Adding Mean Sea Surface (MSS) as an Altimetry Product

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Introduction

Currently our SIO altimetry processing products include: east and north deflections of the vertical, free-air anomaly, and vertical gravity gradient. The approach uses the EGM2008 global geopotential model as a reference in a classic remove/restore processing chain. Here we will add the mean sea surface height as an additional product. We will continue to use the MSS_EGM 2008 model [*Pavlis et al.,* 2012] as the reference and then extract height data from the MSS_CLS 2015 model [*Schaeffer et al.,* 2016]. As usual we will remove the MSS_EGM estimates from the MSS_CLS to form residual heights. Only heights with acceptable uncertainties will be used. These occur mainly along the Envisat and Topex/Jason-1/2 tracklines. We will combine these height data and uncertainties with dense slope data from all the SIO retracked products to form the usual residual east and north slope grids as well a new residual height grid. We will add the MSS_EGM grid to the residual height grid to form a new, higher resolution, MSS_CLS_updated grid. This document provides a detailed analysis of the development of the new MSS_CLS_updated grid.

Difference between CLS and EGM products

To understand the issues related to this analysis we first construct maps of the difference between the MSS from the CLS and EGM products. The starting grids are:

mss_cnes_cls2015.nc - The 2015 MSS from CLS. This grid contains both MSS and its uncertainty.

geoid.egm2008_MeanTide.grd – The EGM2008 geoid computed with a mean tide.

dot.egm2008.grd – Mean dynamic topography associated with this model.

ssh.egm2008.grd = geoid.egm2008_MeanTide.grd + dot.egm2008.grd

As a first sanity check we evaluate the difference mss_cnes_cls2015.nc - ssh.egm2008.grd. This is shown in Figure 1. The mean and standard deviations between the two grids are 0.41 m and 0.89 m, respectively. The median difference –s 0.462. There are some significant differences between the two grids:

(1) Large differences at high latitudes where the CLS heights are generally lower than the EGM heights.
(2) A large residual at the Gulf Stream so the CLS model has a sharper Gulf Stream than the EGM model.
(3) Some major differences along the ACC having amplitudes 0.1 m away from the mean.
(4) Some of the large seamounts in the equatorial Pacific have negative peaks indicating the EGM model has higher, and probably more accurate, peaks than the CLS model.
(5) High latitude coastal areas, such as around Greenland, have a CLS height greater than the EGM height. This is probably related to landward errors in the EGM geoid propagating into the oceans.

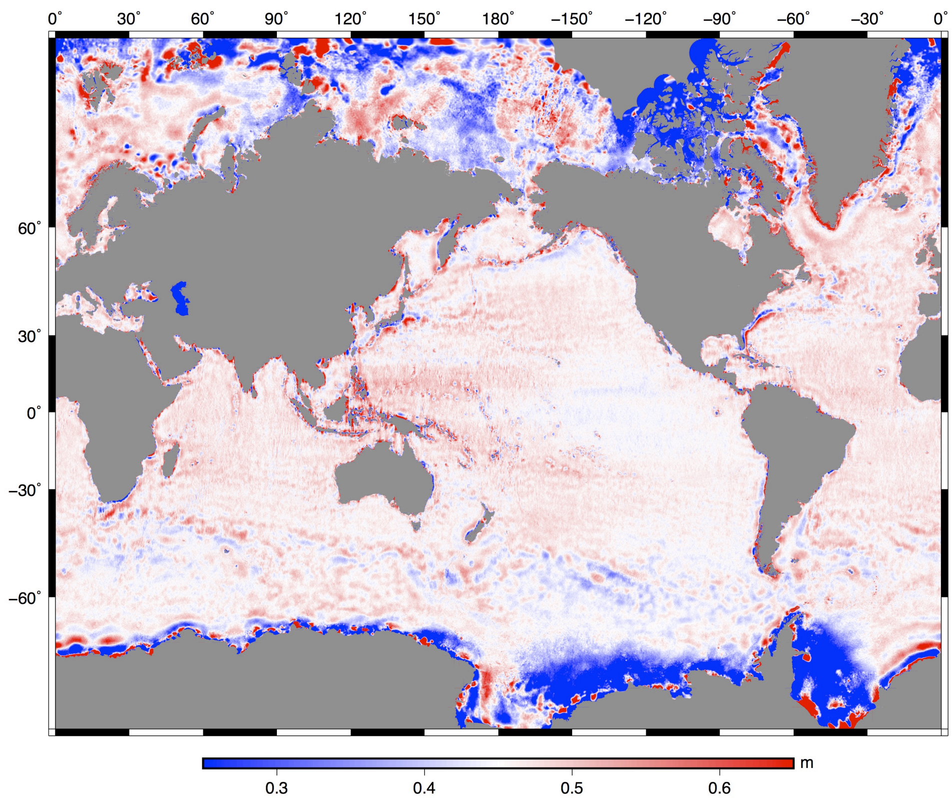

Figure 1. The MSS_CLS model minus the MSS_EGM model. The mean difference is 0.41 m and the standard deviation is 0.89 m. Note these statistics included CLS data extended onto land.

A second sanity check is to compare the MSS_CLS MSS with the EGM geoid. This comparison is shown in Figure 2. The mean difference is 0.21 m and the standard deviation is 1.15 m. The results are pretty much as expected showing the dynamic topography of the oceans.

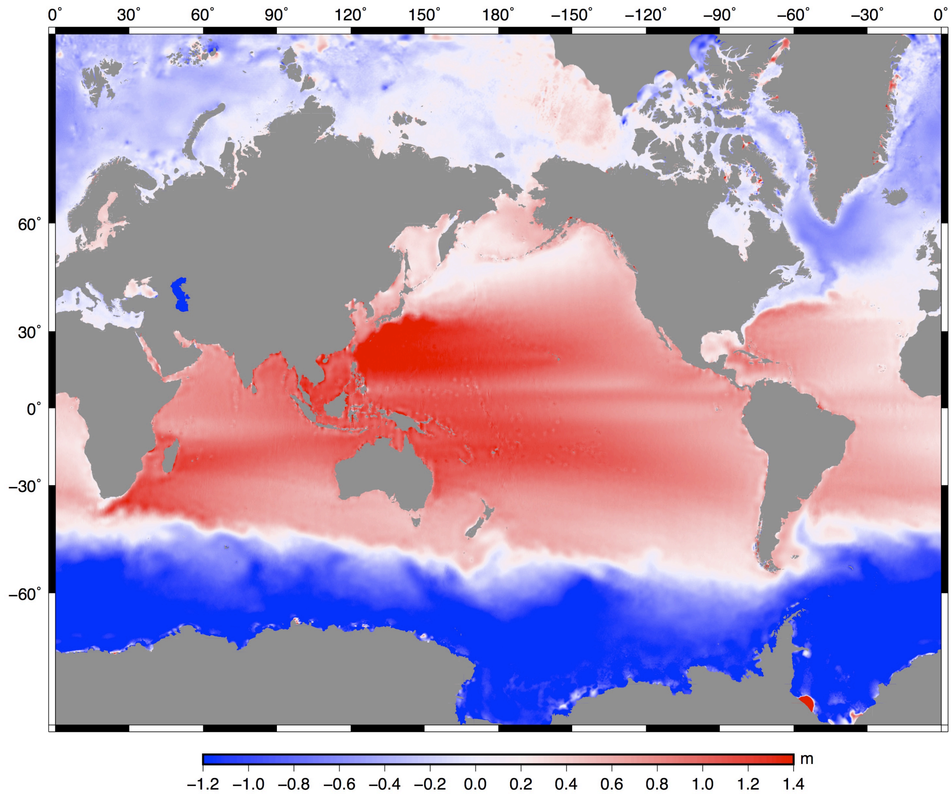

Figure 2. The MSS_CLS model minus the EGM geoid model. The mean difference is 0.22 m and the standard deviation is 1.15 m. Note these statistics included CLS data extracted onto land.

Next we use the CLS error grid to extract only those MSS_CLS minus MSS_EGM difference points that have uncertainties smaller than 2 cm. These will be the data we use in the construction of the combined height/slope least squares analysis. (Note we actually use an 8 cm threshold to keep more height information and reduce the gap area.) A map of these good data is shown in Figure 3. We also constructed a difference grid for an uncertainty threshold of 8 cm. This map in shown in Figure 4.

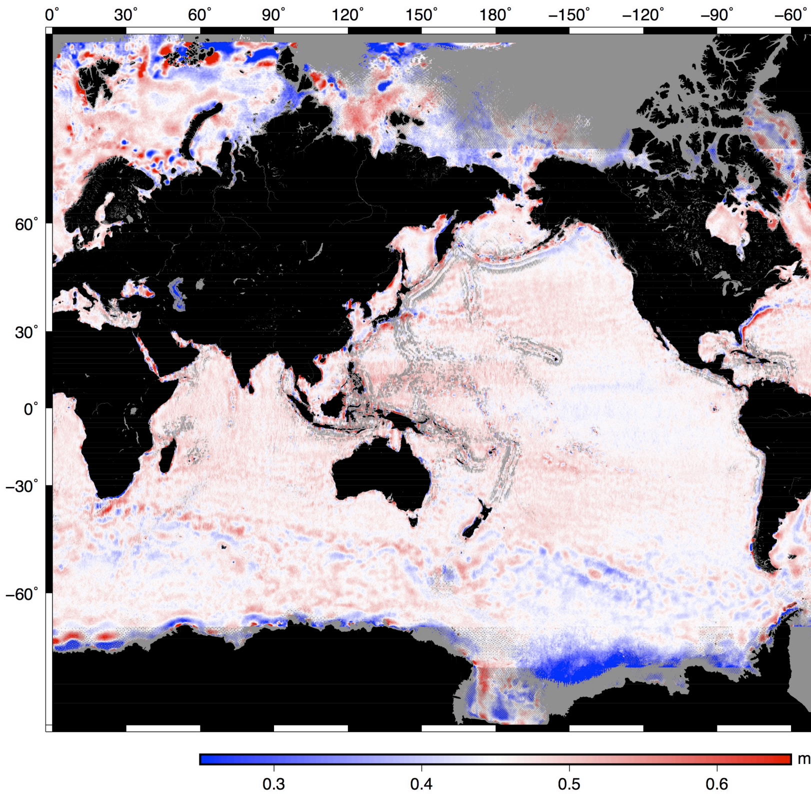

Figure 3. The MSS_CLS model minus the MSS_EGM model at locations where the CLS error is less than 2 cm. The mean difference is 0.45 m and the standard deviation is 0.64 m.

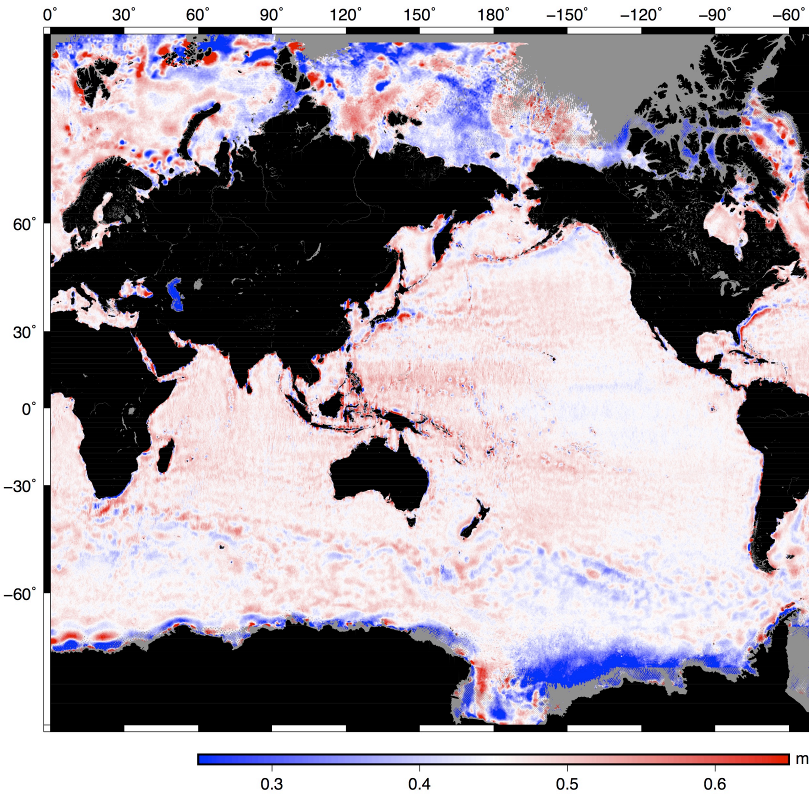

Figure 4. The MSS_CLS model minus the MSS_EGM model at locations where the CLS error is less than 8 cm. The mean difference is 0.44 m and the standard deviation is 0.72 m.

Method

The first method tested for constructing a higher resolution MSS grid has the following algorithm:

Extract height and uncertainties (ERR) data from the MSS_CLS – MSS_EGM grid shown in Figures 4. These form the residual height data and uncertainties. Next assemble all the along-track slope data in the SIO data base. These are processed as described in *Sandwell et al.,* [2014]. Note that a slope correction [*Sandwell and Smith,* 2014] has been included to all the along-track slopes. All the along-track slope data have the EGM slopes removed. These height and slope data are combined in the img_interp program using biharmonic splines in tension [*Wessel and Bercovici*, 1998]. The difference grid is shown in Figure 5 using the standard deviations in the ERR.

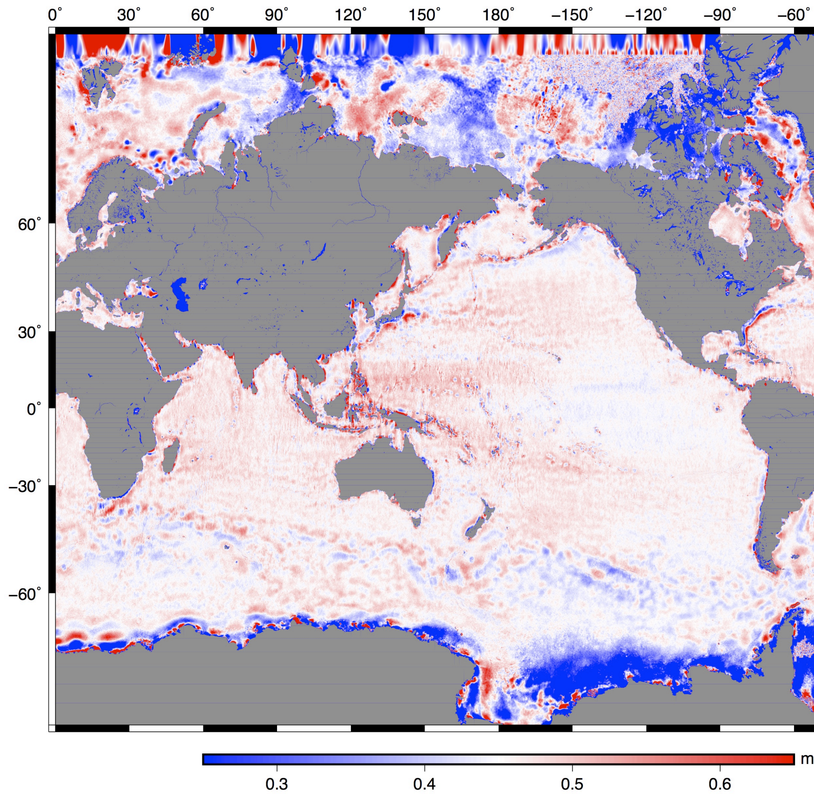

Figure 5. New MSS_CLS_updated – MSS_EGM derived from biharmonic analysis of both heights and slopes. Used original standard deviation provided with the CLS grid and an error threshold of 8 cm to retain CLS height data.

We first do this using the actual uncertainties given in the ERR_CLS grid. A threshold of 8 cm ERR is used to eliminate less certain data (Figure 4). We found that when gridding the heights and slopes together that they are somewhat inconsistent. The height data are smoother than the slope data so using the CLS height constraint lowers the amplitude of the output vertical deflection grids with respect to gridding done when there are no height constraints. Table 1 shows some amplitudes of the east component of vertical deflection in microradian at selected points. This evaluation illustrates the trade-off between fitting the original slope data and fitting the new height data. When the height data are used with their original 1-sigma uncertainty, the gridded slopes are significantly smaller than the slopes when no height data are used. When the height data are used with the 2Xsigma uncertainties then the slopes have a better match to the unconstrained slopes. When the height data are used with the 100Xsigma uncertainties then the slopes match the original slope grids exactly.

The height differences between the new MSS_CLS_updated and the old MSS_CLS are shown in Figure 6 for the 2X height uncertainties. As expected the differences are small along the repeat tracks of the CLS model.

Table 1. East component of deflection of the vertical in microradian at selected points for various multiples of uncertainty for the CLS height data.

x	y	slope data only	1σ heights	2σ heights	100σ*
54	362	15.78	15.78	15.78	15.78
77	1106	14.53	5.78	8.91	14.53
309	2426	12.03	6.40	7.65	12.03
537	4281	15.78	12.65	13.90	15.78
193	5465	14.53	12.65	13.90	14.53

* Note that 100 σ provides a very blocky and poor fit to the height data while there is a prefect fit to the slope data.

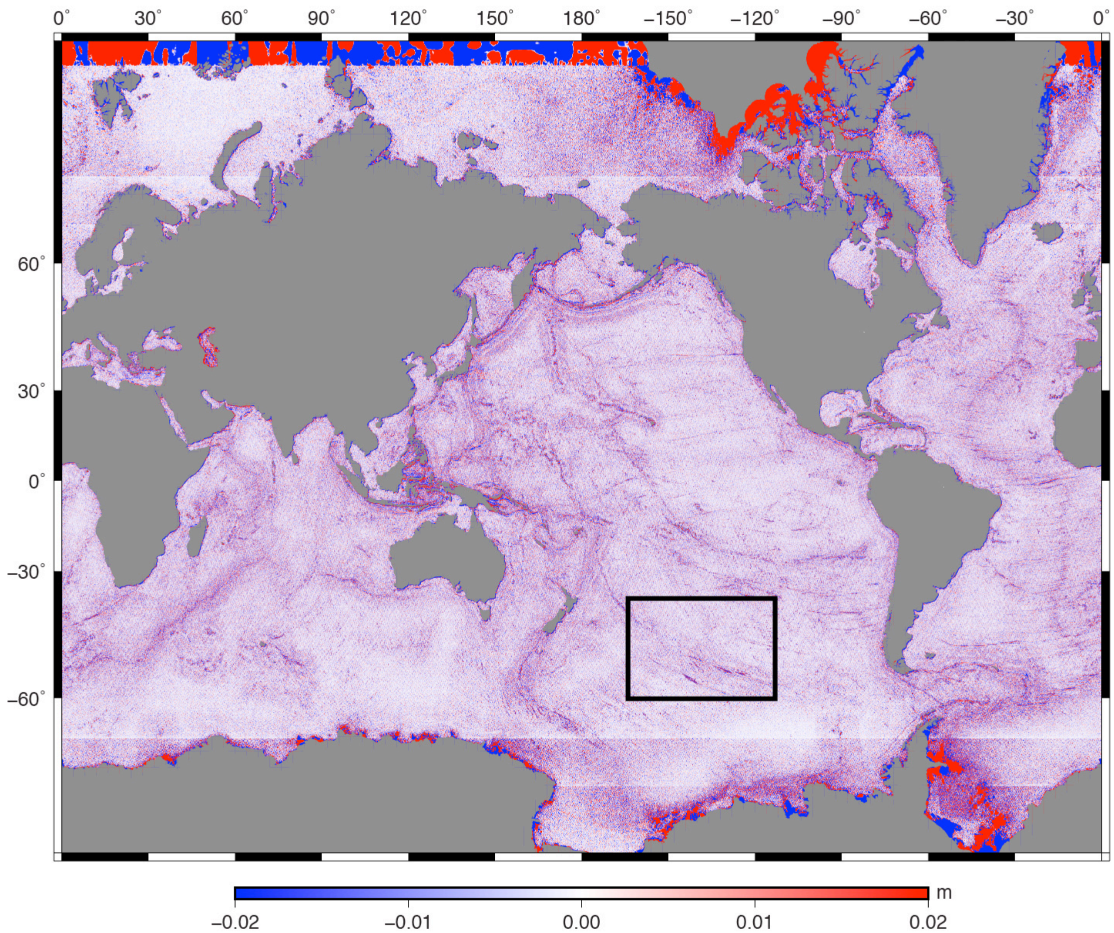

Figure 6. The difference between the new MSS_CLS_updated grid and the original MSS_CLS grid. The box is there area where misfit were evaluated.

We computed the mean standard deviation for the difference between the new MSS_SIO and the MSS_CLS grid for a large area of the South Pacific (-R190/240/-60/-35, box in Figure 6) for a number of cases (Table 2). When the original 1Xsigma was used on the height data for the gridding, the mean and standard deviation are small. As expected, these increase by about 2 times when the 2Xsigma was used on the height data. We decomposed the difference into a high-pass filtered grid and a low pass filtered grid using a Gaussian filter with a 0.5 gain at 60 km. As expected most of the mean difference goes into the low pass and most of the standard deviation is in the high-pass.

Table 2 Statistics on the difference between the updated MSS and the CLS MSS for South Pacific area (-R190/240/-60/-35)

description	mean (mm)	std (mm)
1X sigma on height data	-1.0	5.0
2X sigma on height data	-2.0	8.9
2X sigma, high-pass (60 km)	.003	8.3
2X sigma, low-pass (60 km	-2.0	1.78

As a final analysis we show the difference grid (MSS_CLS_updated – MSS_CLS) for an area around the Aleutian trench (Figure 7). The high-pass difference grid absorbs the small scale differences including the sharp signatures of seamounts (Figure 7a). There are also large differences in coastal areas where the CLS grid does not have valid data. The low-pass filtered grid (Figure 7b) also has some seamount structures but note the scale change from +/-40 to +/-10 mm. Also note that the low-passed version has a sign reversal. The low-pass filtered difference has two red bands parallel to the Aleutian trench. They are located in areas of steep geoid gradient where a slope correction [*Sandwell and Smith,* 2014] was applied to the SIO along-track slope data. No correction was applied to the altimeter height data going into the MSS_CLS grid. The 2X down weighting of the height data relative to the slope data caused the NEW MSS_SIO grid to contain this correction. A plot of the slope correction is provided in Figure 7c for comparison.

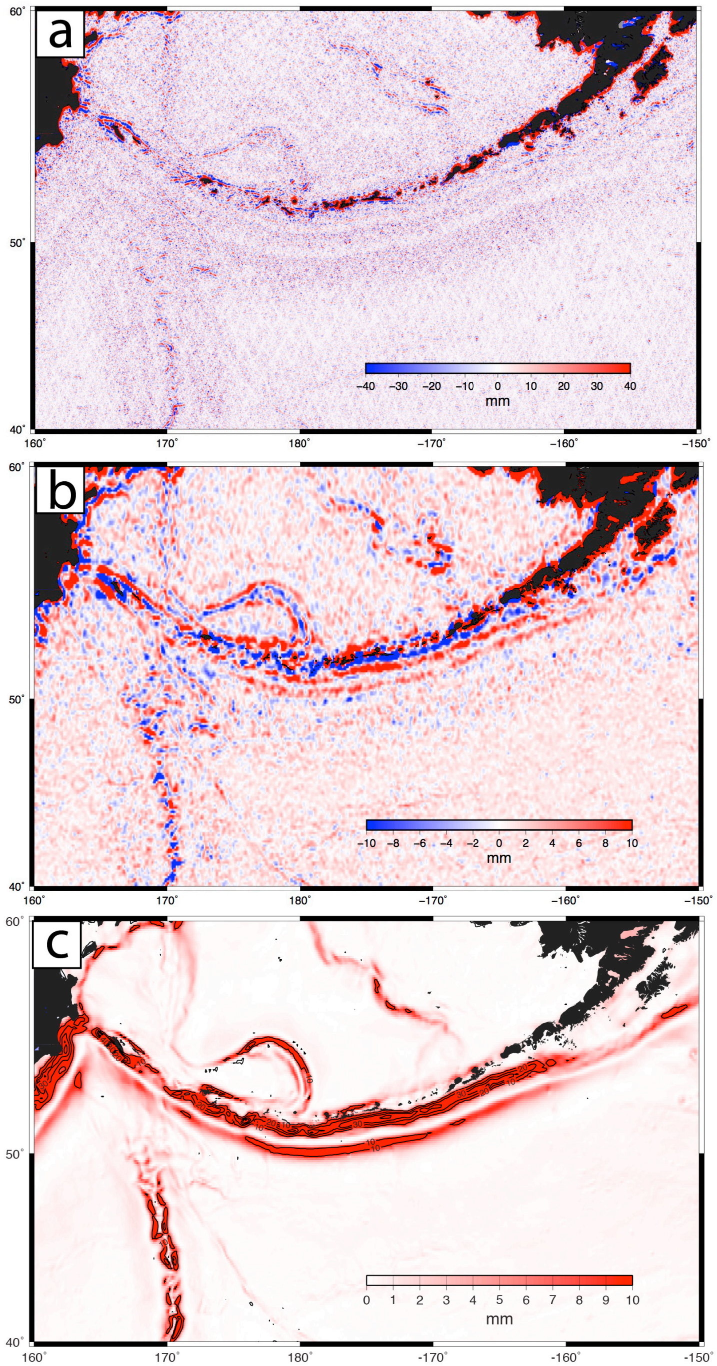

Figure 7. Height difference between new MSS_CLS_updated and old MSS_CLS for the Aleutian trench area where map (a) is high-pass filtered (60 km wavelength) and (b) is low-pass filtered and sign reversed. (c) Height correction needed to be applied to radar altimetry data (1000 km altitude) caused by the off-nadir reflection point in areas of large geoid slope.

Conclusions

We have used the along-track slope data from multiple satellites to tune the CLS MSS model. The approach uses a biharmonic spline in tension [*Wessel and Bercovici*, 1998] to combine the S&S slope data with the CLS height data. The updated grid has small differences from the original grid with a mean difference of -2.0 mm and standard deviation of 8.9 mm. We deliver this new MSS grid back to CLS for testing and evaluation in the original CLS format.

grdmath mss_egm.grd d_mss_sig2.grd ADD = **mss_cls_updated.grd**

References

Pavlis, Nikolaos K., Simon A. Holmes, Steve C. Kenyon, and John K. Factor. "The development and evaluation of the Earth Gravitational Model 2008 (EGM2008)." *Journal of Geophysical Research: Solid Earth 117*, no. B4 (2012).

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