MSSs are provided inside GUT (CLS01 and DNSC08 MSS). These 2 MSS however have been computed using slightly different standards (**Error! Reference source not found.**). In order to understand the impact of these different standards on the MSS computation, the user is invited to carefully read section 3.2.

4.2. Digital Elevation Model

4.2.1. List of DEM products

Various local or global Digital Elevation Models exist. Recently significant improvements have been made for the computation of global DEM thanks to the Shuttle Radar Topography Mission (SRTM). It consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February 2000, providing a global Digital Elevation Model on a 1/1200° resolution grid, whereas previous DEM (like the Global Land One-km Base Elevation (GLOBE) Project from NGDC, NOAA, the GTOPO30 from NPA and ACE (Altimeter Corrected Elevation)) were 1/120° resolution products.

However, the SRTM field suffers from missing data (voids) in areas characterized by smooth surfaces such as calm water and smooth sand sheets that may not scatter enough radar energy back to the sensor. Furthermore, the SRTM field presents a number of artefacts due to both instrument and processing errors.

Solutions exist (for instance the SRTM-CGIAR field) where voids in SRTM data are filled using other elevation data

Current work is done by (DR 20) to complete and enhance the accuracy of the SRTM field using altimetric data from ERS-1 geodetic mission, ERS-2, ENVISAT and Jason missions. It is furthermore complemented with DNSC08MSS at sea. The resulting DEM, called ACE2, is planned to be available early 2009

4.2.2. Recommendation to users

We recommend the ACE2 field to be used as auxiliary data for the GUT toolbox when available.

5. Consistency check with the GOCE standards

In addition to the standards used for processing altimetric data, a number of standards have been chosen for the processing of GOCE data. the user must be aware of Some of these are based on atmospheric and ocean models and it is therefore recommended that, where practicable, the altimetric standards are consistent with the GOCE standards. GOCE standards are described in DR 1 and DR 2.

Within the GOCE processing chain, ocean and atmospheric models are used in the de-aliasing process. For the atmosphere de-aliasing, data from ECMWF will be used. For the ocean circulation de-aliasing, the OMCT model from Hamburg will be used. OMCT is a global baroclinic ocean model developed from the Hamburg Ocean Primitive Equation Model (DR 21) and is driven by ECMWF operational Analysis and Forecast Fields.

The OMCT model has a tidal component that will be turned off for all GOCE applications. To correct for the tidal aliasing, the GOT00.2 tidal model will be used.

One may wonder if the use of an ocean model in the GOCE data processing may have any impact when using GOCE data for ocean applications. The issues here are the following:

1- how the ocean mass variations influence the gradiometer observations? and

2- how errors on the chosen ocean model may propagate into the final geoid error?

In general the ocean-atmosphere short term mass variations have only marginal influence on the gradiometer observations, because this signal in gradiometer measurement bandwidth is below the error of the instrument. However, the solution might be influenced in the very long wavelengths (DR 22). Figure 53 shows the amplitude of the signals due to ocean mass variation as modelized by OMCT within times ranging from 6 hours to 24 hours. We see that the amplitude of this signal is under the GOCE error prediction.

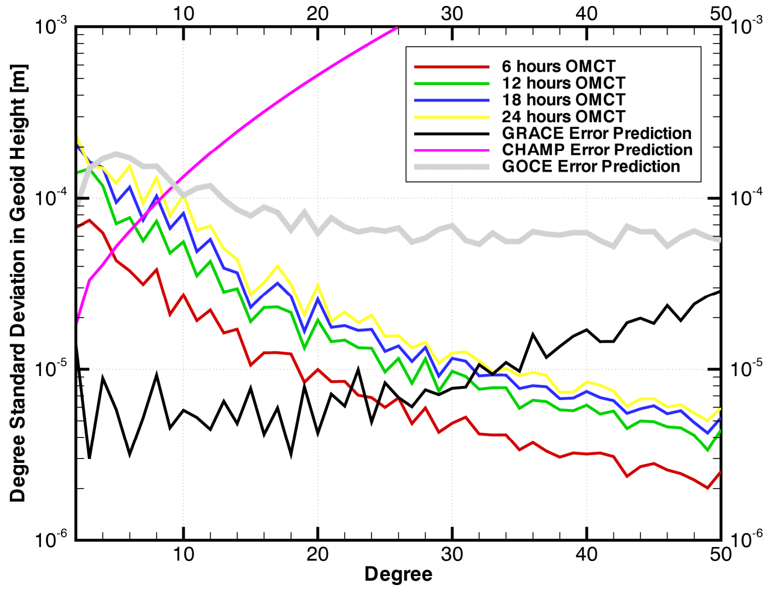


Figure 53: Signals due to ocean mass variations within a specific time compared to the error curves from CHAMP and GRACE and GOCE (courtesy of Th. Gruber)

Regarding the propagation of the OCMT model errors (largely unknown) into the GOCE products, as the signal of the ocean is, to a large extent, below the mission error curve for GOCE, very small impact is expected.

Recommendations to users

As the expected impact of the ocean and atmospheric models used in the de-aliasing is expected to be small in comparison to the error signal of the GOCE data, there is no necessity to be bound by the selection of model used in the GOCE processing

6. References

DR 1: ESA document: GOCE standards GO-TN-HPF-GS-0111

DR 2: GO-MA-HPF-GS-0110: GOCE Level 2 Product Data Handbook, Issue 3.3, 08.05.2007

DR 3 Lefèvre, F., Lyard, F. H., Le Provost, C., Schrama, E. J. O : FES99: A Global Tide Finite Element Solution Assimilating Tide Gauge and Altimetric Information, Issn: 1520-0426 Journal: Journal of Atmospheric and Oceanic Technology Volume: 19 Issue: 9 Pages: 1345-1356

DR 4 R D Ray, A global ocean tide model from Topex/Poseidon altimetry: GOT99.2, NASA Tech. Memo. 209478, Goddard Space Flight Center, 58 pp., 1999.

DR 5 Cartwright, D. E., R. J. Tayler, 1971, "New computations of the tide-generating potential," Geophys. J. R. Astr. Soc., 23, 45-74.

DR 6 Cartwright, D. E., A. C. Edden, 1973, "Corrected tables of tidal harmonics," Geophys. J. R. Astr. Soc., 33, 253-264.

DR 7 Wahr, J. W., 1985, "Deformation of the Earth induced by polar motion," J. Geophys. Res. (Solid Earth), 90, 9363-9368.

DR 8 R. B. Bent, S. K. Llewellyn, and M. K. Walloch, Description and Evaluation of the Bent Ionospheric Model, DBA Systems, Melbourne, Florida, 1972. (B26740)

DR 9 Iijima, B. A., Harris, I. L., Ho, C. M., Lindqwister, U. J., Mannucci, A. J., Pi, X., Reyes, M. J., Sparks, L. C., and Wilson, B. D. 1999: Automated daily process for global ionospheric total electron content maps and satellite ocean altimeter ionospheric calibration based on Global Positioning System data, J. Atmo. Sol. Terr. Phys., 61, 1205–1218.

DR 10 Webref, 2007; International Reference Ionosphere iri.gsfc.nasa.gov

DR 11 Gaspar, P., and F. Ogor, 1996, Estimation and analysis of the sea state bias of the new ERS-1 and ERS-2 altimetric data, (OPR version 6). Technical Report. IFREMER/CLS Contract n° 96/2.246 002/C. (CLS/DOS/NT/96.041).

DR 12 Gaspar, P., S. Labroue & F. Ogor, October 2002: Improving nonparametric estimates of the sea state bias in radar altimeter measurements of sea level J. Atmos. Oceanic Technol., 19, 1690-1707.

DR 13 Labroue, S., P. Gaspar, J. Dorandeu, F. Mertz, OZ. Zanifé, 2006, Overview of the Improvements Made on the Empirical Determination of the Sea State Bias Correction, *15 years of progress in radar altimetry Symposium*, Venice, Italy, 2006

DR 14 Hernandez, F. et al., 2001. Surface Moyenne Oceanique: Support Scientifique à la mission altimetrique Jason-1, et à une mission micro-satellite altimétrique. Contrat SSALTO 2945 - Lot2 - A.1. Rapport final n° CLS/DOS/NT/00.341, CLS, Ramonville St Agne.

DR 15 Andersen, 0., P. Knudsen, 2008:

DR 16 Dorandeu, J., and P. Y. Le Traon, 1999: Effects of global mean atmospheric pressure variations onmean sea level changes from TOPEX/Poseidon, J. Atmos. Oceanic Technol., 16, 1279–1283

DR 17 SALP-MU-P-EA-21065-CLS*, Edition 1.5, October 2006 : Ssalto/*Duacs *User Handbook : (M)*SLA *and (M)*ADT *Near-Real Time and Delayed Time Products*

DR 18 CLS-DOS-NT-05.108*, Edition 1.0, June 2005 Ssalto/*Duacs *product handbook: Mersea regional products*

DR 19 CLS-DOS-NT-05.097, Edition 1.0, July 2005: DT CorSSH and DT SLA Product Handbook.

DR 20 Berry, P.A.M., Smith, R.G., Freeman, J.A., Benveniste, J., 2007: Towards a new Global Digital Elevation Model, Proceedings of the IUGG symposium, Perugia 2007

DR 21 Drijfhout, S.S., Heinze, M. Latif and E. Maier-Reimer, 1996. Mean circulation and internal variability in the Hamburg Ocean Primitive Equation (HOPE) Model. J.Phys.Oceanogr., 26, 559-580.

DR 22 Wunsch, J, Thomas, M and Th. Gruber (2001): Simulation of oceanic bottom pressure for gravity space missions. Geophys. J. Int. (2001) 147, 428–434