GOCE++ Dynamic Topography at the coast and tide gauge unification
GOCE ++ DYCOT

TITLE. WP 2100-D4 Technical Note: Selection of Approach and description of software for coastal mean dynamic topography

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1 Introduction

This deliverable is a combination of a description of the approach (Section 2) and a description of the prototype software (Section 3).

2 Selection of approach

The following sections describe the selection of approach in the GOCE++ project.

2.1 Mean dynamic topography

The mean dynamic topography is estimated using the geodetic approach,

$$MDT = MSS - N, \tag{1}$$

where MSS is the mean sea surface and N is the geoid height. The quality of the MDT depends on the quality of the MSS and the geoid model. The quality of the MSS is generally less good close to the coast, due to lower data coverage both spatially and temporally. Figure 1 shows the track coverage based on TOPEX Poseidon and Jason 1 and 2 around Scandinavia. It is clear that the coverage is sparse close to the coast.
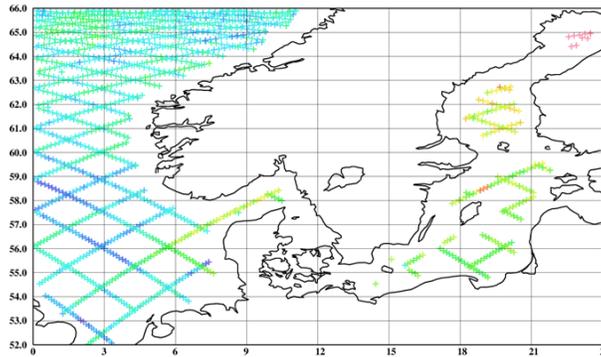

Figure 1: Illustrate the joint T/P-J1-J2 time series with more than 10 years of data (360 repeats).

The MDT may also be derived at tide gauges using a similar approach as (1). These MDT estimates will provide additional information in the coastal region, where the altimetry based estimates are sparse. Hence to improve the MDT in the coastal regions MDT values based on tide gauges are used as constraints. The final MDT is thus a combination of contributions from both altimetry and tide gauges.

To minimize the residue errors in the final MDT it is recommended to uses the same geoid as applied in the altimetric mean sea surface.

2.1.1 MDT gradient along the coast

The geodetic MDT is generally not well constraint in the coastal region, where the MDT contours in some cases crosses the coastline. This is mainly due to the sparse data coverage and that the filter is unconstrained. An example of this is demonstrated in Figure 2 (left) for the east coast of the US.

In the GOCE++ project this is partly accounted for by inserting MDT values over land. After filtering the land values are smoothed into the coastal region and hence aligning the gradients along the coast as demonstrated in Figure 2 (right). It is however crucial to select appropriate values. If the difference between the coastal MDT values and the inserted land values are too large, artificial MDT gradient may be created in the process (see *Figure 7*). In the GOCE++ project tide gauge based MDT values are used as land values.
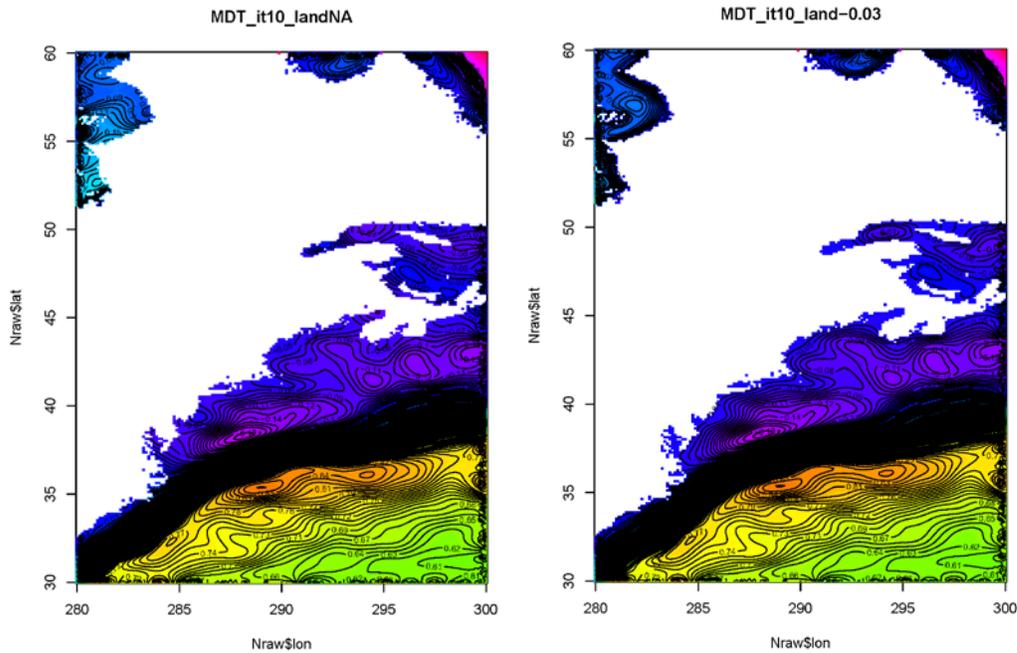

Figure 2: Land value effect. Left: The land values are ignored in the filtering. Right: The land values are set to -0.03 m in the filtering.

2.2 Period issue

Deriving a MDT from either the geodetic method or the oceanographic method entails the use of a reference period. For the oceanographic method the Any Mean sea surface and the reference period used in the project is 2003-2007. To change the reference period of the altimetry based MSS from a period P2 to another period P1 anomalies relative to the period P2 are needed. The expression for the conversion is given by

$$MSS_{P1} = \langle \eta \rangle_{P1} = \langle G+h \rangle_{P1} = G + \langle \overline{h}_{P2} + h'_{P2} \rangle_{P1} = \langle G+h \rangle_{P2} + \langle h'_{P2} \rangle_{P1} = MSS_{P2} + \langle h'_{P2} \rangle_{P1} \quad (2)$$

For instance, let us consider the altimetric Sea Level Anomalies distributed by DTU (DTU15), which are referenced to the period 1993-2012. To compute the DTU15 MSS over a different averaging period e.g. 2003-2007, the SLA averaged over 2003-2007 must be added to the DTU15 initial field.

2.2.1 GOCE ++ Approach:

In the GOCE ++ project we have chosen the 2003-2007 averaging period as this was the period giving the highest amount of tide gauges and an adequately long averaging period to obtain a stable average.
We have provided annual averages for each year in the 20 year averaging period as well as an average over the 20 years period relative to the DTU15MSS.

2.3 Filtering

A spatial filter is used to smooth the raw MDT to minimize omission and commission errors from the geoid. The filter is a simple average filter, where the kernel is an average of the nearest neighbors in each direction. Hence the kernel is a nx times ny matrix, where each weight is given by $1/(nx * ny)$. The filter radius is specified in degrees, and subsequently converted to kernel points in the north-south direction by

$$ny = floor\left(\frac{radius}{grid\ resolution}\right) * 2 + 1. \qquad (3)$$

In the east-west direction the number of kernel points nx are scaled by the latitude.

The filter is applied over both the ocean and land. The tide gauge based MDT values are filed in as land values in the altimetric MDT by linear interpolation. Applying the filter with a relative small radius has the effect of smoothing the tide gauge based MDT values in to the coastal regions, without severely affecting the MDT values in the open ocean. The filter is applied iteratively. Under each iteration the land values are reset to their original values. This enhances the effect of transferring the tide gauge based MDT values to the coastal region and the effect of the filter approaches a Gaussian filter. Improved filtering approaches are described in the technical note D6, which will be available from the project webpage http://gocehsu.eu/.

2.4 Error estimate

To derive analytic uncertainty estimates of the filtered MDT is challenging and probably impossible do to correlations in the field. Another approach to derive uncertainty estimates is by using the bootstrap method. A first strategy is to divide the raw MDT of the selected region into blocks. To create new bootstrap data sets we:

1. Sample with replacement between the different blocks of data
2. Derive the filtered MDT for the bootstrap data set
3. Repeat step 1 and 2 N times
4. We can now derive e.g. the standard deviation of the N MDT solutions in each grid cell

The size of the data blocks is specified by the user. The block size should be chosen large enough to ensure that data is independent but not much larger than the size of the filter. If the blocks are too large there will be large gabs in the filtered MDT and the error will be overestimated.

2.5 Height system consistencies

Since different data types are combined; altimetry and gauge based MDTs, special attention must be given to the height reference system. Hence, to minimize biases between the altimetry and tide gauge based MDTs, the following conditions should preferable be met:

- The altimetric and tide gauge based MSS should be referenced to the same reference ellipsoid and be in the same permanent tide system.
- The two MDTs (altimetry and tide gauge) should be based on the same geoid. Hereunder it is important that
    - the geoids are with respect to the same reference ellipsoid and in the same permanent tide systems.

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.

2.5.1 Reference ellipsoid issue

Both altimetric MSS 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 in 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 3 shows the height differences between the GRIM and TOPEX ellipsoids on a global grid.
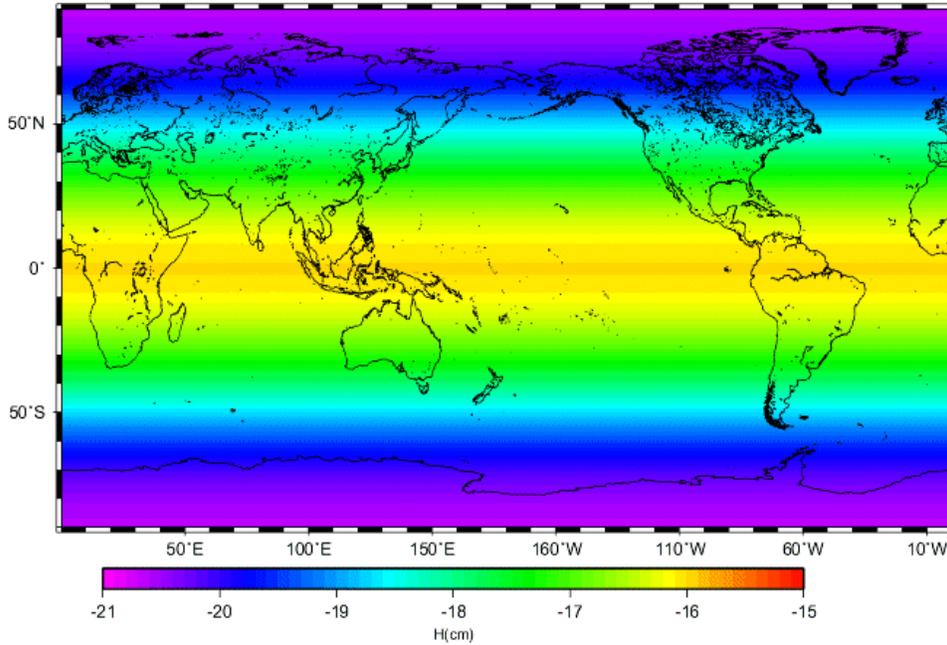
Figure 3: *Height difference between the TOPEX and the GRIM ellipsoids.*

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

Ellipsoid name	a (m)	1/f	Gm (m3/s)
"GRIM"	6378136.46	298.25765	398600.4369e9
"TOPEX"	6378136.3	298.257	398600.4415e9
"GRS80"	6378137.0	298.257222101	398600.5e9
"WGS84"	6378137.0	298.257223563	398600.5e9
WGS84 rev 1	6378137.0	298.257223563	398600.4418e9

Altimetric MSS heights are most commonly computed relative to the TOPEX ellipsoid, while the tide gauge MSS heights are relative to the WGS84 ellipsoid. The differences in latitude between these two reference ellipsoids are relatively small. Hence, the following approximate expression can be used to convert the WGS84 to the TOPEX reference ellipsoid.

$$Ellipsoid_{TOPEX} = Ellipsoid_{WGS84} + \Delta h.$$
$$\Delta h = -\big((aTop) - aWGS\big)\cos(\varphi)^2 + (bTop - bWGS)\sin\varphi^2). \quad (4)$$

Here $aTop$ and $aWGS$ is the equatorial radius of TOPEX and WGS84, respectively, and $bTop$ and $bWGS$ is the polar radius of TOPEX and WGS84, respectively.

2.5.2 Permanent tide system issue

The geoid can be defined in three different permanent tide systems (Ekman, 1989):

1. **Tide-free:** In this case the effect of the sun and moon is removed.
2. **Mean:** In this case the permanent tidal effect of the sun and moon is considered

3. **Zero:** In this case only the indirect effect of the sun and moon is considered, hence, the effect related to the elastic deformation of the Earth.
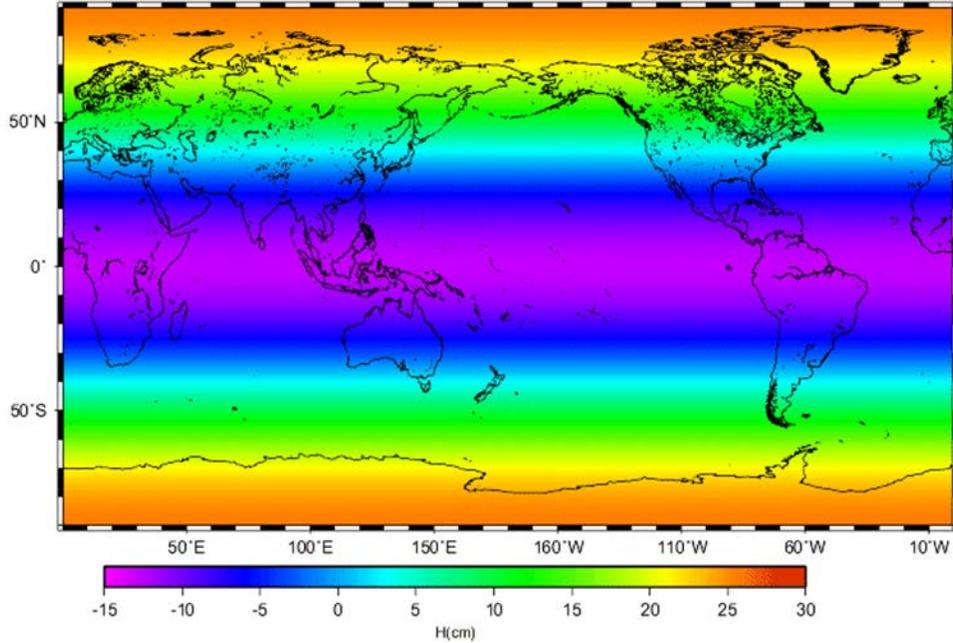
Traditionally, altimetry products are given in the mean tide system, while gauge data connected with GPS is given in the tide-free system. An equations to convert between geoids in the two systems (Ekman, 1989) is presented below

$$N_m - N_f = (1 + k)(0.099 - 0.296 * (\sin \varphi)^2)[\text{in m}] \qquad (5)$$

Here N_m and N_f are the geoid undulations in the mean and free-tide system, respectively, φ is the latitude, and k is a Love number, which is usually 0.3. A similar expression exists for converting ellipsoidal height

$$h_m - h_f = h_2(0.099 - 0.296 * (\sin \varphi)^2)[\text{in m}]. \qquad (6)$$

Here, h_m and h_f are the ellipsoidal height in the mean tide and tide free system, respectively. φ is the latitude and the constant $h_2 = 0.62$.

Tide gauge based MSL, which is references with GPS is naturally given in WGS84 ellipsoid height in the tide free system. To synchronize the tide gauge MSL to the altimetry MSL, expression (4) and (6) can be applied. Further issues with respect to the tide system can be solved by applying the same geoid in the derivation of the MDT for both the altimetry and tide gauge based solutions.

GOCE ++ Approach:

In the GOCE ++ approach we have included global grids to enable the transformation from the tide free to the mean tide system. Furthermore, transformation functionality is provided in the software.

2.6 Inverse barometer correction

The ocean reacts roughly as a huge inverted barometer coming up when atmospheric pressure is low and down when pressure rises. For several reasons it has traditionally been an advantage to apply this correction. Its lowers the standard deviation of the sea level anomalies and it eases the comparison with oceanographic models which do not include an atmosphere.

The mean dynamic atmosphere correction from the MOG2D_IB correction over 20 years are shown in Figure 5. The values are ranging from -10 to 10 cm in the global ocean.

Tide gauges measures the physical variation of sea level. This includes the effect of the inverse barometer. Consequently, when integrating with tide gauges we either need to apply the IB correction to the tide gauges or remove the IB correction from the altimetric models in order to make the two MDT quantities consistent.
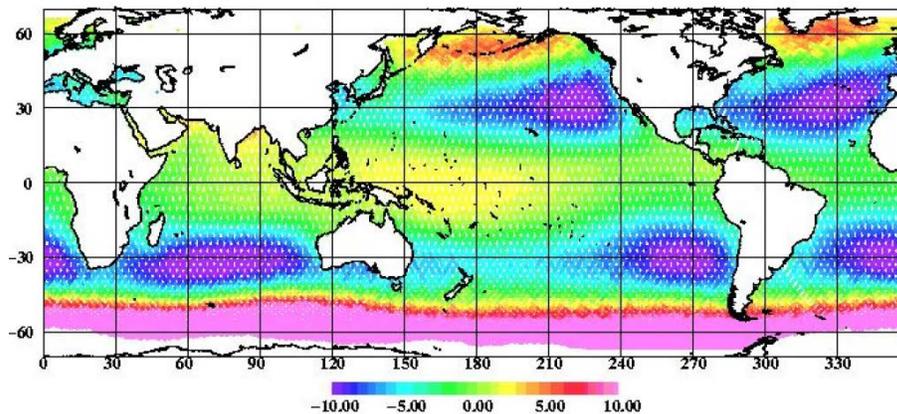

Figure 5: Mean dynamic atmosphere correction from the MOG2D_IB correction over 20 years in centimeters.

2.6.1 GOCE ++ recommendation:

For the computation in GOCE ++ where a certain averaging period is used the averaged MOG2D_IB correction of the chosen period must be computed and re-added to the altimetric MSS/MDT in order to make it consistent with the Tide gauge derived MSS. The quantity must be ADDED to the altimetric MSS.

3 Description of prototype software

This section describes the prototype software for computation of the coastal MDT. Section 3.1 describes the architecture of the software, and section 3.2 gives a short description of the software. A detailed user manual and tutorial is found in Appendix A and B. Appendix C describes the data.

3.1 Architecture

The software architecture is outlined in Figure 6. Data input is shown with green boxes, while purple boxes indicate actions/functions.

- At the zero'th level: If necessary the reference ellipsoid of tide gauge MSS is converted to the reference ellipsoid of the altimetric MSS.
- At the first level the raw altimetric and the tide gauge MDTS are created. If the same geoid model is used, the two MDTs will automatically be in the same permanent tide system.
- At the second level the region of interest is selected.
- At the third level the land/coastal MDT values are estimated based on the selected input data (tide gauge MDT, altimetric MDT or both).
- At the fourth level the raw MDT is filtered, where the ocean values are based on altimetry and the land values are based on input defined at level 3. The filter is applied iteratively N number of times. After each run the land values are reset to the values defined at level 3.
- At the fifth level the final MDT may be displayed and compared with tide gauge estimates. At the level the MDT may also be saved as a NetCDF file.

The output is a MDT which is based on both altimetry and tide gauge data for the selected region.
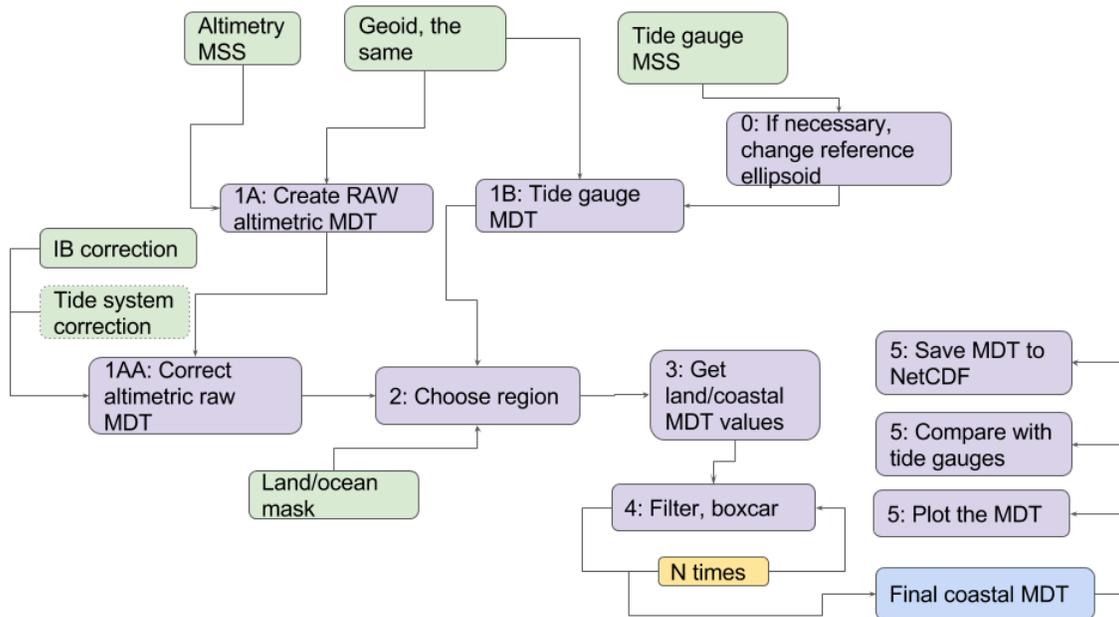

Figure 6: Flowchart of the software architecture. Boxes with a green color indicate data input, while boxes in purple indicate actions/functions.

3.2 Description of software elements

The software "coastMDT" is implemented in the open source programming language "R" https://www.r-project.org/. The software is constructed as an R-package, which works as an R library. The package is available from https://github.com/cavios/coastMDT, where

installation instructions also are found. Installation instructions are also found in Appendix B.

The package "coastMDT" consists of a set of main functions, which are listed and briefly described in Table 2.

Table 2: *Overview of core functions*

Function	Description
compareWithTG	Function to compare altimetric and tide gauge based MDT values at tide gauge stations.
ellipsoidTF2MT	Get correction to go from a tide free to a mean tide ellipsoid.
getData	Function that downloads the data used for constructing the coastal MDT.
getError	Function to estimate the Error of the MDT via the bootstrap approach
getLandVal	Function to estimate MDT values over land/coast.
getSubGrid	Function to extract a regional grid from a global grid.
getSubTG	Function to extract a subset of the tide gauge MDT values.
Grid2file	Function to save the MDT grid to a NetCDF file.
iterativeAveSmoother	Iterative average filter.
plotMDT	Function for plotting the MDT.
readncdf1var	Function to read NetCDF file with one variable.
readRegGridBin	Function to read a regular gridded binary file
tideConvert	Function to convert between different permanent tidal systems.
Wgs2topCorr	Function that estimates the height difference between WGS84 and TOPEX ellipsoids.

The available data, which can be downloaded with the function getData

Data	Description
landmask8	Land/ocean mask on 1/8 degree (0-360 degree) grid.
dDTU15MSS_ref2003_2007	Grid to transform the DTU15 MSS (DTU15MSS)

	to the MSS of the reference period 2003-2007. The grid is defined on 1/8 degree (0-360 degree) grid.
eigen6c4r	Geoid model based on EIGEN-6C4 on 1/8 degree (0-360 degree) grid.
dacCor5Y_2003_2007	Dynamic atmosphere correction for the 5-year reference period 2003-2007 on 1/8 degree (0-360 degree) grid.
ibCor5Y_2003_2007	Inverse barometer corrections for the 5-year reference period 2003-2007 on 1/8 degree (0-360 degree) grid.
TG	Tide gauge based MSL relative to WGS 84 (tide free) ellipsoid heights. The file also contains geoid height based on eigen6c4r.
mean2TF_addThis	Conversion from mean tide to tide-free system on 1/8 degree (0-360 degree) grid.
TF2mean_AddThis	Conversion from tide-free to mean tide system on 1/8 degree (0-360 degree) grid.
difmss15eig6c4r	Raw MDT based on the mean sea surface DTU15MSS and the geoid model eigen6c4r.

3.2.1   Limitations and issues

In the software it is possible to combine altimetry and tide gauge based MDTs to improve the MDT at the coast. However, biases related to different reference systems or other issues may cause non intentional artificial MDT gradients. This is partly accounted for in the software. In the region of interest the difference between the altimetry and gauge based MDT values are estimated. The bias is hereafter estimated as the median of the all differences. *Figure 7* gives an example of unintended MDT gradients around Madagascar, which has arisen due to a bias between the selected land values and the MDT values in the vicinity of the coast.
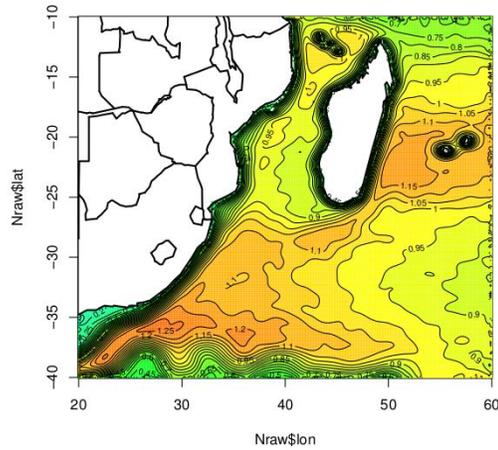
Figure 7: Example of artificial MDT gradient due to bias between land and ocean MDT values.

3.3 Improvements

This section lists various improvements which can be implemented in future versions of the software "coastMDT".

- The distribution of land values: Currently the land values of the MDT are distributed by simple linear or nearest neighbor interpolation. However, a careful evaluations of the MDT length scales in the coastal regions from e.g. ocean model MDTS would be helpful in order to distribute the land values in a more realistic manner.
- Error estimates of the input data e.g. the MSS and tide gauge data will help to improve the final MDT.
- To improve the coastal MDT in poorly surveyed areas. Knowledge of the MDT gradient would be helpful in order to align the MDT contours along the coast.
- Finally other data could be included such as ocean models and drifter data.

4 References

Ekman, M., Impacts of Geodynamic Phenomena on system Heights and Gravity, *Bulletin Geodesique, 63(3), 281-296,1989.*

5   Appendix A: User manual

6   Appendix B: User Tutorial

7   Appendix C: Data manual