

Consolidating Sea Level Change from Altimetry with GRACE and Argo

Bachelor's Thesis

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Abstract

A near-global spatial trend analysis is performed for the period 1992-2016. The analysis is based on altimetry data from both NASA and ESA satellites. The analysis indicated a good consistency between the two agencies data contributions. The total sea level variations were investigated in the period April 2002-November 2014 for the area between 60°S and 70°N. The contributions to the total sea level rise on $2,6 \pm 0,0$ mm/yr is investigated. There is two contributions: the thermal expansion were estimated from the Argo floats project, the mass variations were estimated from the GRACE projects. The analysis resulted in spatial analysis for the total sea level, the steric heights and the mass-induced heights. And time series for global and regional areas. The findings in this study shows that the sea level budget can be closed globally from the time series based on altimetry, GRACE and Argo data. For the regional areas it was only closed for the Antarctic Oceans. The other regions is influenced by among other things El Niño/La Niña and the Antarctic Oscillation, hence the fluctuations are too big, to close the sea level budget for these areas.

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1 Introduction

During the last decades and on even longer time scales the climate has changed. The climate changes influence all the different geophysical parameters on Earth. One of the most discussed changes is the global temperature and as a cause of that the changes in the global sea level. The global sea level variations (SLVs) is a direct measure of the climate changes there is happening. Rising seas will influence the life of millions of people living near the coast. To prepare ourselves there is a need to know more about the changes.

Since the first altimetry satellites were send up in the beginning of the 1970s it has been possible to monitor the sea surface height (SSH). But not until the introduction of TOPEX/Poseidon and ERS-1 in the 1990s where the measurements precise enough to begin the study of the SLVs. According to the IPCC fifth assessment report the global mean sea level rise (GMSL) during 1992-2010 was $3,2 \pm 0,4$ mm/yr including GIA (Church et al., 2013). This result is based on the measurements from altimetry satellites and is a clear indication of a global rise. From altimetry the total sea level height is determined. The GMSL rise is a result of two main contributions to the changing sea level.

The changes in the SSH is the result of mostly two processes taking place. The first contribution is the thermal expansion which occurs when there is a change in the total heat content and salinity in the sea water. These changes is called the steric height variations.

The second major contribution is the change in mass, which occurs in the exchange of water masses between the ocean and other water reservoirs. This change in sea level is called mass-induced height.

With these two contributions known the total budget of sea level variations can be determined. The sea level budget is expressed as

$$SLV_{total} = SLV_{steric} + SLV_{mass} \quad (1)$$

Since the development of precise measures of the SSH and the steric and mass components a number of studies have investigated the sea level budget and tried to close it. A study by Feng and Zhong (2015) investigated the sea level budget in 2005-2014 and found that the budget can be closed inside the uncertainties. Another study by Leuliette and Miller (2009) closed the sea level budget in the period January 2004 to December 2007.

This project will expand previous investigations of the spatial trends. The spatial analysis will be expanded to a near-global coverage, resulting in global trend maps. Furthermore the sea level budget will be investigated to see if the budget can be closed in the period April 2002-November 2014. In the end the regional mean sea level variations will be determined to investigate the regional sea level budgets.

The project consist of two parts; the first part is the global spatial analysis of the sea level anomalies, steric heights and the mass-induced heights. The second part is the sea level budget, where the monthly contributions from the mass-induced and steric heights is determined and compared to the overall sea level change. The sea level budget consist of the time series for the three observations and the determination of the trends.

As the last thing in the second part the sea level change and the contributions to it is investigated for the four regional areas: The Atlantic Ocean, The Pacific Ocean, The Indian Ocean and everything south of 30°S. The last analysis is made to compare the changes regionally with the global changes. The sea level budget is investigated on regional scale as well. The definition of the four areas in this project can be seen on the map in Figure 1.

These analysis will include corrected altimetry observations from a number of different satellites to determine the total sea level height. To determine the mass-induced height, the GRACE satellites ocean height variation datasets is included. The Argo array project provides salinity and temperature measurements from the upper ocean and is used to determine the steric heights.

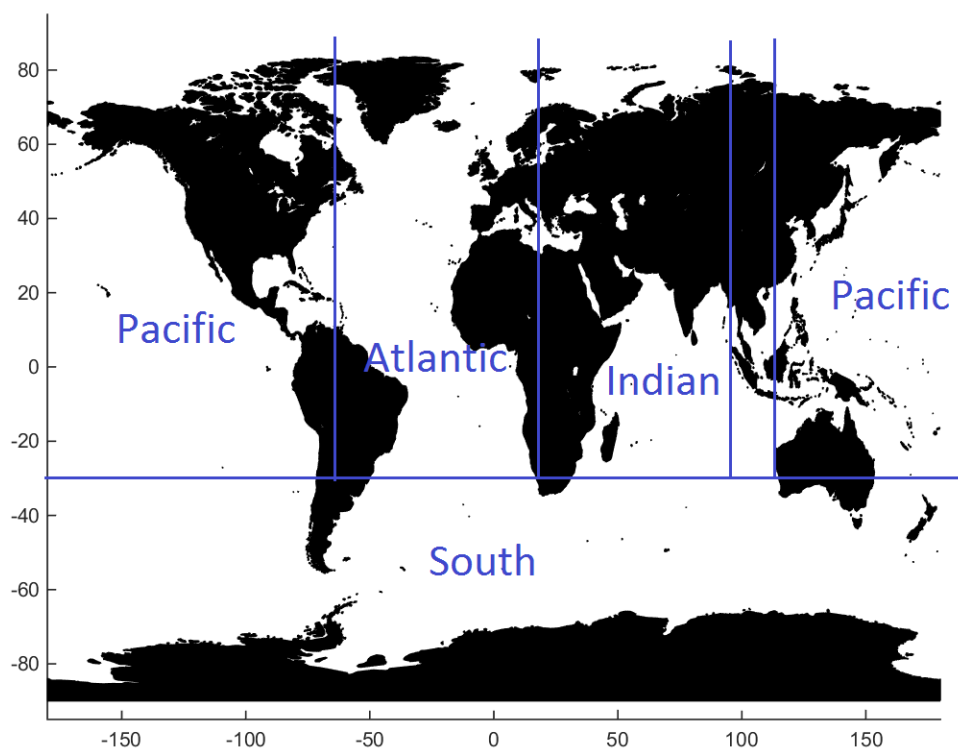


Figure 1: World map and the four regions to be investigated.

2 Background

This section goes through radar altimeter theory at first. The corrections applied to the altimetry satellite measurements to obtain a sea level anomaly with high precision is mentioned briefly. The theory behind gravimetry satellites and profiling floats used to determine the the mass-induced height and steric height is explained. The missions used in this project is gone through with a description of how the measures is performed. At last the calculation of steric heights based on temperature, pressure and salinity is presented as is methods for smoothing annual signals.

2.1 SSH from radar altimeter theory

A radar altimeter measures the altitude between a satellite or aircraft and a surface. The surface can be the sea, ice or land. To determine the global SSH the altimetry satellites is employed, since they provide a global coverage and high precision measurements.

An altimeter transmits a radar pulse towards the sea surface, where it interacts with the surface. The pulse scatters and part of it is send back to the satellite, where the elapsed time is measured. Pulses are transmitted with a few seconds interval. A pulse travels by the speed of light and with this knowledge the distance from satellite to the surface can be determined by the following equation.

$$h_{obs} = \frac{1}{2}ct \quad (2)$$

Here h_{obs} is the observed height to a reference point. t is the time it takes the pulse to travel forth and back from the sea surface. The reference point is defined by an ellipsoid, which is a mathematical defined surface approximating the shape of the Earth surface. The distance between the satellite and the reference ellipsoid is measured by a GPS on board of the satellite. With known distance to the reference ellipsoid and the sea surface it is possible to determine the SSH.

This method for measuring the SSH is introducing some errors for which there should be corrected. In Figure 2 is an illustration of the altimeter measurements and the corrections. The corrections used in the project is introduced in Section 2.2.

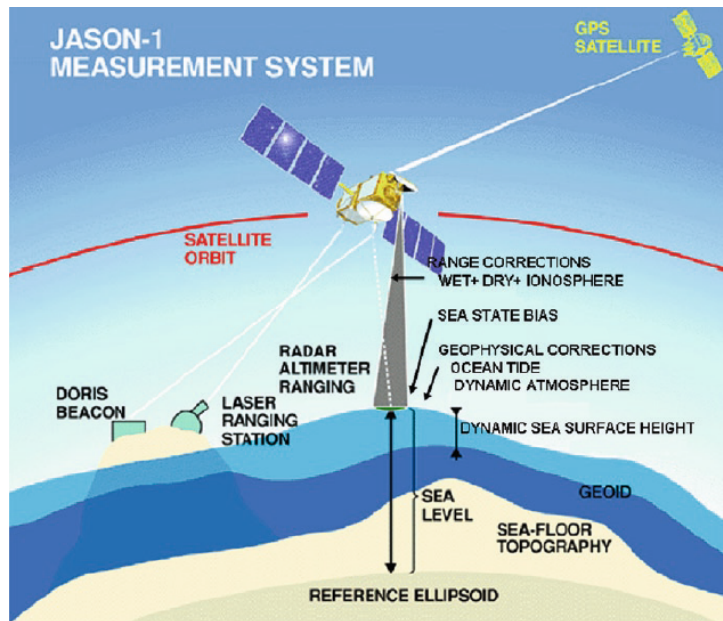


Figure 2: Illustration of altimeter measurements and the corrections applied. The measure of interest is the gray line, which is the distance between the reference ellipsoid and the sea surface. From the sea level and mean sea surface height the sea level anomaly can be determined. (Andersen and Scharroo, 2011, p. 106).

2.2 Corrections

2.2.1 Altimeter Corrections

The errors in the measured sea level is caused by the radar pulses travel through the atmosphere and the use of equipment. There is errors connected with the wind on and currents in the sea which also interferes with the measurements. The corrections for this can be separated into three categories: atmospheric corrections, geophysical corrections and instrumental corrections.

The atmospheric corrections handles the delay in the radar pulses travel time through the atmosphere which leads to three corrections: *the dry tropospheric correction*, *the wet tropospheric correction*, and *the ionospheric correction*. The geophysical corrections accounts for the *inverse barometer correction* and *tide correction*. And the instrumental corrections is for the *sea state bias*.

When studying sea surface variations, it is convenient to use the sea level anomalies, h_{sla} . The anomaly is found by referring the SSH to the mean sea surface height (MSSH). Hence the equation with corrections to find the sea level anomalies is given as

$$h_{sla} = H - h_{obs} - \Delta h_{dry} - \Delta h_{wet} - \Delta h_{iono} - \Delta h_{ssb} - h_{tides} - h_{atm} - h_{MSS} \quad (3)$$

The expression is derived by Andersen and Scharroo (2011, p. 109). When using the sea level anomaly all the data is referring to the MSSH. With the same reference it is easier to work with and compare the data from different altimetry satellites. The corrections is applied in the RADS database, the exact model used in the database will not be mentioned further, but can be found in the RADS manual (Scharroo, 2012).

2.2.2 Reference frame offset

The last correction needed to be able to join the different satellite missions is the *reference frame offset*. When working with joint multi-mission satellites it is important to make sure that the various altimeters is using the same reference frame. Therefore it is necessary to correct for *reference frame offset*. The correction includes the offsets from the reference frame, differences in orbit and in the altimeter-dependent correction models. When corrected, the multi-missions altimeter measurements can be joint since they are in the same reference frame.

In the RADS database TOPEX/Poseidon is used as the reference frame. It could for instance have been a different satellite, as long as the reference frame is the same for all the satellite missions to be joint.

The altimeter corrections and the *reference frame offset* is one of the default settings in the RADS database, Section 3.1. The corrections mentioned are all described in detail in Andersen and Scharroo (2011).

2.2.3 Glacial isostatic adjustment

Another important correction is the glacial isostatic adjustment (GIA). GIA is a constant estimated to be $-0,3$ mm/yr by Peltier and Luthcke (2009). This correction is necessary since the ocean basins is getting slightly bigger, hence the sea level is decreasing a bit. To apply the correction it has to be subtracted from the global trend determined based on of the altimetric measurements. When subtracted the trend will be $0,3$ mm/yr bigger. The data in the RADS database, Section 3.1, is not corrected for GIA.

The gravity measurements from GRACE measures the GIA as well. The GRACE measurements is corrected, but not for GIA. This means that the signal from GIA in the mass-induced heights is still there.

2.3 Altimetry satellites

The two space organizations National Aeronautics and Space Administration (NASA) and Centre National d'études spatiales (CNES) is working on joint altimetry satellite missions. Three of their joint missions is the Topex/POSEIDON (T/P), Jason-1 (J1) and Jason-2 (J2) which continuously have provided altimetry data since 1992 and is still in function. The follow-on mission Jason-3 (J3) was launched in January 2016 to continue the measures from the previous missions.

All the joint missions shares the same initial orbit, the initial orbits is listed in Tabel 1. When a new mission is launched, the old satellite is manoeuvred to another orbit, still performing the same measurements. The NASA/CNES missions only provide data in the area between 66°S and 66°N .

Table 1: The initial orbit data for the satellite missions T/P, J1, J2, ERS-1, ERS-2, EnviSat, CryoSat-2 and GRACE. (Podaac and NASA, 2016d,b,c,a; ESA, 2016c,b,a)

	T/P, J1 and J2	ERS-1, ERS-2 and Envisat	CryoSat-2	GRACE
Inclination	66°	98.5°	92°	89°
Reference altitude	1,336 km	800 km	717 km	456 km
Repeat period	9,9 days	35 days	369 days	App. 30 days
Passes in a cycle	254	1002	.	.

The European Space Agency (ESA) has their own altimetry satellites for geophysical investigations. Their first satellite was ERS-1 launched in 1991 followed by ERS-2, Envisat and Cryosat-2. These satellites provides continuously data from 1991 an up till today.

ERS-1, ERS-2 and Envisat is covering the same grid, whereas CryoSat-2 has its own orbits, details listed in Table 1. Different from the NASA/CNES missions, the ESA missions is covering the Earth globally. The global coverage is to cover the Arctic and Antarctic ice sheets, which is part of ESAs area of interest. Some caution should be taken when using the sea level anomalies near the ice sheets, in these areas there can be sea ice which causes errors.

2.4 Satellite gravimetry

The GRACE twin satellites is measuring the Earth’s gravity field and investigates the water reservoirs over ice, land and oceans. It is a joint mission between NASA and Deutsches Zentrum für Luft- und Raumfahrt (DLR). GRACEs orbit is not repeated, but it covers the Earth in about a month. The orbit data for GRACE is listed in Table 1. GRACE was launched in 2002 and is still in function.

GRACE consist of two satellites, separated by around 220 km. The gravity field measurements is performed by relating the distance between the two satellites. When there is an increase in the gravity field the first satellite will speed up and the distance between them will increase. When the increased gravity field is between the two satellites the distance between them will decrease. Similar when the gravity field ahead is decreasing the distance between the pair will decrease, and when in between the distance will increase. These changes can be measured down to a micrometer per second in the relative velocity. And from these measurements it is possible to make detailed analysis of the gravity field and thereby changes in the global mass distribution.

From the gravity field the mass-induced sea level height can be determined.

2.5 Argo floats

The Argo array project consist of almost 4000 profiling floats globally. The deployments of the Argo profiling floats began in 2000 and is still expanding. The floats are free drifting and measures the salinity and temperature for the upper 2000 m of the sea. The purpose with the Argo project is to monitor the temperature, salinity and the ocean velocities continuously. The goal is to get a global coverage with a high spatial solution, but at this moment the project only covers the area between 60°S and 70°N with a good resolution (University of California, 2016). The global gridded datasets from the first years of the Argo project should be used with some caution, since the number of floats were limited and therefore the resolution is low.

Figure 3 is an illustration of how a profiling float works. The floats is working in a 10-day interval. The floats sink down to 1000 m, where the float drifts to measure the ocean velocities. After this it sinks down to 2000 m, where the floats start to measure the salinity and temperature on the way up. When they reach the surface, they communicate all the analysis to a satellite together with their position. From these data it is possible to determine the upper-ocean velocity, since the start and end position for the 10-days period is known. From the temperature and salinity profiles it is possible to determine the thermal expansion of the sea water. The thermal expansion is one of the two main contributors to the rising sea level, which is called the steric height as well. In the next section the calculation of the steric height is introduced.

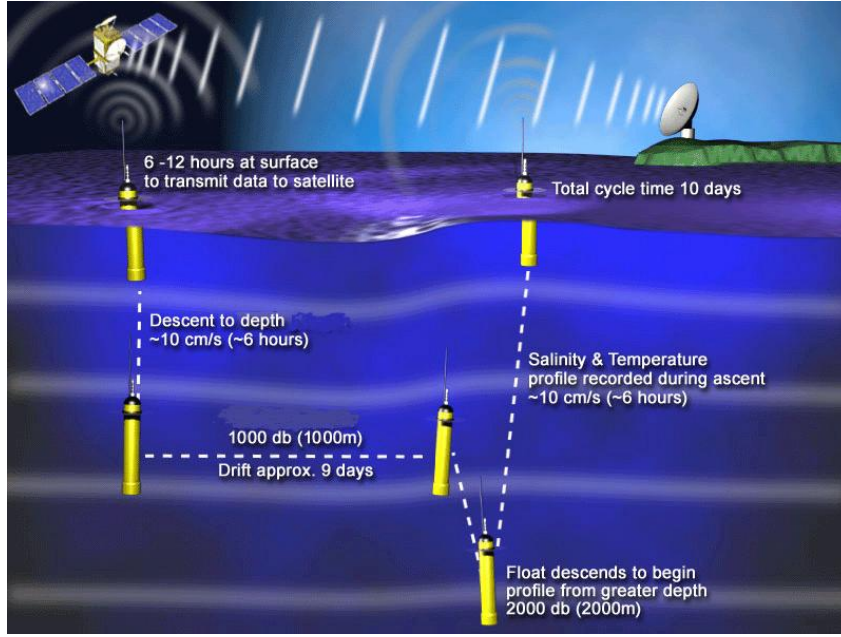


Figure 3: The data collecting cycle for floats in the Argo array project. (University of California, 2016).

2.6 Steric height

The Argo floats data array consist of temperature and salinity measurements for different pressure levels down to 2000 dbar. The steric height is expressed by which amount the water column between two points expands, if the temperature and salinity changes from the standard values. The standard values is $T_0 = 0^\circ \text{C}$ and $S_0 = 35,0 \text{ psu}$ (practical salinity unit). The calculation is made relative to a reference level, where the reference level is at a depth where there is no motion and the pressure is assumed to be constant. The reference level here is 2000 dbar since the Argo floats measures this far down and it is a level of approximately no motion.

The formula for the steric height is derived from the hydrostatic equilibrium equation and can be expressed as

$$SH(z_1, z_2) = \frac{1}{g} \int_{z_1}^{z_2} \frac{\Delta\rho(T, S, p)}{\rho_0(T_0, S_0, p)} dz \quad (4)$$

Where ρ_0 is the reference density, ρ is the actual density and $\Delta\rho = \rho - \rho_0$. g is the gravitational acceleration. z_1 and z_2 is the depths in which between the water column is analysed.

2.7 Weighted mean

For spatial global means it is more accurate to determine the weighted mean. In the analysis following later in the project the Earth is divided into squares of $1^\circ \times 1^\circ$ or $5^\circ \times 2^\circ$. The actual area covered by the squares, will depend on the latitude, the further north and south the smaller an area. Therefore when calculating the GMSL rates an error will occur, if all squares are weighted equal. Therefore it is necessary to calculate the weighted mean instead, so that each square is weighted depending on their north-south position. The following equation express how the weighted mean, \bar{h} , is calculated

$$\bar{h} = \frac{\sum h \cos\left(\frac{\pi}{180} \cdot lat\right)}{\sum \cos\left(\frac{\pi}{180} \cdot lat\right)} \quad (5)$$

2.8 Annual signals

In the time series for the different observations, different annual signals will occur. The signals originate from the delayed reactions on a change in the global and local temperatures. The hydrologic cycle on Figure 4 illustrates the transport of water on Earth. When the temperature rises, the snow will melt on land and this will run out in the oceans. The way from the glaciers to the ocean is long. Hence the mass change in the sea will be delayed from the temperature change. The sea will only rise if the amount of water running into the oceans is bigger than the amount that evaporates.

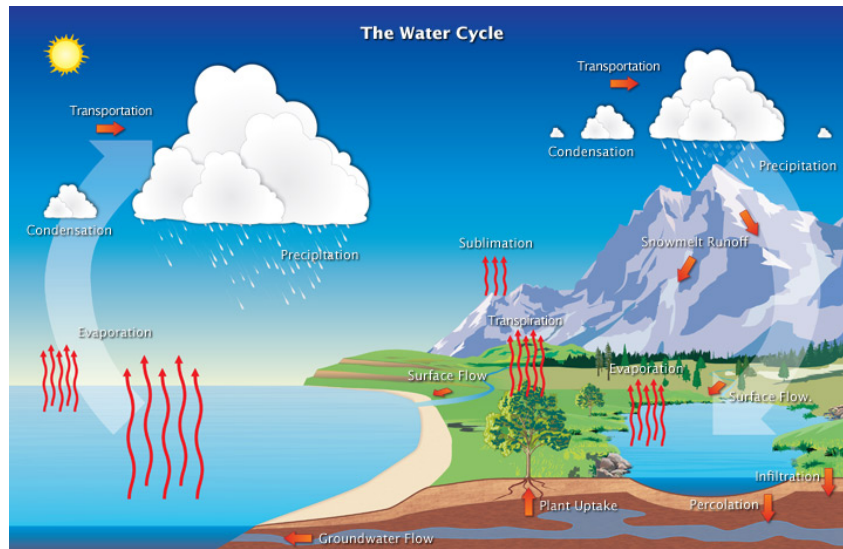


Figure 4: The Earth's water cycle. The figure can be used to explain why seasonal signals occurs. (NASA, 2016a)

Furthermore the steric sea level variations is delayed from the actual change in temperature. It takes some time for the water to warm up, specially when it is down in the deeper layers of the ocean causing another annual signal.

The annual signals have to be smoothed to make it possible to compare the steric height and the mass-induced height with the total sea level. There are various methods for smoothing annual signals. Two of them will be mentioned here.

The first method is a moving average. The moving average takes the average of the first numbers in the sample, then moves one number up, leaving the first behind, to make a new average. When the annual signal is removed over a year, the average should be taken in steps of 13, since the number of months is 12. In matlab this is done by using the function `smooth`. Since the average should be of 13 numbers, the command would be: `smooth(sample,13)`.

The second method is to do a least squares fit to a trigonometric function.

3 Data

This project is based on data from different observations: altimetry satellites, gravimetry satellites and profiling floats. In this section the data is described, hence where is the data available and substracted from and which time periods and areas are the data covering.

To get a long time series of data, the data from T/P, J1 and J2 is selected for the global analysis for the first part. Furthermore the data from ERS-1, ERS-2, Envisat and Cryosat is selected to cover the lower and higher latitudes, where the other missions does not cover. The spatial analysis is performed for the steric height and mass-induced height as well, extracted from the Argo floats project and the GRACE mission.

For the second part where the sea level budget is analysed the total SLVs is only determined from J1 and J2. In this part GRACE and Argo is used as well for the time series and to evaluate the sea level budget.

3.1 RADS

The Radar Altimeter Database System (RADS) contains the data for all altimetry satellites described in Section 2.3. The RADS database is developed at Delft University of Technology and now at the National Oceanic and Atmospheric Administration (NOAA) (Scharro et al., 2013). RADS is a database containing complete datasets from eleven altimetry satellites. The database is continuously updated for working satellite missions.

With the RADS database it is possibly to access corrected altimetry data, where the corrections applied is the ones mentioned in Section 2.2, which is the default settings in RADS (Scharro, 2012). Downloading a RADS datafile it contains the columns *track id*, *latitude*, *longitude*, *sea level anomaly*, *time*.

In Table 2 the used altimetry data time periods for the project is presented for the two parts. The T/P, J1 and J2 data periods is chosen for the spatial part so they do not exceed.

From E1, E2, N1 and C2 all the data possible is used. These data will be used to cover the Arctic and Antarctic areas between 64°S and 64°N. In these areas it is more difficult to perform radar altimetry measurements because of the sea ice. Therefore we use all the data available, even though some of the datasets covers the same periods. Specially here it is important that the data is corrected for the reference frame offset, so the data can be joint.

Table 2: Table of the different altimetry satellites and for which periods their data is used in the two parts. For CryoSat-2 the cycles is not repeated as for the other satellites, therefore its cycles is not included. Dates are in dd-mm-yyyy.

Part 1	Date started	Date ended	Cycles
TOPEX/Poseidon	01-01-1993	04-02-2002	11:345
Jason-1	05-02-2002	12-07-2008	3:239
Jason-2	04-07-2008	08-01-2016	1:276
Part 2			
Jason-1	04-04-2002	26-01-2009	9:425
Jason-2	04-07-2008	08-11-14	1:233
Both parts			
ERS-1	01-08-1991	02-06-1996	1:156
ERS-2	29-04-1995	04-07-2011	0:169
Envisat	14-05-2002	22-10-2010	6:94
CryoSat-2	14-07-2010	17-03-2016	-

3.2 GRACE

The gravimetry data is provided as monthly gridded data with grid size $0,5^\circ \times 0,5^\circ$. The gravimetry data is global, which means that the measurements covering the land is included as well. The GRACE mass concentration (mascon) solution dataset used for the project is obtained at Wiese et al. (2015). In Watkins et al. (2015) the dataset and the methods used to make it is described in detail. The dataset covers the Earth globally in the period spanning from April 2002 to November 2014. Since this period with data is the most narrow, it defines the period for which the sea level budget is investigated and the different observations is compared.

3.3 ARGO

Argo floats data is provided in various forms. It is possible to obtain the original Argo data, as well as some Universities or Institutes provides different Argo products. In this project the used Argo data is from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). JAMSTEC provides a monthly gridded dataset for temperature and salinity. The dataset is called MOAA GPV and is further described in Hosoda et al. (2008) and collected at JAMSTEC (2016).

The dataset is provided as one file for each month, starting January 2001 and up to February 2016. The monthly files consists of the gridded temperature and salinity data ($1^\circ \times 1^\circ$) for 25 different pressure levels down to 2000 km (2000 dbar).

The monthly gridded data is used since it is consistent with the gravimetry data, which makes it possible to compare the different contributions. Therefore the time period used for the Argo floats is spanning from April 2002 to November 2014 as well.

The MOAA GPV dataset covers from 60°S to 70°N which is the area chosen for this projects analysis. The northern hemisphere is covered by a larger number of floats, which is the why the analysis is performed to a higher degree.

4 Methods

This section goes through all the methods used in the data processing. The different data is provided in different solutions and time periods. For the first part the spatial analysis is done individually for each data source. For the total sea level a spatial analysis is made for the period 1992-2016 and April 2002-November 2014. For the second part, time series are made for global and regional areas. For the analysis the data has to be in the same solution, etc. have to be in the same grid and time. The calculations is based on the data introduced in the previous section.

4.1 Spatial analysis

The spatial analysis for the period 1992-2016 based on the altimetry satellites data consist of two parts; first for the area between 64°S and 64°N and second for the areas north and south from this. The main part is covered by the NASA satellites, and the northern and southern parts is covered by the ESA satellites.

The NASA data is analysed using a script provided by Ole Baltazar Andersen. The script estimates the sea level anomaly for each track in a 1° x 1° resolution. The trend for each grid cell is determined as the slope coefficient in a linear fit. The result is a grid with the spatial trends.

The analysis north of 64°N and south of 64°S is made by using all the ESA data in 1992-2016. Here the sea level anomaly for each track is determined in a 5° x 2° grid. The trend for each grid cell is found by a linear regression in Matlab with the function polyfit for a first degree polynomial. The grid data is then interpolated to a 1° x 1° grid this way it is possible to join the two spatial analysis. They are then plotted on the same map. In Appendix A and B the script for the data processing and plotting is included.

The data processing for the total sea level height trend spatial plot in the period for April 2002-November 2014 only consists of J1 and J2. The methods are the same as before. The spatial trends inside a grid with size 1° x 1° is determined and plotted on a map.

The Argo data is provided in a 1° x 1° monthly grid. Each datafile contains values for the salinity and temperature down to 2000 dbar. From these files the steric height is determined using Matlab functions provided by Ole Baltazar Andersen, Appendix G. The result is a matrix containing the steric heights for each grid cell for each month. Script for the steric height determination is included in Appendix H. The GRACE data is in a 0,5° x 0,5° monthly grid. The global maps for the Argo and GRACE missions showing the steric height trends and mass-induced height trends is made by applying a linear fit for each point in the grid. The trend is the regression from the linear fit, which is the one to be plotted. The script for the data processing for the Argo dataset is included in Appendix I and for GRACE in Appendix E.

The uncertainties for the spatial plots is calculated inside a 95% confidence interval. The uncertainty is the standard deviation of the mean expressed as follows

$$\sigma_m = k \cdot \frac{\sigma}{\sqrt{N}} \quad (6)$$

where $k = 1,96$ for a 95% confidence interval. σ is the standard deviation of the sample and N is the number of samples.

4.2 Time series

For the time series the data has to be in the same resolution. Therefore the GRACE grid is changed to a 1° x 1° grid. The steric heights and mass-induced heights is in a 1° x 1° grid in the area 60°S, 70°N. For the time series analysis it is necessary that the data is in the same grid, and sorted by the same landmask. When comparing the datasets it is important, that the landmask used is the same for all types of data. The Argo dataset composes the narrowest landmask, why the altimetry data and GRACE data is sorted with it.

For the altimetry data to be in the same resolution as the other two datasets, the data from J1, J2 and ESA data is gridded to a grid with the size 1° x 1° and the monthly mean for each grid cell is determined. This is included in Appendix C.

The Argo landmask is applied to the altimetry and the mass-induced heights. The global monthly means is determined by the weighted mean method from Section 2.7. Seasonal variations will occur, which is removed with a smoothing of the data, Section 2.8 The time series for altimetry, steric height and mass-induced height is plotted together. The steric height + mass-induced height is plotted as well. There is produced five different time series plots: a global time series, for the Pacific Ocean, the Atlantic Ocean, the Indian Ocean and for the part below 30°S. At last the trends and uncertainties is determined with a linear least squares fit and the standard deviation of this. All the calculations done for altimetry, Argo and GRACE can be found in Appendix I, F and D.

The Argo data is not referred to a surface like the altimetry or GRACE data. The reference point for the Argo is determined as an arbitrary point. It makes no difference for the steric height trend if a constant value is subtracted from all the variations. The steric height variation reference is determined as $h_{steric,1} = h_{mass,1} - h_{total,1}$. This is the constant subtracted from each value, determined from the heights from GRACE and altimetry in the first month of the analysis. The time series plot commands can be found in Appendix J.

5 Results

The results from the data processing is presented in this section. First the spatial analysis is presented for the total sea level height in the period 1992-2016. The spatial analysis of the total sea level height, the steric height and the mass-induced height will be presented hereafter for the period of investigation, Apr. 2002-Nov. 2014. The GMSL rate from the different observations is listed in table. At last the global and regional time series is presented together with a table containing the trends and uncertainties.

5.1 Spatial analysis

5.1.1 GMSL rates from altimetry

Figure 5 is the near-global spatial analysis based on the altimetry data. To be able to verify the analysis with other studies, the GMSL rate is calculated for the area between 66°N and 66°S, this is the common area of investigation. All the spatial trends for different areas and periods is presented in Table 3. For the global analysis the GMSL rate is $3,2 \pm 0,1$ mm/yr.

The spatial analysis of the total sea level height have a good transition at the two lines 64°N and 64°S. This means there is a good consistency between the ESA and NASA satellites measurements. The blue areas at the north and south pole is where there is an ice cover, that seems to be melting.

The plot shows spatial variances ranging from beneath 10 mm/yr and up to 10 mm/yr. Most dominating is the positive trends. In the region around the mid-latitudes of the Indian Ocean and the West Pacific Ocean the trends are around three times as high as the global average trend. In the area around 120°W,60°S there is a significant drop in the sea level.

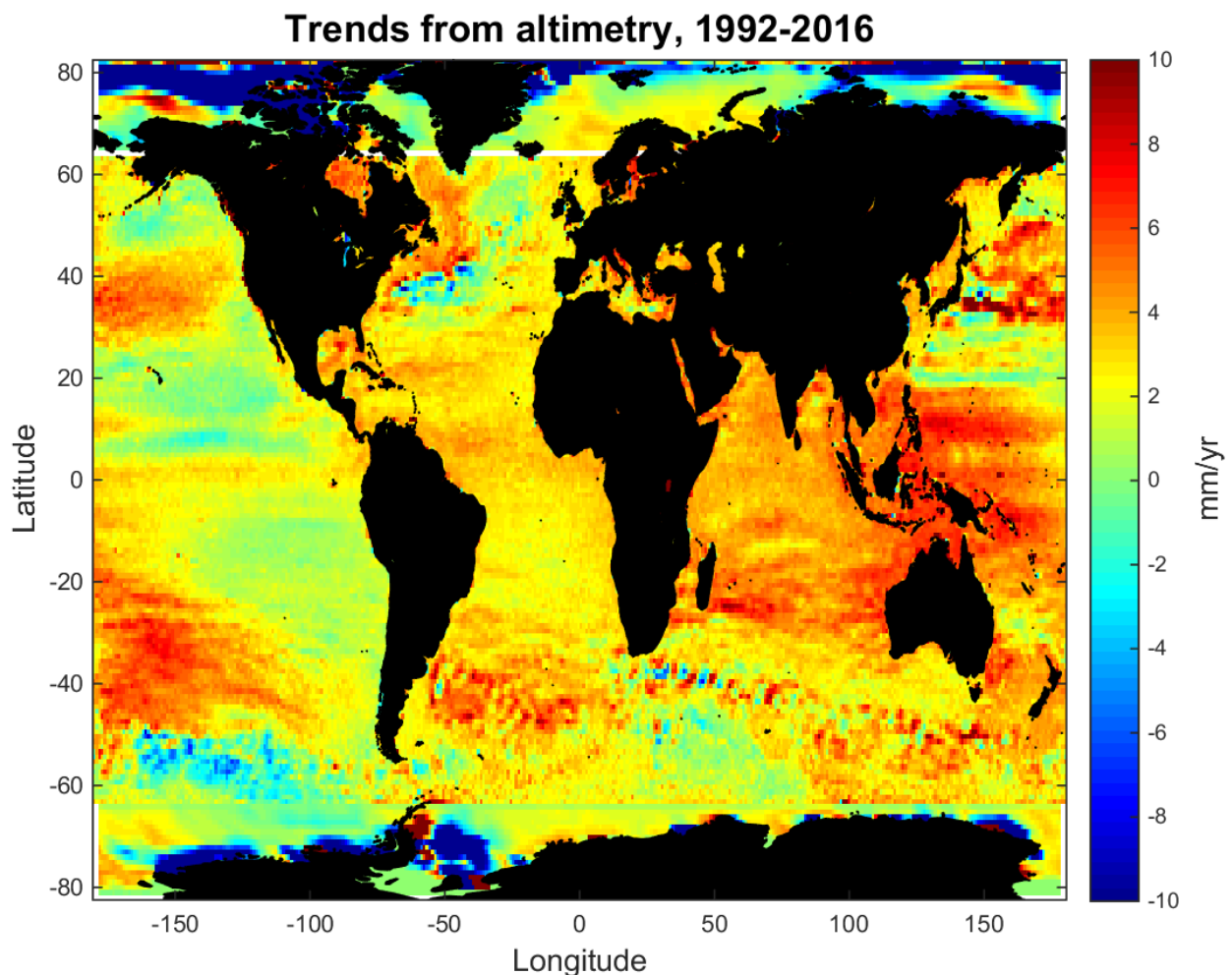


Figure 5: Global trend plot based on altimetry data. The data covering the area between 64°N and 64°S is the NASA data, the south and north areas is trends from the ESA data.

5.1.2 Total sea level height

The total sea level height is determined from Jason-1, Jason-2 and ESA-data in the period April 2002-November 2014. These data will be used for the spatial comparison with the two contributions and for the time series. The ESA-data has been included to cover the area above 64°N, but as it can be seen on Figure 6 there is no data in this area. The ESA-data coverage was not good enough to be gridded as a monthly grid at 1° x 1°.

As in the previous spatial result, the same tendencies can be observed from this analysis. In this period the trends in the mid-latitude area for the Indian Ocean and West Pacific are even more significant. The drop around 120°W,60°S has become more dominant as well. The GMSL rate for this period and area is $2,6 \pm 0,1$ mm/yr.

Overall the spatial variations from Figure 5 has become more significant in the narrowed time period for the analysis leading to Figure 6.

Total sea level height trends from altimetry, April 2002-November 2014

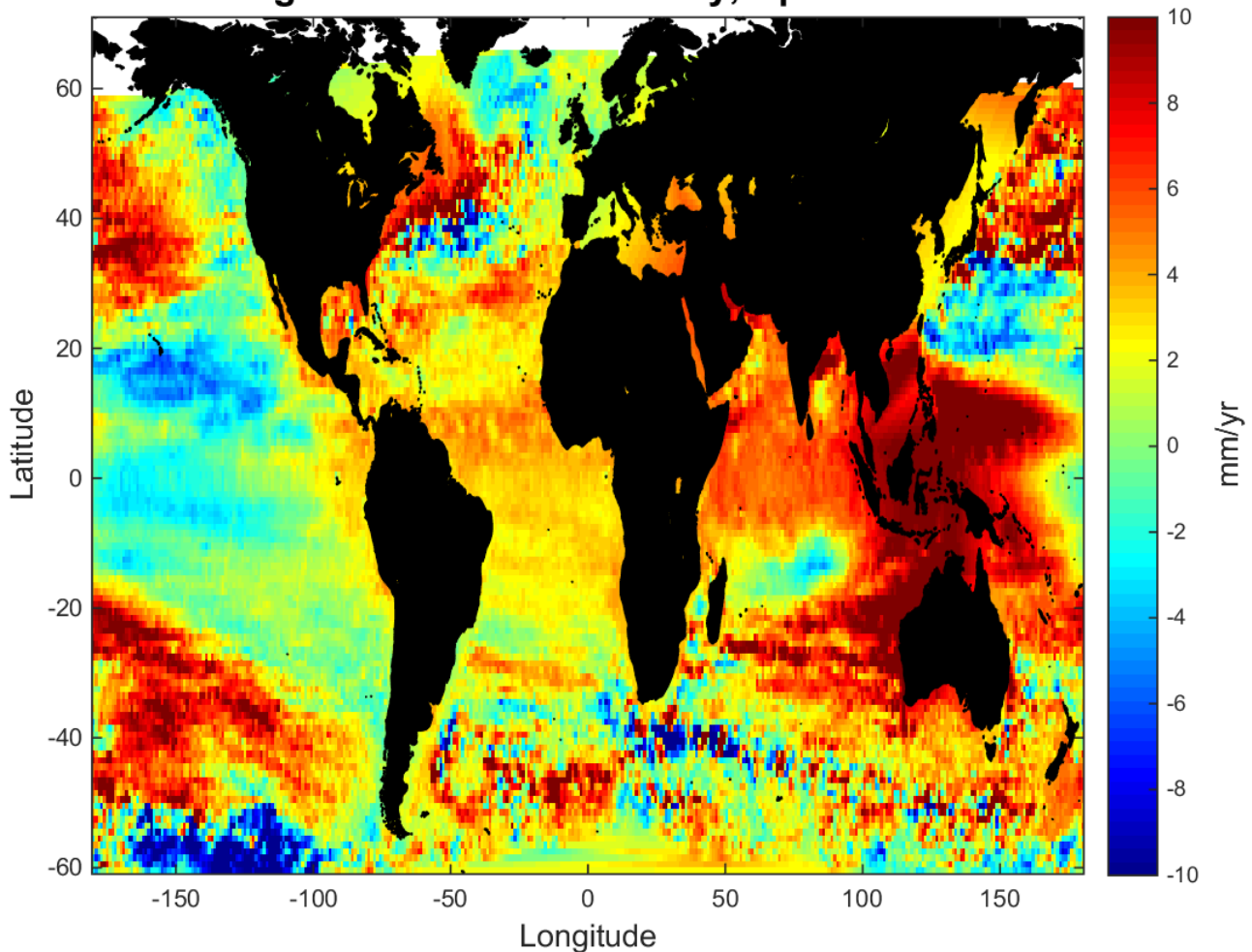


Figure 6: Trends based on data from altimetry. Notice that the area where the ESA data should cover is white, hence there is no data.

5.1.3 Mass-induced height

Figure 7 visualizes the spatial analysis of the GRACE data. The dataset, the analysis is based on, is interpolated to a grid with monthly values. Therefore the plot is so smooth, since the data has already been interpolated. For the comparison and time series it is only the part between 60°S and 70°N there will be used, furthermore the Argo mask will be applied.

For the mass-induced height the spatial variances is varying from 5 mm/yr and up to 8 mm/yr, in some areas the trends are even higher and lower than this. The GMSL rate from mass changes is $1,6 \pm 0,0$ mm/yr. For the area to be compared the trend is $1,2 \pm 0,0$ mm/yr, Table 3. This makes sense because there is a huge rise at the north pole which is avoided in the second trend.

The drop around 120°W,60°S is dominating here as well. As for the mid-latitude areas around the Indian Ocean and the West Pacific Ocean the trends are varying a lot. In the Indian Ocean there is a drop, wherein there is a rise. The difference in this area are up around 20 mm/yr.

North of Russia, around 60°E, 80°N, there is a huge drop, significantly bigger than the drops anywhere else.

Mass-induced height trends from GRACE, April 2002-November 2014

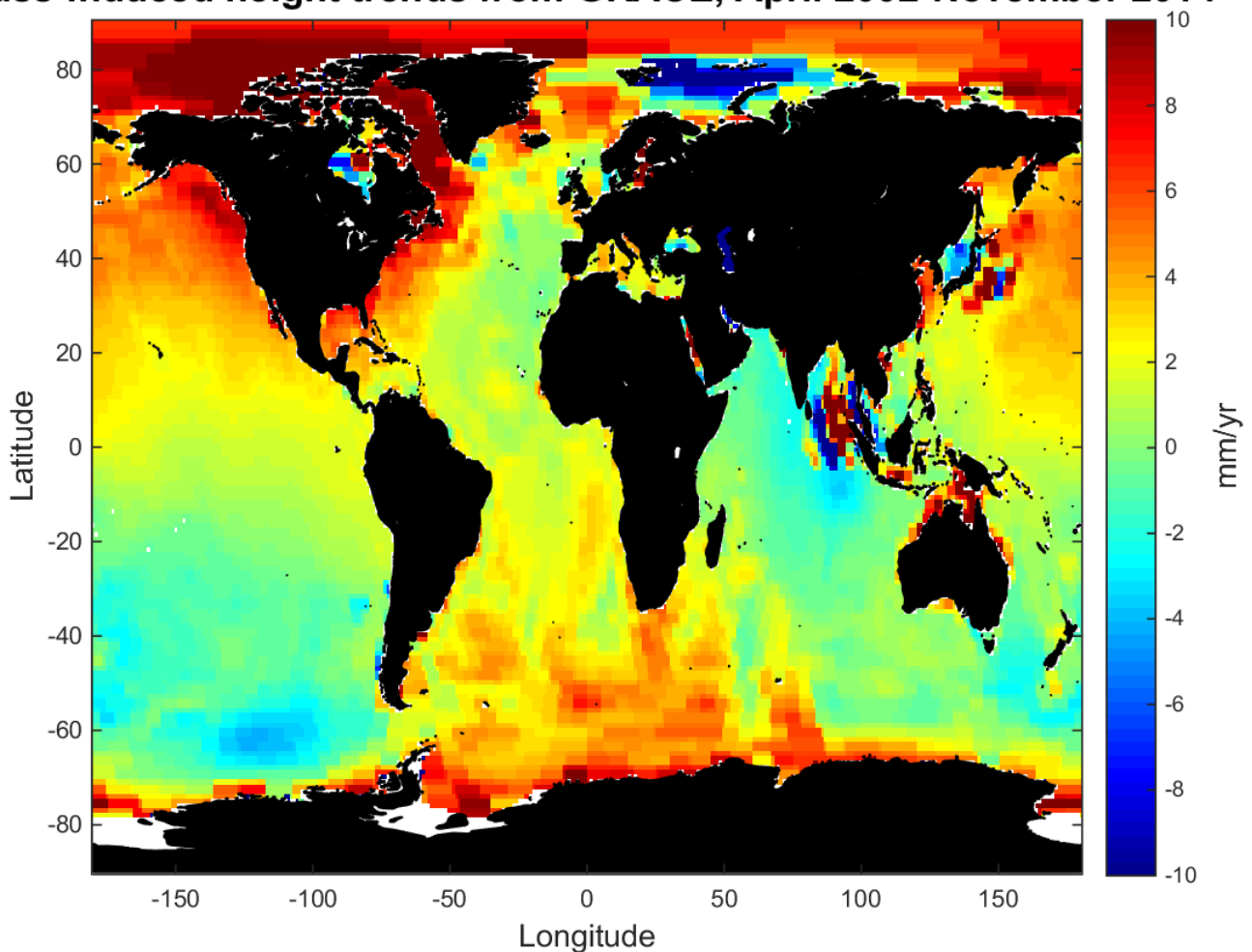


Figure 7: Spatial mass-induced sea level trends from the GRACE satellites.

5.1.4 Steric height

From the Argo floats a monthly gridded dataset has been used to make a spatial analysis. The resulting plot can be viewed in Figure 8. As with the spatial plot from GRACE, it is smoothed compared to the one based on the altimetry data. The entire dataset from Argo is used, since it has the smallest spatial coverage.

Data in the area between the mid-latitude Indian Ocean and West Pacific Ocean is not existing, the floats is not operating in this area. But still a rise in the West Pacific Ocean can be observed. In the Southern Ocean below 30°S there is almost an overall rise. The GMSL rate from the thermal expansion is $1,0 \pm 0,0$ mm/yr.

Steric height trends from ARGO April 2002-November 2014

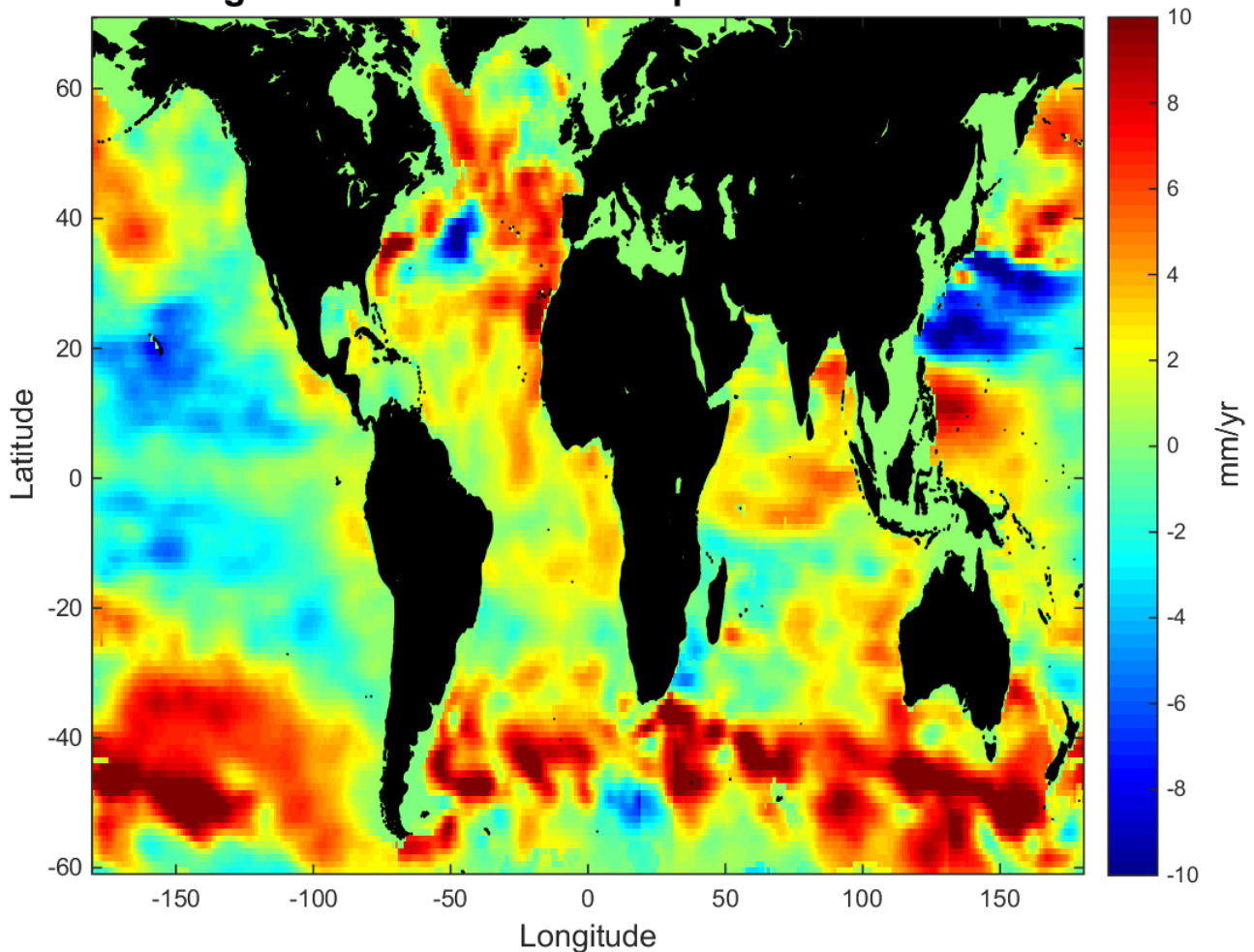


Figure 8: Steric spatial sea level height trends from ARGO floats

5.2 Compare spatial plots

The spatial plots is compared with each other in different variations. The comparisons can be seen on Figure 9. The goal was to find some coherence when consolidating the different changes and compare them. In Figure 9a the values was expected to be around zero, which is only happening in some areas. As for Figure 9b, c and d they were supposed to show approximately the same tendencies as the spatial plots presented in Figure 6, 7 and 8.

Generally for all the spatial plots the local trends are varying a lot. Even though the plots are compared the unique trends for each spatial analysis is dominating this comparison. A coherence is not easily seen.

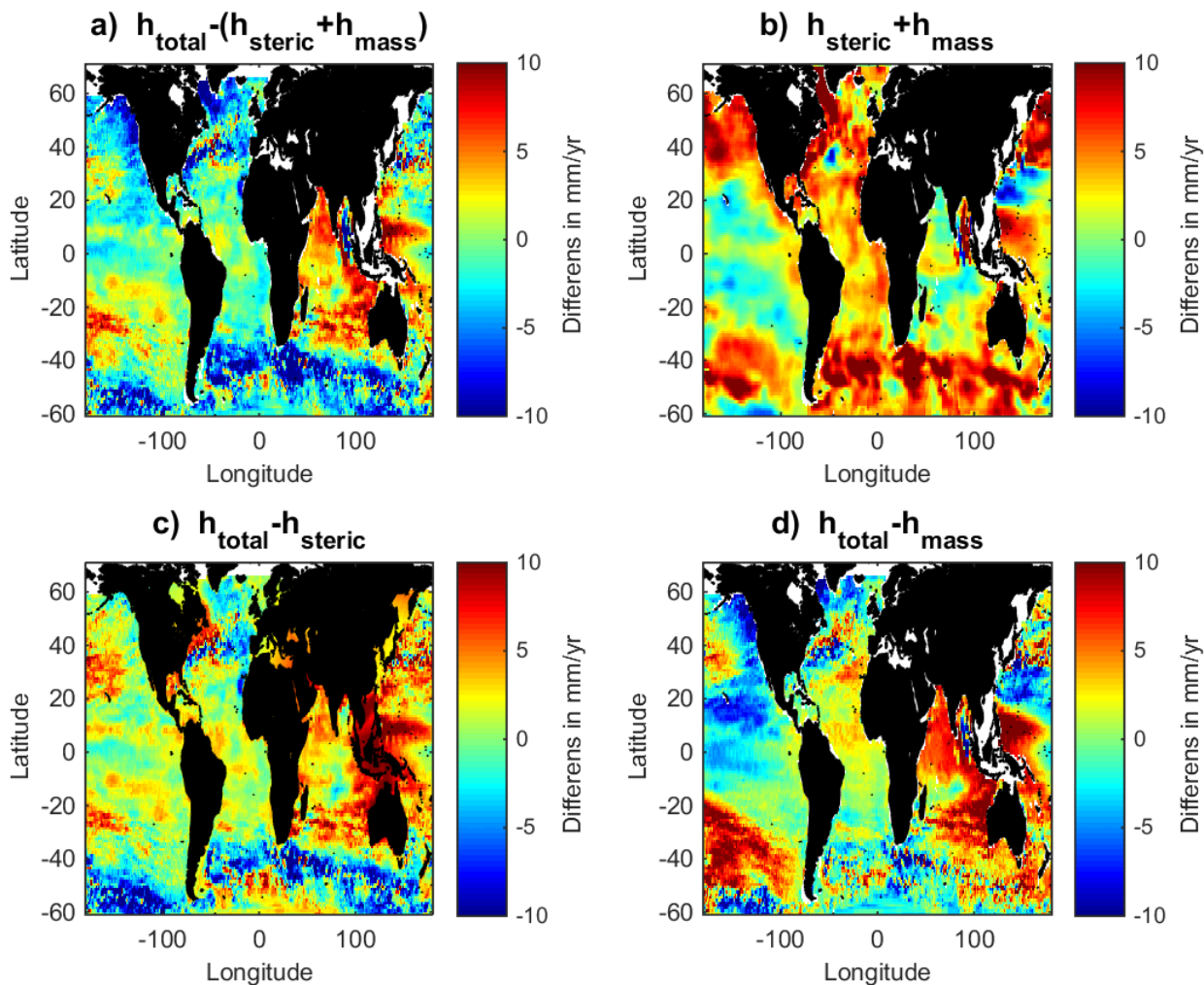


Figure 9: **a)** is the components subtracted from the total sea level height. If the sea level budget was closed perfectly all the trends would be around zero. **b)** The total sea level height from the sum of the components contributing. **c)** The mass-induced heights from the total sea level height and the steric heights. **d)** The steric height from the total sea level height and the mass-induced heights.

5.3 Spatial trends

All the spatial GMSL rates is collected in Table 3. The rates is calculated from the spatial analysis using the weighted mean method. The spatial rates can be used to compare with other studies. Furthermore the sea level budget can investigated for the spatial part.

Table 3: GMSL rates from the spatial analysis in different areas and time periods. The uncertainties is determined with the standard deviation of mean, for most of the rates it is approximately 0 mm/yr.

	Period	Area	Trend mm/yr
Total sea level	1992-2016	66°S-66°N	2,9 ± 0,0
Total sea level	1992-2016	82°S-82°N	3,2 ± 0,1
Total sea level	Apr. 2002-Nov. 2014	60°S-70°N	2,6 ± 0,0
Mass-induced	Apr. 2002-Nov. 2014	89°S-89°N	1,6 ± 0,0
Mass-induced	Apr. 2002-Nov. 2014	60°S-70°N	1,2 ± 0,0
Steric	Apr. 2002-Nov. 2014	60°S-70°N	1,0 ± 0,0

5.4 Time series

5.4.1 Temporal trends

The trends as a result of all the time series is presented in Table 4. Based on these trends it is possible to discuss if the sea level mass budget is a reality or if further investigations is necessary. Following is the time series by which the trends is calculated from.

Table 4: Trend of the total sea level rise and the components contributing to it. The trends is for global and regional areas. The trends and uncertainties is determined from a linear least squares fit and the standard deviation of it.

Trend [mm/yr]	Total height	Steric height	Mass-induces height	Steric + mass
Global	2,6 ± 0,1	1,0 ± 0,1	1,5 ± 0,5	2,4 ± 0,1
Atlantic	2,7 ± 0,2	1,2 ± 0,1	2,1 ± 0,3	3,1 ± 0,2
Indian	4,1 ± 0,2	0,5 ± 0,1	-0,2 ± 0,8	0,4 ± 0,2
Pacific	2,3 ± 0,2	-0,2 ± 0,1	2,2 ± 0,6	1,8 ± 0,1
South pole	2,1 ± 0,2	3,7 ± 0,3	0,8 ± 0,4	4,3 ± 0,3

5.4.2 Smoothing method

To decide which method the time series should be smoothed with, both methods have been applied on the global mass-induced height variations. The plot containing the smoothing can be seen on Figure 10. The trigonometric function is smoothing the signals, but still preserves much of it just with a smaller amplitude. The running average removes most of the annual signals. For the rest of the results containing time series the running average will be used for smoothing.

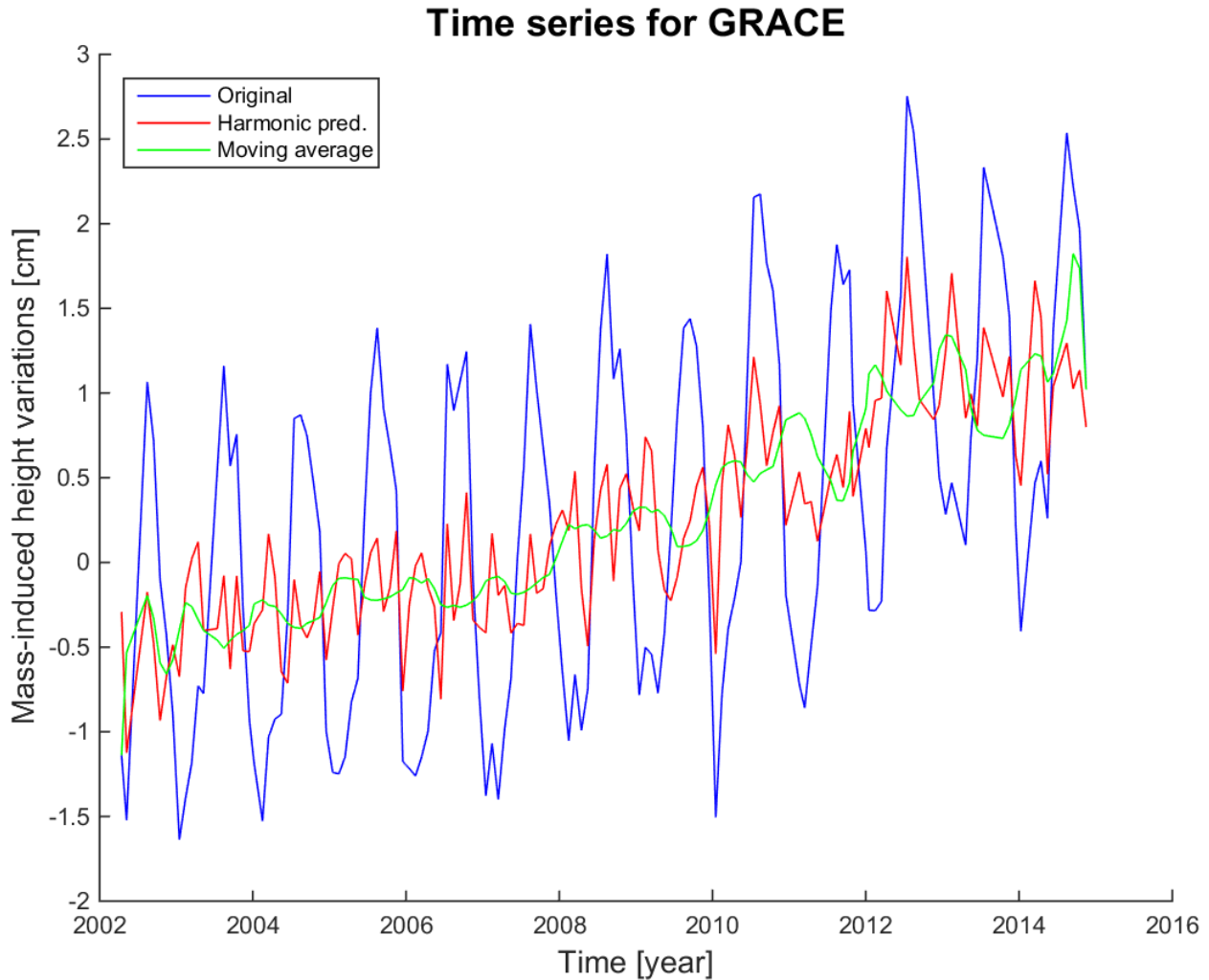


Figure 10: Monthly variations in the mass-induced height from GRACE. The two methods for smoothing the data is applied to the mass-induced height to illustrate the differences.

5.4.3 Global

The global time series in Figure 11 shows the variations in the GMSL for the total sea level height, the contributions and the sum of the contributions. The total sea level corresponds almost with the sum of the steric height and the mass-induced height until 2010. After 2010 there is a drop in the total sea level, where the steric height and mass-induced heights are constant. After the drop the two profiles follow until 2013, where there is a drop in the mass height variations.

The trends for this time series and the following time series can be read in Table 4.

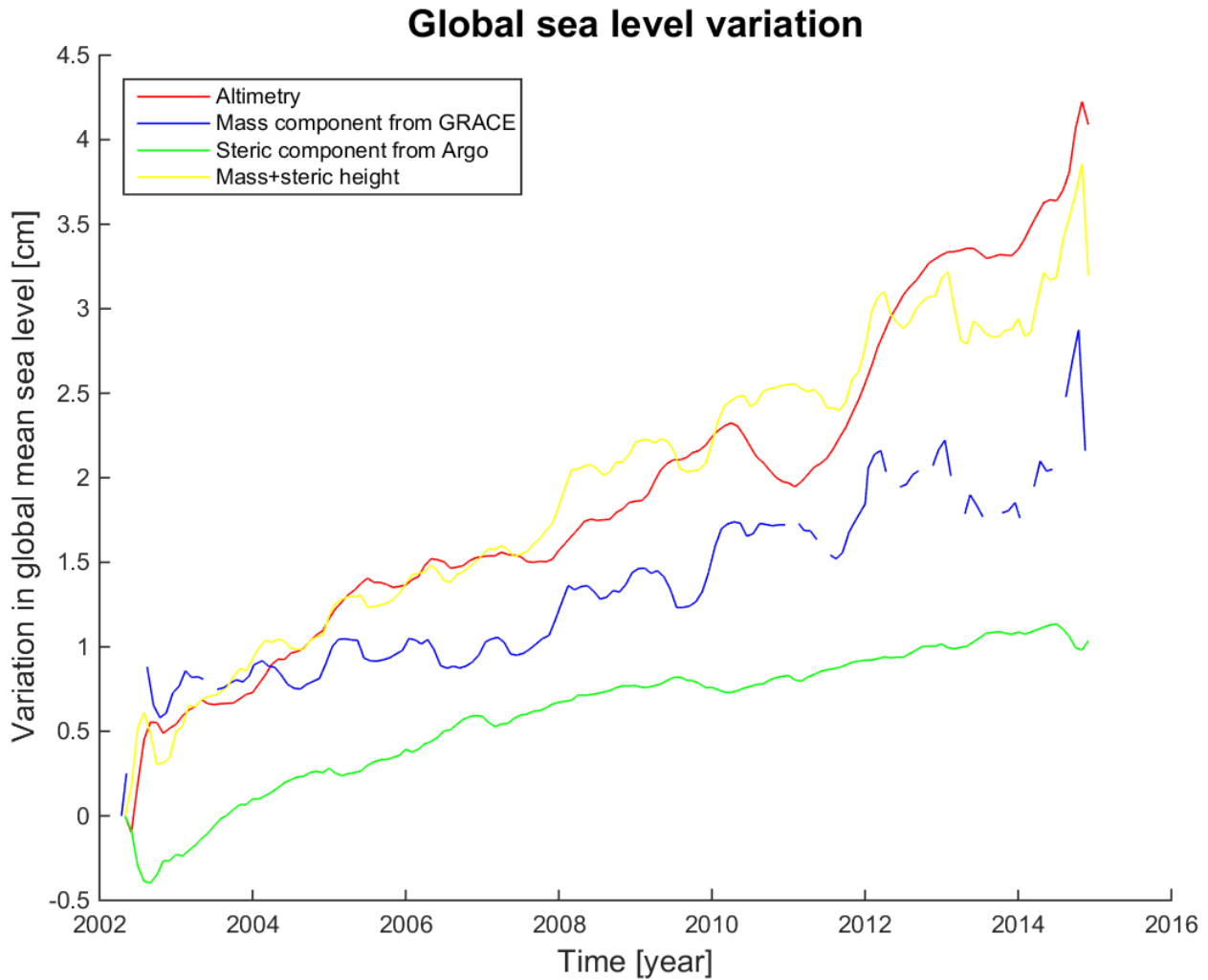


Figure 11: The global averaged monthly sea level variations.

5.4.4 Pacific Ocean

The Pacific Oceans time series is presented in Figure 12. The steric height is almost constant, with a trend on $-0,2 \pm 0,1$ mm/yr. In the total sea level there a some fluctuations. In 2010-2011 the total sea level height variation drops around 1 cm. In 2011-2015 the variations grows with almost 4 cm, which is a big rise in the variations. The mass-induced height variations follows the total sea level until 2010, after this the curve still follows the total sea level height variations, but the variations are smaller.

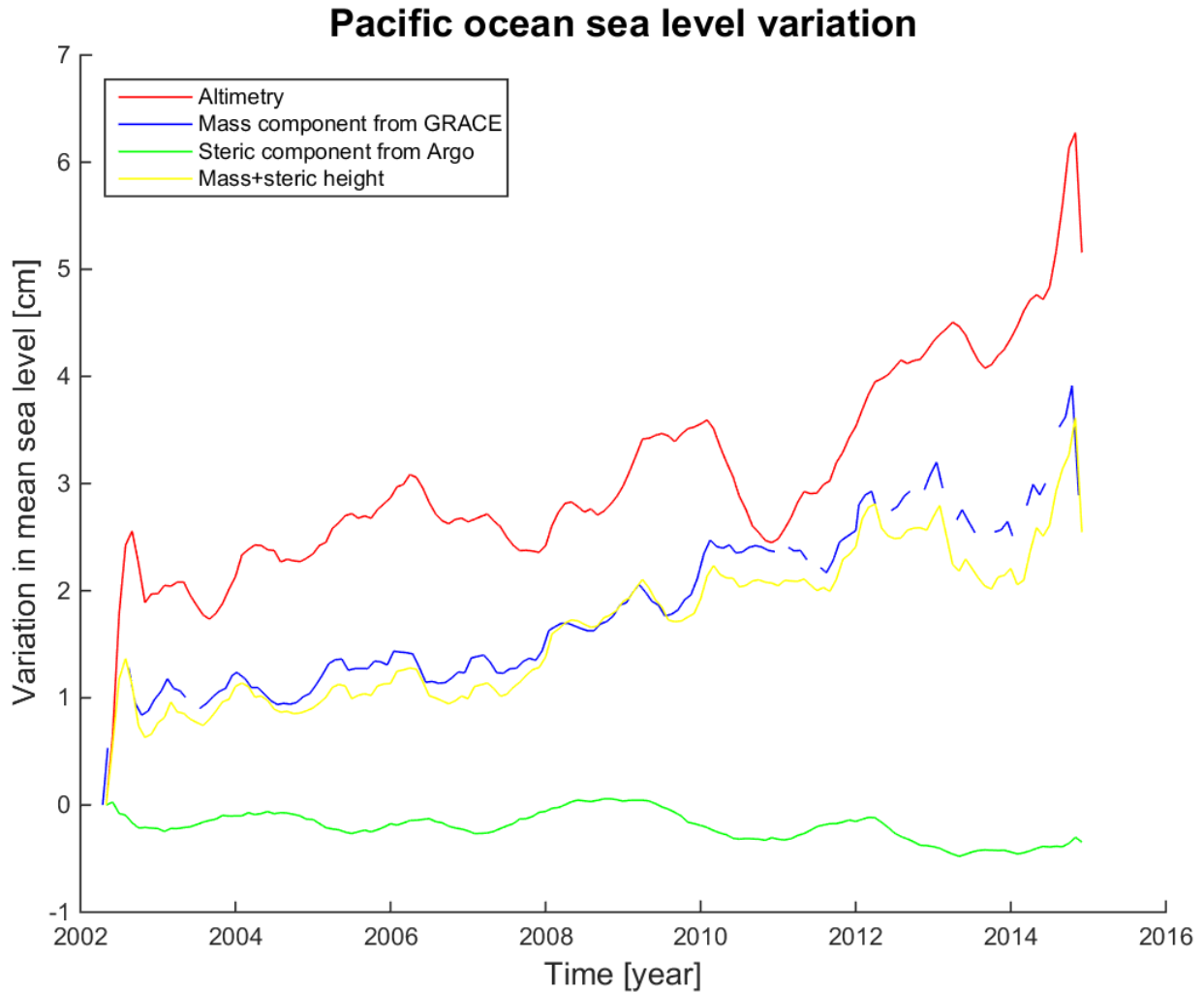


Figure 12: Monthly averages time series for the Pacific ocean.

5.4.5 Atlantic Ocean

The Atlantic Ocean time series can be viewed in Figure 13. The variations is not significantly big, except for the beginning and end of the time series. These errors occur because of the smoothing done on the time series, which can not be avoided.

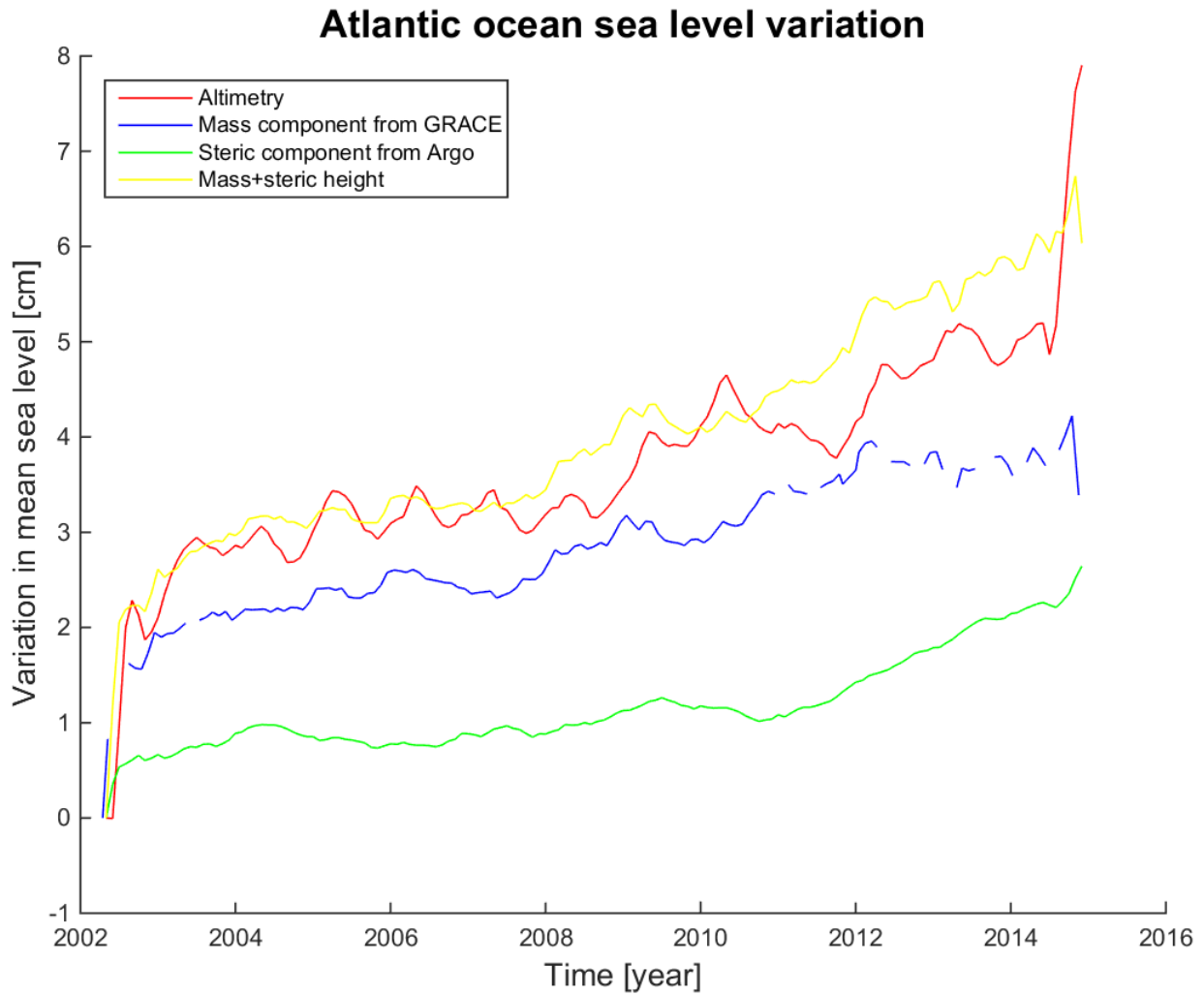


Figure 13: Monthly averages time series for the Atlantic Ocean.

5.4.6 Indian Ocean

For the Indian Ocean the total sea level height variations is clearly different from the sum of the steric and mass-induced height variations. The trends from Table 4 indicates the same. The total sea level height is increasing with $4, 1 \pm 0, 2$ mm/yr where the increase/decrease from the two contributors is much smaller. Around 2006-2007 there is a huge rise lasting only a year in the total sea level height variations. In the period around 2010-2011 the total sea level height variation drops with around 2 cm. After this the total sea level height is raising continuously from 2011 and until at least 2015 with around 4 cm. The mass-induced height have a drop around 2009, and from 2010-2015 it is fluctuating around the same level.

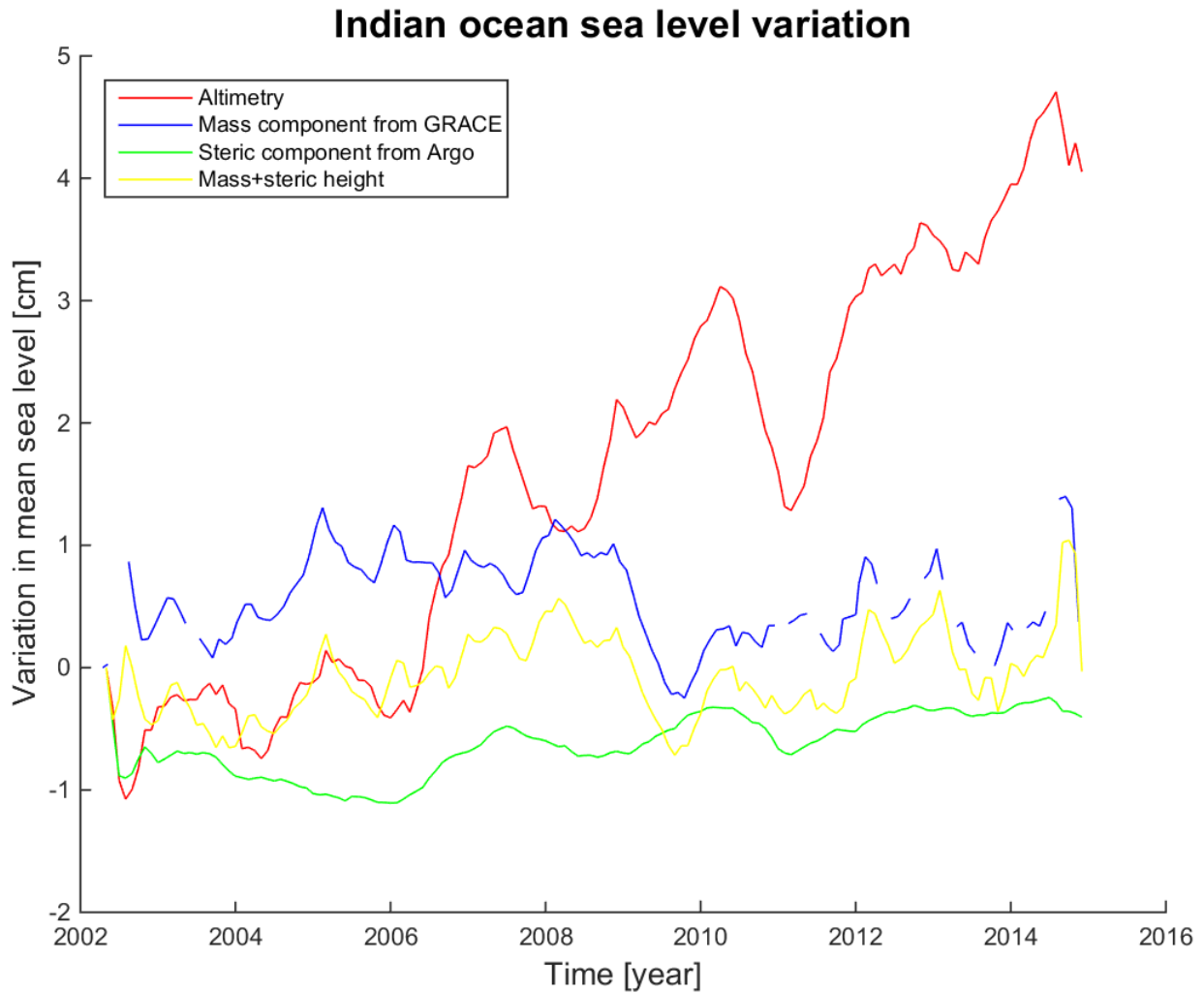


Figure 14: Monthly averages time series for the Indian ocean.

5.4.7 South pole

The time series for the south pole, Figure 15, is much different compared to the previous time series. In this region the steric height variations is the dominating. The mass-induced height variations and the total sea level height variations is nothing compared to the steric. Even though the steric height is raising rapidly, the fluctuations is small and no certain years is being noticed.

The same is for the total height, the fluctuations is small and in between 2008-2014 the variation is only 2 cm.

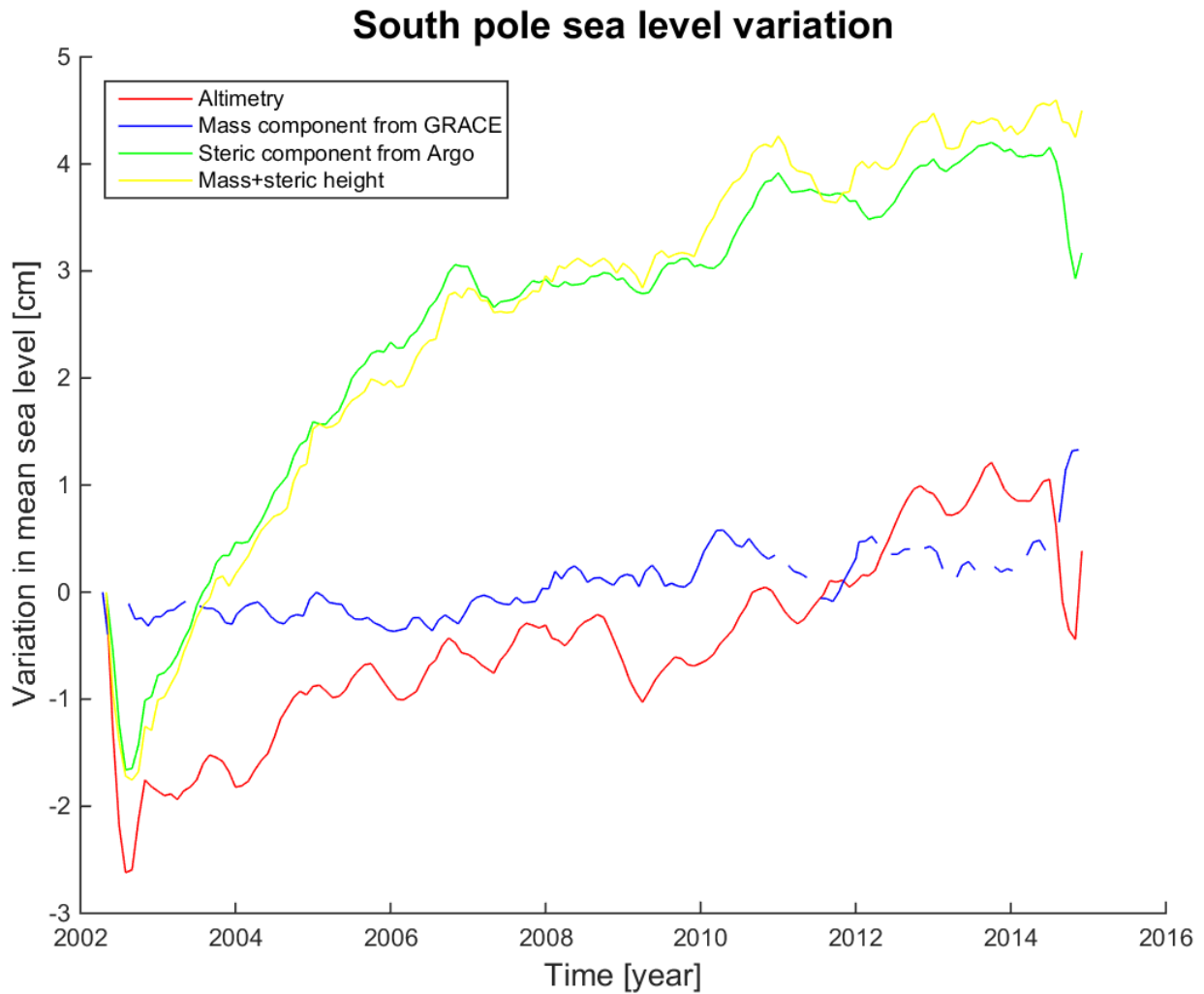


Figure 15: Monthly average time series for the south pole part below 30°S, below latitude -30.

6 Discussion

This section is a discussion of the results obtained in the project. The section will contain a discussion of the measurement methods, the data processing and the results. After the discussion it should be possible to make some conclusions about the sea level budget and what the investigations can teach us. Future perspectives is discussed as well.

6.1 Data processing

When consulting the trends in Table 3 and Table 4 it is seen that the uncertainties for the trends is not that significant, if even existing. The uncertainties is derived from the data processing with the standard deviation of the mean and from a linear least squares fit. The data processing of the different types of data will always contribute with some uncertainties. The uncertainties that arises during all the aspects of the data processing is not taken into account in the calculations. The actual uncertainties for the entire date processing is therefore expected to be larger, since it must be accumulating during the processing. The uncertainties only gets bigger, when the different types of observations have to be merged. The uncertainties must necessarily be bigger than calculated.

The Argo and GRACE data was already in a monthly gridded format. For the altimetry data this had to be done by finding the monthly means for each grid cell. To obtain this data format something will be lost. When the time series is smoothed and the trends is determined afterwards, there will be some errors. Even though the data processing will cause errors in the results, the errors still seem to be small compared with the actual results obtained. It is still possible to analyse and interpret the spatial plots and time series.

6.2 Spatial analysis

The results from the spatial analysis of the total sea level in Figure 5 is compared with the fifth assessment report. The results from the analysis in 1992-2016 gave a GMSL rise at $2,9 \pm 0,0$ mm/yr. This result compares well with the fifth assessment IPCC report stating a GMSL rise at $3,2 \pm 0,4$ mm/yr, GIA included (Church et al., 2013). This result is used to confirm that the analysis made on the spatial total sea level can be used and expanded to other types of observations.

The three spatial plots all indicate a rise bigger than the average trends in the area around the mid-latitudes for the Indian Ocean and the West Pacific Ocean. When consulting the time series for the Indian Ocean it is noticed that the total sea level is rising, the rate is $4,1 \pm 0,2$ mm/yr. The time series for the Pacific Ocean cannot tell something about this area, since the Pacific is to big for these trends to influence the rest of the ocean. The area around the Indian Ocean was in 2004 hit by the Sumatra-Andaman earthquake and in 2011 the Tohoku-Oki earthquake. These earthquakes can be part of the explanation of what has been happening and why the trends and time series is behaving this way. It is expected that there will be a rise in the mass-induced height since an earthquake would change the mass balance. In 2004 there is a rise in the mass-induced height and in the total sea level height which the first earthquake can explain. In 2011 the mass-induced height is constant in the period around the earthquake, here it is only the total sea level height that is changing extremely. One of the explanations can be, that the GRACE data in this area and period has been smoothed for the variations originating from the earthquake.

The spatial analysis for the steric height is indicating a rise almost overall below 30°S . This is confirmed by the time series analysis for this part as well. The steric height trend is $3,7 \pm 0,3$ mm/yr, which exceeds the total sea level by far. In this area the Antarctic Oscillation (AO) is dominant and must be influencing the paths of the floats and the measurements. If the floats get caught by a strong current the equipment will be disturbed and the measurements will include these fluctuations. The Argo floats is not made for too strong currents, where they are thrown around.

Furthermore the area below 30°S are some places dominated by sea ice, which makes the altimetry data invalid for the areas with ice. The ice is influencing the gravity measurements from GRACE as well, why these results should be considered with some caution.

The drop around 120°W , 60°S is visible on both the spatial plots for the total sea level and the mass-induced trend map. A suggestion would be, that the sea level pressure is somehow different in that area. Furthermore the Antarctic currents and sea ice is having some influence there which mixes up everything.

The comparison of the spatial analysis was supposed to show some coherence between the three different observations. Instead the comparisons shows that the local trends in the different analysis is big and varying. This leads to the local trends from each map dominating in the resulting comparison. For example was Figure 9b, the sum of the steric and mass trends, supposed to be compared with Figure 6 and be coherent. The two figures can be compared and in some areas they show the same trends, for example in the Pacific Ocean. As for the southern part the steric trends is dominating and not comparable to the total trends. The comparisons can be used as an illustration of the spatial analysis and their coherence.

For the spatial analysis the sea level budget can be discussed. Consulting Table 3 the spatial trends does not indicate that the sea level budget can be closed spatially. The ranges for the uncertainties is non-existing. For the analysis there should be some uncertainties which is not covered by the calculations. If the uncertainties had been bigger, then the spatial sea level budget could have been closed.

6.3 Time series

In the Pacific Ocean the time series showed some major changes in the total sea level. The spatial analysis is not helping explaining these changes. The spatial analysis shows that in the Pacific Ocean the trends for the total sea level is spanning from -10 mm/yr to 10+ mm/yr. The Pacific Ocean is influenced by different oscillations. The most dominating is the El Niño Southern Oscillation (ENSO). With ENSO some of the variations can be explained. If we take a look at the Oceanic Niño Index (ONI), the index is based on the sea surface temperature (SST) (GGWeather, 2016). The index is only used to find out when El Niño /La Niña was dominating. The index shows a drop in the period 2010-2011 and a rise during 2014-2015. These observations fits with the time series from the Pacific Ocean, where we saw a drop followed by a rise. That the event in 2011 is caused by La Niña is supported by Fasullo et al. (2013). They claim that the exceptional drop in 2011 is partly because of La Niña and the influence of other oscillations in that area. With this the rapid changes in the Pacific is explained overall.

The steric height trend is $-0,2 \pm 0,1$ mm/yr. During El Niño/El Niña years the ocean currents is changing rapidly and with high speed, whereas the measurements from the Argo floats comes with some uncertainties.

The last ocean is the Atlantic Ocean. The time series, Figure 13, is more stable compared to the others. The Atlantic Ocean is more isolated for the Antarctic Oscillation (AO). Following this the Argo floats is not thrown around by the currents, whereas the measurements is more precise and consistent. In this area the mass-induced heights and total height is considered to be consistent and there is no need for further explanation.

The sea level budget has to be made up for the global and regional areas. The sea level budget is discussed from the results presented in Table 4. For the global area the sea level budget can be closed inside the ranges of the uncertainties. The total height trend is $2,6 \pm 0,1$ mm/yr and the steric+mass trend is $2,4 \pm 0,1$ mm/yr. On a regional scale the sea level budget can only be closed for the Atlantic Ocean. As discussed earlier, the Atlantic Ocean is isolated and the states more stable, hence the results more precise. As for the rest of the regional areas the sea level budget can not be closed. As discussed previously the uncertainties for the trends is most certainly bigger, but this is not made clear with these calculations. The global time series includes all of the regional variations. The regional variations is explaining the variations in the global analysis.

6.4 Future perspectives

The Argo floats project continue to expand with more floats joining. An increase in the number of floats will provide the temperature- and salinity profiles in a better resolution, hence more precise analysis can be performed. The other two means of observations is still getting better as well. The altimetry measurements is still performed, and the new Jason-3 satellite was launched in January 2016 and others will follow. The GRACE satellite is still in function as well, and a follow-on mission is planned to be launched in 2017 (NASA, 2016b).

With the expanded observations the sea level budget investigations can be extended. A future investigation can be an expanded analysis of the sea level budget both globally and regionally. A goal for the future analysis could be to try and close the sea level budget for the regional areas. Furthermore the spatial and temporal analysis can be improved, so that the local oscillations and other events can be sorted out and the actual rises investigated.

7 Conclusion

In this project both spatial and temporal analysis has been performed. An extended investigation of spatial altimetry trends was conducted for 1992-2016. It was shown that there is a good agreement between the data from the NASA and ESA satellites. With this it was made possible to perform a near-global spatial analysis for the total sea level height trends. Spatial analysis has been performed on both GRACE and Argo data to determine the contributions from a change in mass and from thermal expansion. The analysis was performed for the period April 2002-November 2014 and for the area between 60°S and 70°N. The result for this where spatial maps with the mass-induced height trends and the steric height trends. The spatial plots for the three different observations was compared. It was shown that the spatial parts is not coherent because of local variations in the different observations. Furthermore the sea level budget was consolidated spatially, but it was not possible to close it.

The temporal analysis for period April 2002-November 2014 and for the area between 60°S and 70°N contributed with time series for the five different parts investigated. From the time series the trends for the total sea level height, steric heights and mass-induced height was determined. On behalf of this, the temporal sea level budget was investigated. On global scale it was possible to close the sea level budget with a total sea level height trend on $2,6 \pm 0,1$ mm/yr and a steric+mass-induced height trend on $2,4 \pm 0,1$ mm/yr. On regional scales it was only possible to close the sea level budget for the Antarctic Ocean. For the Indian Ocean, the Pacific Ocean and the southern part the fluctuations were to big, originating from ENSO and AO among others.

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Appendices

A Trends from ESA altimetry data

```
% Annual trends for 5x2 squares, ESA-data
clear all; close all;
format_spec = '%f%f%f%f%f';
delimiter= 'tab';
headernum=0;
year1 = 60*60*24*365.25;

%Load data
fid = fopen('north.dat.all.txt');
data = textscan(fid,format_spec,'Delimiter',delimiter,'headerlines',headernum);
fclose(fid);

squares = 1;
for lat = 64:2:82
% for lat = -82:2:-64 %For the south area
    for lon = 0:5:355
        ind = find(data{1,2}>lat & data{1,2}<(lat+2) & data{1,3}>lon &...
            data{1,3}<(lon+5) & data{1,4}>-5.0 & data{1,4}<5.0);

        h = data{1,4}(ind)*1000; %Get the anomaly in mm
        t = data{1,5}(ind);
        t=t/year1;

        %Fit data for each square to a linear model
        p = polyfit(t,h,1);

        %Coordinates for the trends - middel of square
        lat1 = (lat+(lat+2))/2;
        lon1 = (lon+(lon+5))/2;

        %Saving in matrix
        annual(squares,:) = [lat1 lon1 p(:,1)];

        squares = squares +1;
    end
end

%Save datafile for the global plot
save('north_annual.txt','annual','-ascii');
%save('south_annual.txt','annual','-ascii');
```

B Global trend map from altimetry

```
clear all; close all;

%Load data
data = load('C:\Users\Ida\Documents\DTU\Bachelor\Data\annual.dat');
north= load('C:\Users\Ida\Documents\DTU\Bachelor\Databehandling\North\north_annual.txt');
south = load('C:\Users\Ida\Documents\DTU\Bachelor\Databehandling\South\south_annual.txt');

lon_north=north(:,2);
lon_north = wrapTo180(north(:,2));
lon_south = south(:,2);
lon_south = wrapTo180(south(:,2));

latdata = data(:,2);
londata = data(:,3);
londata = wrapTo180(londata);
trend = data(:,5)*10; %Trend in cm/yr to mm/yr

%% Weighted mean between -66 and 66 latitude
ind = find(data(:,2)>-66 & data(:,2)<66);
h_mean = trend(ind);
lat_mean = latdata(ind);
temp = h_mean.*cos(pi/180*lat_mean);
sum1 = nansum(temp);
sum2 = nansum(cos(pi/180*lat_mean(:)));
mean = sum1/sum2;

%Uncertainty
1.96*std(h_mean)/sqrt(length(h_mean))

%% Contour map with trends

%Middel
[xq,yq] = meshgrid(-179.5:1:179.5, -64:1:64);
vq = griddata(londata, latdata, trend, xq, yq);

%North
[xq1,yq1] = meshgrid(-179.5:1:179.5, 64:1:82);
vq1 = griddata(lon_north, north(:,1), north(:,3), xq1, yq1);

%South
[xq2,yq2] = meshgrid(-179.5:1:179.5, -82:1:-64);
vq2 = griddata(lon_south, south(:,1), south(:,3), xq2, yq2);

vq3 = [vq2; vq; vq1];

b = imagesc(-180:1:180,-82:1:82,vq3);
set(b,'AlphaData',~isnan(vq3));
set(gca,'YDir','normal')
c=colorbar; caxis([-10 10]);colormap(jet);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');
ylabel(c, 'mm/yr', 'FontSize',13)
xlabel('Longitude', 'FontSize',13); ylabel('Latitude', 'FontSize',13);
title('Trends from altimetry, 1992-2016','FontSize',16);

%Global trend and uncertainty
vq3(vq3>50) = NaN;

A = -83:1:83;
A = flipplr(A);
Latitude = repmat(A',1,360);
H = vq3;
W = cos(pi/180*Latitude);
meanData = nansum(H(:).*W(:)) / nansum(W(:));

1.96*nanstd(vq3(:))/sqrt(length(vq3(:)))
```

C Altimetry, spatial analysis and time series

```
clear all; close all;

%Seconds on a month
% month = 2592000;
month = 2629746;

format_spec = '%f%f%f%f%f';
% fid_mean = fopen('mean1.txt');
% mean1 = textscan(fid_mean,format_spec);

%% North
textfiletype = 'C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\Altimetry\*.txt';
filenames = dir(textfiletype);
filenames_j1 = ['jason1n.000060.txt'; 'jason1n.060120.txt'; 'jason1n.120180.txt';...
               'jason1n.180240.txt'; 'jason1n.240300.txt'; 'jason1n.300360.txt'];
filenames_j2 = ['jason2n.000060.txt'; 'jason2n.060120.txt'; 'jason2n.120180.txt';...
               'jason2n.180240.txt'; 'jason2n.240300.txt'; 'jason2n.300360.txt'];
number_of_files = 6;

%Esa
fid_esa = fopen('C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\North\north_dat_all.txt','r');
esa = textscan(fid_esa,format_spec);
t_esa = esa{1,5};
h_esa = esa{1,4};
lat_esa = esa{1,2};
lon_esa = esa{1,3};
t_esa = t_esa/month;
t_esa = floor(t_esa);

cond = find(t_esa>(210) & t_esa<((374)));
t_esa = t_esa(cond);
h_esa = h_esa(cond);
lat_esa = lat_esa(cond);
lon_esa = lon_esa(cond);

%Analyse for the north area with both ESA + NASA data
tic
for ii = 1:number_of_files
    file_j1 = filenames_j1(ii,:);
    file_j2 = filenames_j2(ii,:);

    fid_j1 = fopen(file_j1,'r');
    j1 = textscan(fid_j1,format_spec);
    fclose(fid_j1);
    fid_j2 = fopen(file_j2,'r');
    j2 = textscan(fid_j2,format_spec);
    fclose(fid_j2);

    t_j1 = j1{1,5};
    h_j1 = j1{1,4};
    lat_j1 = j1{1,2};
    lon_j1 = j1{1,3};

    t_j2 = j2{1,5};
    h_j2 = j2{1,4};
    lat_j2 = j2{1,2};
    lon_j2 = j2{1,3};

    t_j1 = t_j1/month;
    t_j1 = floor(t_j1);
    t_j2 = t_j2/month;
    t_j2 = floor(t_j2);

    data = [lat_j1 lon_j1 h_j1 t_j1 ; lat_j2 lon_j2 h_j2 t_j2 ;...
           lat_esa lon_esa h_esa t_esa ];
    lat_dat = data(:,1);
    lon_dat = data(:,2);
    h_dat = data(:,3)*1000;
    t_dat = data(:,4);

    squares = 1;

    for lat = 0:1:70
```

```

for lon = floor(min(lon_j1)):1:floor(max(lon_j1))
    cond1 = find(data(:,1)>lat & data(:,1)<(lat+1) & data(:,2)>lon...
        & data(:,2)<(lon+1));

    h_dat_1 = h_dat(cond1);
    t_dat_1 = t_dat(cond1);
    temp_t = unique(t_dat);

    data1 = [h_dat_1 t_dat_1];

    for jj=1:numel(temp_t)
        auxind=temp_t(jj);
        avrg_height(:,jj) = nanmean(data1(find(data1(:,2)==auxind),1));
    end

    mean_dat(lon+1,lat+1,:) = avrg_height;
    squares = squares+1;
end
end
filename = [ 'mean_n' num2str(ii) '.mat' ];
save(filename, 'mean_dat');
end
toc

%% South
clearvars mean_dat
textfiletype = 'C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\Altimetry\*.txt';
filenames = dir(textfiletype);
filenames_j1 = ['jason1s_000060.txt'; 'jason1s_060120.txt'; 'jason1s_120180.txt';...
    'jason1s_180240.txt'; 'jason1s_240300.txt'; 'jason1s_300360.txt'];
filenames_j2 = ['jason2s_000060.txt'; 'jason2s_060120.txt'; 'jason2s_120180.txt';...
    'jason2s_180240.txt'; 'jason2s_240300.txt'; 'jason2s_300360.txt'];
number_of_files = 6;

%Analyse for the north area with both ESA + NASA data
tic
for ii = 1:number_of_files
    file_j1 = filenames_j1(ii,:);
    file_j2 = filenames_j2(ii,:);

    fid_j1 = fopen(file_j1,'r');
    j1 = textscan(fid_j1,format_spec);
    fclose(fid_j1);
    fid_j2 = fopen(file_j2,'r');
    j2 = textscan(fid_j2,format_spec);
    fclose(fid_j2);

    t_j1 = j1{1,5};
    h_j1 = j1{1,4};
    lat_j1 = j1{1,2};
    lon_j1 = j1{1,3};

    t_j2 = j2{1,5};
    h_j2 = j2{1,4};
    lat_j2 = j2{1,2};
    lon_j2 = j2{1,3};

    t_j1 = t_j1/month;
    t_j1 = floor(t_j1);
    t_j2 = t_j2/month;
    t_j2 = floor(t_j2);

    data = [lat_j1 lon_j1 h_j1 t_j1 ; lat_j2 lon_j2 h_j2 t_j2];
    lat_dat = data(:,1);
    lon_dat = data(:,2);
    h_dat = data(:,3)*1000;
    t_dat = data(:,4);

    squares = 1;

for lat = -60:1:0
    for lon = floor(min(lon_j1)):1:floor(max(lon_j1))
        cond1 = find(data(:,1)>lat & data(:,1)<(lat+1) & data(:,2)>lon...
            & data(:,2)<(lon+1));
        h_dat_1 = h_dat(cond1);

```

```

t_dat_1 = t_dat(cond1);
temp_t = unique(t_dat);

data1 = [h_dat_1 t_dat_1];

for jj=1:numel(temp_t)
    auxind=temp_t(jj);
    avrg_height(:,jj)= nanmean(data1(find(data1(:,2)==auxind),1));
end
mean_dat(lon+1,lat+61,:) = avrg_height;
squares = squares+1;
end
end
filename = [ 'mean_s' num2str(ii) '.mat' ];
save(filename, 'mean_dat');
end
toc

exit;

```

D Altimetry, trends and time series

```
clear all; close all;

%Load altimetry data
n1 = load('mean.n5.mat');
n2 = load('mean.n6.mat');
s1 = load('mean.s6.mat');
m1 = n1.mean_dat;
m2 = n2.mean_dat;
m3 = s1.mean_dat;

%Load Argo data
h=load('C:\Users\Ida\Documents\DTU\Bachelord\Databehandling\ARGO\JAMSTEC\steric.h.mat');
SH = h.steric.h*100; %From dynamic height (dyn m = 10 m^2/s^2) to mm
lat_dat = ncread('C:\Users\Ida\Documents\DTU\Bachelord\Databehandling\ARGO\JAMSTEC\TS.200501-GLB.nc', 'LATITUDE');
lon_dat = ncread('C:\Users\Ida\Documents\DTU\Bachelord\Databehandling\ARGO\JAMSTEC\TS.200501-GLB.nc', 'LONGITUDE');
lon_dat = double(lon_dat); lat_dat = double(lat_dat);

%Make matrice of data
m2 = m2(301:end, :, :);
mat = cat(1, m1, m2);
mat = cat(2, m3, mat);
mat = mat(:, :, 1:152); %The period to be worked with

%Apply Argo landmask on altimetry data
Latitude = repmat(lat_dat', [360 1]); %Latitude in a grid
for lat = 1:length(lat_dat)
    for lon = 1:length(lon_dat)
        if SH(lon, lat, :) == 0 %Sort out the land, where land has 0-value
            mat(lon, lat, :) = NaN;
            Latitude(lon, lat) = NaN;
        end
        if isnan(mat(lon, lat, :)) == 1
            mat(lon, lat, :) = NaN;
            Latitude(lon, lat) = NaN;
        end
    end
end

time=2002+4/12:1/12:2014+11/12;
month=1;

%Weighted mean for each month, global
for t=1:length(time)
    H = mat(:, :, t);
    W = cos(pi/180*Latitude);
    meanData(month, :) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('alt_glo.txt', 'meanData', '-ascii')

%Weighted mean for each month, Pacific
%Lon, 115-290, above -30 lat
lat_pac = Latitude(115:290, 32:end);
mat_pac = mat(115:290, 32:end, :);
month=1;
for t=1:length(time)
    H = mat_pac(:, :, t);
    W = cos(pi/180*lat_pac);
    mean_pac(month, :) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('alt_pac.txt', 'mean_pac', '-ascii')
figure(3)
plot(time, mean_pac)
title('Pacific')

%Weighted mean for each month, Atlantic
%Lon, 20 and 290/-75, above -30 lat
lat_atl = [Latitude(1:20, 32:end); Latitude(291:end, 32:end)];
A = mat(1:20, 32:end, :);
B = mat(291:end, 32:end, :);
mat_atl = cat(1, A, B);
month=1;
```

```

for t=1:length(time)
    H = mat_atl(:, :, t);
    W = cos(pi/180*lat_atl);
    mean_atl(month, :) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('alt_atl.txt', 'mean_atl', '-ascii')
figure(4)
plot(time, mean_atl)
title('Atlantic')

%Weighted mean for each month, Indian
%Lon 20-95, above -30 lat
lat_ind = Latitude(21:94, 32:end);
mat_ind = mat(21:94, 32:end, :);
month=1;
for t=1:length(time)
    H = mat_ind(:, :, t);
    W = cos(pi/180*lat_ind);
    mean_ind(month, :) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('alt_ind.txt', 'mean_ind', '-ascii')
figure(5)
plot(time, mean_ind)
title('Indian')

%Weighted mean for each month, south pole (under -30 lat)
%Everything under -30 lat
lat_sou = Latitude(:, 1:31);
mat_sou = mat(:, 1:31, :);
month=1;
for t=1:length(time)
    H = mat_sou(:, :, t);
    W = cos(pi/180*lat_sou);
    mean_sou(month, :) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('alt_sou.txt', 'mean_sou', '-ascii')
figure(6)
plot(time, mean_sou)
title('South')

%Spatial analysis, finding global trends
count = 1;
for lat = 1:length(lat_dat)
    for lon = 1:length(lon_dat)
        temp_h = squeeze(mat(lon, lat, :));
        p = polyfit(time, temp_h, 1);
        annual(count, :) = [Latitude(lon, lat) lat_dat(lat) lon_dat(lon) p(1)];
        count = count + 1;
    end
end

%Sort out NaNs in dataset
cond=~(isnan(annual(:, 4)));
lat = annual(:, 2);
h = annual(:, 4);

lon = wrapTo180(annual(:, 3));

%Timeseries plot
figure(1)
plot(time, meanData, 'b-')
xlabel('Time [yr]', 'FontSize', 13); ylabel('Variation [mm]', 'FontSize', 13);
title('Monthly altimetry variations, Feb 2002–November 2014', 'FontSize', 16);

%Spatial plot
figure(2)
[xq, yq] = meshgrid(-179.5:1:179.5, -60.5:1:70.5);
vq = griddata(lon(cond), lat(cond), h(cond), xq, yq);
h1 = imagesc(-180:1:180, -60.5:1:70.5, vq);
set(h1, 'alphadata', ~isnan(vq));
set(gca, 'YDir', 'normal');
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'mm/yr', 'FontSize', 13);
xlabel('Longitude', 'FontSize', 13); ylabel('Latitude', 'FontSize', 13);

```



```
title('Total sea level height trends from altimetry, April 2002-November 2014','FontSize',16);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');

temp = h(cond).*cos(pi/180*lat(cond));
sum1 = nansum(temp);
sum2 = nansum(cos(pi/180*lat(cond)));
mean1 = sum1/sum2;

uncert = 1.96*nansd(h(cond))/sqrt(length(h(cond)));

% save('alt_grid.txt','vq','-ascii')
```

E GRACE, spatial analysis

```
clear all; close all;

%Loading the data
grace = load('C:\Users\Ida\Documents\DTU\Bachelor\Data\GraceJPL.mat');
landmask = load('C:\Users\Ida\Documents\DTU\Bachelor\Data\dtu10_land.txt');

lon_dat = grace.lon;
lat_dat = grace.lat;
time = grace.time;
time = time/365.25+2002; %Time from days to years
height = 10*grace.lwe.thickness; %Multiply by 10 to get the anomaly in mm

%Shape the landmask to the format of the height matrix
landmask = sortrows(landmask,2);
landmask_h = landmask(:,5);
landmask_lon = wrapTo360(landmask(:,3));
landmask_lat = reshape(landmask(:,2), [720 360]);
landmask_h = reshape(landmask_h, [720 360]) ;
landmask_h = fliplr(rot90(landmask_h,-1));
height = fliplr(rot90(height,-1));

%Apply landmask on data
Latitude = repmat(lat_dat, [1 720]); %Corresponding latitudes for each height
for lat = 1:length(lat_dat)
    for lon = 1:length(lon_dat)
        if landmask_h(lat,lon)>0 %Sort out the land
            height(lat,lon,:)=NaN;
            Latitude(lat,lon)=NaN;
        end
    end
end

%Calculate the global monthly mean (-89,75;89,75 lat)
month=1;
for t=1:length(time)
    H = height(:,:,t);
    W = cos(pi/180*Latitude);
    meanData(month,:) = nansum(H(:).*W(:)) / nansum(W(:));
    month=month+1;
end

%Data for the spatial plot
count = 1;
for lat = 1:length(lat_dat)
    for lon = 1:length(lon_dat)
        temp_h = squeeze(height(lat,lon,:));
        p = polyfit(time, temp_h,1);
        annual(count,:) = [Latitude(lat,lon) lat_dat(lat) lon_dat(lon) p(1)];
        count = count +1;
    end
end

lat_ann = annual(:,1);
lon_ann = annual(:,3);
lon_ann = wrapTo180(lon_ann);
height1 = annual(:,4);
lat_plot = annual(:,2);

%Calculate annual sea level change with weighted mean for the global
%spatial part (-89,75;89,75 lat)
temp = height1.*cos(pi/180*lat_ann);
sum1 = nansum(temp);
sum2 = nansum(cos(pi/180*lat_ann(:)));
mean_global = sum1/sum2;

uncert_global = 1.96*nanstd(height1)/sqrt(length(height1));

%Plot of timeline, global
figure(1)
plot(time,meanData,'b-','MarkerSize',10)
xlabel('Time [year]');ylabel('Mass-induces sea level variations [mm]');
title('Monthly sea level variation with GRACE')
fitlm(time,meanData)
```

```

polyfit(time,meanData,1)

%Global spatial plot
figure(2)
[xq,yq] = meshgrid(-179.5:1:179.5, -89.5:1:89.5);
vq = griddata(lon_ann, lat_plot, height1, xq, yq);
h1 = imagesc(-180:1:180,-90:1:90,vq);
set(h1,'alphadata',~isnan(vq));
set(gca,'YDir','normal');
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'mm/yr', 'FontSize',13);
xlabel('Longitude', 'FontSize',13); ylabel('Latitude', 'FontSize',13);
title('Mass-induced height trends from GRACE, April 2002–November 2014','FontSize',16);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');

%Calculate the global monthly mean (-70;60 lat)
height(321:end,,:)=[];
height(1:58,,:)=[];
Latitude(321:end,,:)=[];
Latitude(1:58,,:)=[];
lat_dat(321:end,,:)=[];
lat_dat(1:58,,:) = [];

%Calculate the global monthly mean (-70;60 lat)
month=1;
for t=1:length(time)
    H = height(:, :,t);
    W = cos(pi/180*Latitude);
    meanData(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end

%Data for the spatial plot
count = 1;
for lat = 1:262
    for lon = 1:length(lon_dat)
        temp_h = squeeze(height(lat,lon,:));
        p = polyfit(time, temp_h,1);
        annual(count,:) = [Latitude(lat,lon) lat_dat(lat) lon_dat(lon) p(1)];
        count = count +1;
    end
end

lat_ann = annual(:,1);
lon_ann = annual(:,3);
lon_ann = wrapTo180(lon_ann);
height1 = annual(:,4);
lat_plot = annual(:,2);

%Calculate annual sea level change with weighted mean for the requested
%area
temp = height1.*cos(pi/180*lat_plot);
sum1 = nansum(temp);
sum2 = nansum(cos(pi/180*lat_plot(:)));
mean = sum1/sum2;

uncert = 1.96*nanstd(height1)/sqrt(length(height1));

%Plot of timeline, requested area
figure(3)
plot(time,meanData,'b-','MarkerSize',10)
xlabel('Time [year]');ylabel('Mass-induced sea level variations [mm]');
title('Monthly sea level variation with GRACE')
fitlm(time,meanData)
polyfit(time,meanData,1)
save('GRACE.time.txt','time','meanData','-ascii');

%Global spatial plot
figure(4)
[xq,yq] = meshgrid(-179.5:1:179.5, -59.5:1:69.5);
vq = griddata(lon_ann, lat_plot, height1, xq, yq);
h1 = imagesc(-180:1:180,-60:1:70,vq);
% h1 = imagesc(vq)
set(h1,'alphadata',~isnan(vq));
set(gca,'YDir','normal');
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'mm/yr', 'FontSize',13);

```

```
xlabel('Longitude', 'FontSize',13); ylabel('Latitude', 'FontSize',13);  
title('Mean sea level rates from GRACE','FontSize',16);  
  
hold on  
geoshow('landareas.shp', 'FaceColor', 'black');
```

F GRACE, time series

```
clear all; close all;

%Loading GRACE data
grace = load('C:\Users\Ida\Documents\DTU\Bachelor\Data\GraceJPL.mat');
lon_dat = grace.lon;
lat_dat = grace.lat;
time = grace.time;
% time_month = time/30.5;
time = time/365.25+2002; %Time from days to years
% time_month = time/12;

%Fill the empty months with NaN
height = 10*grace.lwe.thickness; %Multiply by 10 to get the anomaly in mm
vec = NaN(720,360);
height_1 = cat(3, height(:,:,1:2),vec,vec, height(:,:,3:12), vec, height(:,:,13:102),...
    vec, height(:,:,103:106), vec, height(:,:,107:116), vec, height(:,:,117:120), vec,...
    height(:,:,121:124), vec, height(:,:,125:128), vec,vec, height(:,:,129:132),vec,...
    height(:,:,133:136),vec,height(:,:,137:end));
height = height_1;
vec = NaN;
time_1 = [time(1:2)' vec vec time(3:12)' vec time(13:102)']...
    vec time(103:106)' vec time(107:116)' vec time(117:120)' vec...
    time(121:124)' vec time(125:128)' vec vec time(129:132)' vec...
    time(133:136)' vec time(137:end)'];
time = time_1;
%
% save('grace.time.txt','time','-ascii')

%Loading Argo data
h=load('C:\Users\Ida\Documents\DTU\Bachelor\Databehandling\ARGO\JAMSTEC\steric.h.mat');
SH = h.steric.h*100; %From dynamic height (dyn m = 10 m^2/s^2) to mm
lat_dat = ncread('C:\Users\Ida\Documents\DTU\Bachelor\Databehandling\ARGO\JAMSTEC\TS.200501-GLB.nc','LATITUDE');
lon_dat = ncread('C:\Users\Ida\Documents\DTU\Bachelor\Databehandling\ARGO\JAMSTEC\TS.200501-GLB.nc','LONGITUDE');
lon_dat = double(lon_dat); lat_dat = double(lat_dat);

%Cut in the GRACE-data, to fit -60,5:70,5 lat
height(:,321:end,:)=[];
height(:,1:58,:)=[];

%Spatial solution from 0,5x0,5 to 1x1 degree
count_lat = 1;
count_lon = 1;
count_t = 1;
for lat = 1:2:262
    for lon = 1:2:720
        for t = 1:length(time)
            h_grace(count_lon,count_lat,count_t) = (height(lon,lat,t)+...
                height(lon+1,lat,t)+height(lon,lat+1,t)+height(lon+1,lat+1,t))/4;
            count_t = count_t+1;
        end
        count_lon = count_lon +1;
        count_t = 1;
    end
    count_lat = count_lat +1;
    count_lon = 1;
end

%Apply Argo mask on data
Latitude = repmat(lat_dat',[360 1]); %Corresponding latitudes for each height
for lat = 1:length(lat_dat)
    for lon = 1:length(lon_dat)
        if SH(lon,lat,:)==0 %Sort out the land, where land has 0-value
            h_grace(lon,lat,:)=NaN;
            Latitude(lon,lat)=NaN;
        end
    end
end

%Spatial analysis, determining the trend
count = 1;
for lat = 1:length(lat_dat)
    for lon = 1:length(lon_dat)
```

```

        temp_h = squeeze(h_grace(lon,lat,:));
        p = polyfit(time, temp_h,1);
        annual(count,:) = [Latitude(lon,lat) lat_dat(lat) lon_dat(lon) p(1)];
        count = count +1;
    end
end

%Calculate the global monthly mean (-60,5;70,5 lat)
month=1;
for t=1:length(time)
    H = h_grace(:,:,t);
    W = cos(pi/180*Latitude);
    meanData(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('grace_glo.txt','meanData','-ascii')

%Weighted mean for each month, Pacific
%Lon, 115-290, above -30 lat
lat_pac = Latitude(115:290,32:end);
mat_pac = h_grace(115:290,32:end,:);
month=1;
for t=1:length(time)
    H = mat_pac(:,:,t);
    W = cos(pi/180*lat_pac);
    mean_pac(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('grace_pac.txt','mean_pac','-ascii')
figure(3)
plot(time,mean_pac)
title('Pacific')

%Weighted mean for each month, Atlantic
%Lon, 20 and 290/-70, above -30 lat
lat_atl = [Latitude(1:20,32:end); Latitude(291:end,32:end)];
A = h_grace(1:20,32:end,:);
B = h_grace(291:end,32:end,:);
mat_atl = cat(1,A,B);
month=1;
for t=1:length(time)
    H = mat_atl(:,:,t);
    W = cos(pi/180*lat_atl);
    mean_atl(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('grace_atl.txt','mean_atl','-ascii')
figure(4)
plot(time,mean_atl)
title('Atlantic')

%Weighted mean for each month, Indian
%Lon 20-95, above -30 lat
lat_ind = Latitude(21:94,32:end);
mat_ind = h_grace(21:94,32:end,:);
month=1;
for t=1:length(time)
    H = mat_ind(:,:,t);
    W = cos(pi/180*lat_ind);
    mean_ind(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('grace_ind.txt','mean_ind','-ascii')
figure(5)
plot(time,mean_ind)
title('Indian')

%Weighted mean for each month, south pole (under -30 lat)
%Everything under -30 lat
lat_sou = Latitude(:,1:31);
mat_sou = h_grace(:,1:31,:);
month=1;
for t=1:length(time)
    H = mat_sou(:,:,t);
    W = cos(pi/180*lat_sou);
    mean_sou(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));

```

```

    month=month+1;
end
save('grace_sou.txt','mean_sou','-ascii')
figure(6)
plot(time,mean_sou)
title('South')

%Spatial plot
figure(1)
[xq,yq] = meshgrid(-179.5:1:179.5, -60.5:1:70.5);
vq = griddata(annual(:,3), annual(:,2), annual(:,4), xq, yq);
h1 = imagesc(-180:1:180,-60.5:1:70.5,vq);
% h1 = imagesc(h-grace(:, :, 8))
set(h1, 'alphadata', ~isnan(vq));
set(gca, 'YDir', 'normal');
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'mm/yr', 'FontSize',13);
xlabel('Longitude', 'FontSize',13); ylabel('Latitude', 'FontSize',13);
title('Mean sea level rates from GRACE', 'FontSize',16);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');
% save('grace_grid.txt','vq','-ascii');

%Timeseries plot global
figure(2)
plot(time,meanData,'b-','MarkerSize',10)
xlabel('Time [year]');ylabel('Mass-induced sea level variations [mm]');
title('Monthly sea level variation with GRACE')
% fitlm(time,meanData)
% polyfit(time,meanData,1)
save('GRACE_time_mask.txt','time','meanData','-ascii');

```

G Steric height calculation from salinity and temperature profiles

Matlab functions by Nathan Bindoff, University of Tasmania

```
function [dh,delta]=stericheight(p,t,s,pref)
%
% function [dh,delta]=stericheight(p,t,s,pref)
%
% p m*1 column vector of standard pressures
% t m*n matrix of temperatures (NaN used as flags)
% s m*n matrix of salinities (NaN used as flags)
% pref scalar of reference pressurre
[m,n]=size(t);
dh=zeros(m,n);
delta=zeros(m,n);
for j=1:n
    [dh(:,j), delta(:,j)]=dynht2(p,t(:,j),s(:,j),pref);
end

function [dh, delta] =dynht2(p,t,s,pref)
% function [dh,delta] =dynht2(p,t,s,pref)
%
% Input arguments:
% p m*1 vector of pressures in decibars
% t m*1 vector of temperature, deg celsius (ipts-68)
% s m*1 vector of salinity psu (ipss-78)
%
% Output arguments:
% dh m*1 vector of dynamic height (dynamic m = 10 m**2/s**2)
% delta m*1 vector of specific volume anomaly (dimensionless)
%
% dynamic height [dynamic m = 10 m**2/s**2] referenced to 'pref'
% units:
%     reference press pref      decibars
%     pressure      p          decibars
%     temperature   t          deg celsius (ipts-68)
%     salinity      s          psu (ipss-78)
%     delta         spec. vol. anomaly dimensionless
% r. schlitzer (5/18/89) modified by c. wunsch 2/2/90
%%(replaced loop by cumsum operation for speed) and
%%returns specific volume anomaly -delta
% modified by N.L. Bindoff
% (i) to work with NaN flags for missing data
% (ii) to give dynht wrt to the bottom or the pref. Values below
%     bottom topography or non-existent are all set to NaN in
% this code.
%
m=length(p);
dh=zeros(m,1);
n=max(find(~isnan(t)));
id=find(p==pref);
if length(id)==0, fprintf('dynht: no data at pref= %g\n',pref), end
delta=eos80(p,t,s)-v350p(p);
dp=p(2:n)-p(1:n-1);
mdel=(delta(1:n-1)+delta(2:n))/2;
dh(2:n)=-cumsum(dp.*mdel);
% minus sign because of direction of
% integration; 0 for surface value
if id > n,
    dh(1:n)=dh(1:n)-dh(n);
else
    dh(1:n)=dh(1:n)-dh(id);
end
dh(n+1:m)=NaN*ones(m-n,1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```


H ARGO, steric height trends

```
clear all; close all;

textfiletype = 'C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\ARGO\JAMSTEC\*.nc';
filenames = dir(textfiletype);
number_of_files = length(filenames);

%Load information same for all files
lat = ncread('C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\ARGO\JAMSTEC\TS_200501_GLB.nc', 'LATITUDE');
lon = ncread('C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\ARGO\JAMSTEC\TS_200501_GLB.nc', 'LONGITUDE');
pres = ncread('C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\ARGO\JAMSTEC\TS_200501_GLB.nc', 'PRES');
pref = 2000;

%Counters
count = 1;
count1= 1;
month=0;

%Preallocate space
monthly = zeros(length(lon),length(lat),1);
steric_h = zeros(length(lon),length(lat),number_of_files);

for ii = 1:number_of_files
    file = filenames(ii,1).name;
    temp = ncread(file, 'TOI');
    sal = ncread(file, 'SOI');

    for jj = 1:length(lon)
        for kk = 1:length(lat)
            [dh(:,1) delta(:,1)] = stericheight(pres,squeeze(temp(jj,kk,:)),squeeze(sal(jj,kk,:)),pref);
            monthly(jj,kk,:) = nansum(dh);
        end
    end
    steric_h(:,:,count) = monthly;
    count = count+1;
    month = month+1
end
steric_h = double(steric_h);

save('steric_h.mat','steric_h');
```

I ARGO, spatial analyses and time series

```
clear all; close all;

%Load the calculated steric height
h=load('steric.h.mat');

SH = h.steric.h*100; %From dynamic height (dyn m = 10 m^2/s^2) to mm

%Data to use in the calculations
lat = ncread('C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\ARGO\JAMSTEC\TS-200501-GLB.nc', 'LATITUDE');
lon = ncread('C:\Users\Ida\Documents\DTU\Bachelor\Datahandling\ARGO\JAMSTEC\TS-200501-GLB.nc', 'LONGITUDE');
time = (2002+4/12):1/12:(2014+11/12);
lat = double(lat);
lon = double(lon);

%Spatial analysis, determine Argo trends
count1 = 1;
for jj = 1:length(lon)
    for kk = 1:length(lat)
        p = polyfit(time, squeeze(SH(jj, kk, :)), 1);
        trend1(count1, :) = [lat(kk) lon(jj) p(1, :)];
        count1 = count1+1;
    end
end

% trend1 = double(trend1);
% save('trend_annual_ARGO_0516.txt', 'trend1', '-ascii');

%Spatial plot
figure(1)
[xq, yq] = meshgrid(-179.5:1:179.5, -60.5:1:70.5);
vq = griddata(trend1(:, 2), trend1(:, 1), trend1(:, 3), xq, yq);
b = imagesc(-180:180, -60.5:1:70.5, vq);
set(b, 'AlphaData', ~isnan(vq));
set(gca, 'YDir', 'normal')
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'mm/yr', 'FontSize', 13);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');
xlabel('Longitude', 'FontSize', 13); ylabel('Latitude', 'FontSize', 13);
title('Steric height trends from ARGO April 2002–November 2014', 'FontSize', 16)
save('argo_grid.txt', 'vq', '-ascii')

%Spatial weighted mean
temp = trend1(:, 3) .* cos(pi/180*trend1(:, 1));
sum1 = nansum(temp);
sum2 = nansum(cos(pi/180*trend1(:, 1)));
mean1 = sum1/sum2;

uncert = 1.96*nanstd(trend1(:, 3))/sqrt(length(trend1(:, 3)));
%%

%Global monthly mean
Latitude = repmat(lat', [360 1]); % latitude correspond
month = 1;
for t=1:length(time)
    A = SH(:, :, t);
    W = cos(pi/180*Latitude);
    meanData(month, :) = nansum(A(:) .* W(:)) / nansum(W(:));
    month=month+1;
end
save('argo_glo.txt', 'meanData', '-ascii')

%Weighted mean for each month, Pacific
%Lon, 115–290, above -30 lat
lat_pac = Latitude(115:290, 32:end);
% lat_pac =
mat_pac = SH(115:290, 32:end, :);
month=1;
for t=1:length(time)
    H = mat_pac(:, :, t);
    W = cos(pi/180*lat_pac);
    mean_pac(month, :) = nansum(H(:) .* W(:)) ./ nansum(W(:));
    month=month+1;
end
```

```

save('argo_pac.txt','mean_pac','-ascii')
figure(3)
plot(time,mean_pac)
title('Pacific')

%Weighted mean for each month, Atlantic
%Lon, 20 and 290/-70, above -30 lat
lat_atl = [Latitude(1:20,32:end); Latitude(291:end,32:end)];
A = SH(1:20,32:end,:);
B = SH(291:end,32:end,:);
mat_atl = cat(1,A,B);
month=1;
for t=1:length(time)
    H = mat_atl(:,:,t);
    W = cos(pi/180*lat_atl);
    mean_atl(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('argo_atl.txt','mean_atl','-ascii')
figure(4)
plot(time,mean_atl)
title('Atlantic')

%Weighted mean for each month, Indian
%Lon 20-95, above -30 lat
lat_ind = Latitude(21:94,32:end);
mat_ind = SH(21:94,32:end,:);
month=1;
for t=1:length(time)
    H = mat_ind(:,:,t);
    W = cos(pi/180*lat_ind);
    mean_ind(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('argo_ind.txt','mean_ind','-ascii')
figure(5)
plot(time,mean_ind)
title('Indian')
%Weighted mean for each month, south pole (under -30 lat)
%Everything under -30 lat
lat_sou = Latitude(:,1:31);
mat_sou = SH(:,1:31,:);

month=1;
for t=1:length(time)
    H = mat_sou(:,:,t);
    W = cos(pi/180*lat_sou);
    mean_sou(month,:) = nansum(H(:).*W(:)) ./ nansum(W(:));
    month=month+1;
end
save('argo_sou.txt','mean_sou','-ascii')
figure(6)
plot(time,mean_sou)
title('South')

t2 = time*2*pi;
t2 = t2';
e = [cos(t2) sin(t2)];
c = e\mean_sou;
sst2 = cos(t2)*c(1)+sin(t2)*c(2);
h2 = mean_sou - sst2;

figure(7)
plot(time,h2)
hold on
plot(time,mean_sou)

%Timeseries plot
figure(2)
plot(time,meanData,'.-')
xlabel('Time [yr]','FontSize',13);ylabel('Steric height variation [cm]','FontSize',13);
title('Monthly variation in steric height ARGO, April 2002–November 2014','FontSize',16)
polyfit(time, meanData,1)
fitlm(time,meanData')
meanData = meanData';
save('Argo.time.txt','time','meanData','-ascii')

```

J Joint time series analysis

```
clear all; close all;

%Loading data
argo = load('C:\Users\Ida\Documents\DTU\Bachelor\Databehandling\ARGO\JAMSTEC\Argo-time.txt');
grace = load('C:\Users\Ida\Documents\DTU\Bachelor\Databehandling\GRACE\GRACE-time.txt');
alt = load('C:\Users\Ida\Documents\DTU\Bachelor\Databehandling\Altimetry\altimetry-time.txt');

grace_t = load('grace-time.txt');
alt_t = 2002+4/12:1/12:2014+11/12;
argo_t = argo(1,:);

%Grace time without the points with no data
grace_t1=grace_t(~isnan(grace_t));

%Timeseries for the mass-induced height in different areas from GRACE
format_spec = '%f';
filename = ['grace_glo.txt'; 'grace_atl.txt' ; 'grace_ind.txt' ; 'grace_pac.txt'; 'grace_sou.txt'];
num_of_files = 5;
for ii = 1:num_of_files
    % for ii = 1
    file = filename(ii,:);

    fid = fopen(file,'r');
    grace = textscan(fid,format_spec);
    fclose(fid);
    h_grace = grace{1,1}/10;
    h_grace1 = h_grace;
    grace_h1 = h_grace1(h_grace1~=0);

    %Remove annual signals with smooth
    grace_h(ii,:) = smooth(h_grace,13);
    grace_h(ii,:) = grace_h(ii,:)-grace_h(ii,1);

    %Calculate trends and uncertainties with least squares method
    x = grace_t1';
    X = [x.^1 x.^0] ;
    y = grace_h1;

    %Linear coefficients
    beta_grace(:,ii) = (X'*X)\X'*y;
    s(ii) = (y-X*beta_grace(:,ii))'*(y-X*beta_grace(:,ii))/((length(grace_h1)-2));

    %Uncertainties
    uncert(:,ii) = s(ii)*inv(X'*X);
    uncert_grace(ii) = sqrt(uncert(1,1))*2;

    %For the smoothing plot
    if ii==1
        %Harmonic smoothing
        t2 = grace_t1*2*pi;
        t2 = t2';
        e = [cos(t2) sin(t2)];
        c = e\grace_h1;
        slv2 = cos(t2)*c(1)+sin(t2)*c(2);
        slv = grace_h1 - slv2;

        grace_smooth = smooth(grace_h1,13)
        figure(1)
        hold on
        plot(grace_t1',grace_h1,'b',grace_t1,(slv'),'r',grace_t1,grace_smooth,'g')
        hold off
        title('Time series for GRACE','FontSize',16);
        xlabel('Time [year]','FontSize',13);ylabel('Mass-induced height variations [cm]','FontSize',13)
        legend('Original','Harmonic pred.','Moving average','Location','northwest')
    end
end

%Timeseries for the total height in different areas from Altimetry
filename = ['alt_glo.txt'; 'alt_atl.txt' ; 'alt_ind.txt' ; 'alt_pac.txt'; 'alt_sou.txt'];
num_of_files = 5;
for ii = 1:num_of_files
    file = filename(ii,:);
```

```

fid = fopen(file, 'r');
alt = textscan(fid, format_spec);
fclose(fid);
h_alt = alt{1,1}/10;

%Remove annual signals with smooth
alt_h(ii,:) = smooth(h_alt,13);
alt_h(ii,:) = alt_h(ii,:)-alt_h(ii,1);

%Calculate trends and uncertainties with least squares method
x = alt.t';
X = [x.^1 x.^0] ;
y = alt_h(ii,:)' ;

%Linear coefficients
beta_alt(:,ii) = (X'*X)\X'*y;
s(ii) = (y-X*beta_alt(:,ii))'*(y-X*beta_alt(:,ii))/((length(alt_h)-2));

%Uncertainties
uncert(:,ii) = s(ii)*inv(X'*X);
uncert_alt(ii) = sqrt(uncert(1,1))*2;
end

%Timeseries for the steric height in different areas from Argo
filename = ['argo_glo.txt'; 'argo_atl.txt' ; 'argo_ind.txt' ; 'argo_pac.txt'; 'argo_sou.txt'];
num_of_files = 5;
for ii = 1:num_of_files
    file = filename(ii,:);

    fid = fopen(file, 'r');
    argo1 = textscan(fid, format_spec);
    fclose(fid);
    h_argo = argo1{1,1}/10;

    h_sub(ii)=-alt_h(ii,1)+grace_h(ii,1);
    h_sub1(ii) = -h_sub(ii)+h_argo(1);
    h_argo = h_argo-h_sub1(ii);

    %Remove the annual signal with smooth
    argo_h(ii,:) = smooth(h_argo,13);
    argo_h(ii,:) = argo_h(ii,:)-argo_h(ii,1);

    %Calculate trends and uncertainties with least squares method
    x = argo.t';
    X = [x.^1 x.^0] ;
    y = argo_h(ii,:)' ;

    %Linear coefficients
    beta_argo(:,ii) = (X'*X)\X'*y;
    s(ii) = (y-X*beta_argo(:,ii))'*(y-X*beta_argo(:,ii))/((length(argo_h)-2));

    %Uncertainties
    uncert(:,ii) = s(ii)*inv(X'*X);
    uncert_argo(ii) = sqrt(uncert(1,1))*2;
end

%Trends and uncertainties for the joint timeseries of the steric and
%mass-induced heights
for ii = 1:5
    %Calculate trends and uncertainties with least squares method
    x = grace.t';
    X = [x.^1 x.^0] ;
    y = grace_h(ii,:)+argo_h(ii,:);

    fitlm(x,y(:))
end

%The spatial grids
alt_grid=load('alt_grid.txt');
grace_grid = load('grace_grid.txt');
argo_grid = load('argo_grid.txt');

%The difference in the grids, showing correlation

```

```

figure(2)
subplot(2,2,1)
diff = alt_grid - (grace_grid+argo_grid);
b = imagesc(-180:180,-60.5:1:70.5,diff)
set(b,'AlphaData',~isnan(diff));
set(gca,'YDir','normal')
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'Differens in mm/yr', 'FontSize',10);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');
xlabel('Longitude','FontSize',10);ylabel('Latitude','FontSize',10);
title('a)  $h_{\{total\}}-(h_{\{steric\}}+h_{\{mass\}})$ ','FontSize',13)

subplot(2,2,2)
diff = grace_grid + argo_grid;
b = imagesc(-180:180,-60.5:1:70.5,diff)
set(b,'AlphaData',~isnan(diff));
set(gca,'YDir','normal')
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'Differens in mm/yr', 'FontSize',10);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');
xlabel('Longitude','FontSize',10);ylabel('Latitude','FontSize',10);
title('b)  $h_{\{steric\}}+h_{\{mass\}}$ ','FontSize',13)

subplot(2,2,3)
diff = alt_grid-argo_grid;
b = imagesc(-180:180,-60.5:1:70.5,diff)
set(b,'AlphaData',~isnan(diff));
set(gca,'YDir','normal')
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'Differens in mm/yr', 'FontSize',10);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');
xlabel('Longitude','FontSize',10);ylabel('Latitude','FontSize',10);
title('c)  $h_{\{total\}}-h_{\{steric\}}$ ','FontSize',13)

subplot(2,2,4)
diff = alt_grid - grace_grid;
b = imagesc(-180:180,-60.5:1:70.5,diff)
set(b,'AlphaData',~isnan(diff));
set(gca,'YDir','normal')
c=colorbar; caxis([-10 10]); colormap(jet); ylabel(c, 'Differens in mm/yr', 'FontSize',10);
hold on
geoshow('landareas.shp', 'FaceColor', 'black');
xlabel('Longitude','FontSize',10);ylabel('Latitude','FontSize',10);
title('d)  $h_{\{total\}}-h_{\{mass\}}$ ','FontSize',13)

% save('argo_grid.txt','vq','-ascii')

%Plot of timeseries for the different parts
figure(3)
hold on
plot(alt_t,alt_h(1,:),'r',grace_t,grace_h(1,:),'b',argo_t,argo_h(1:),'g',...
     argo_t,argo_h(1:)+grace_h(1:),'y')
legend('Altimetry','Mass component from GRACE','Steric component from Argo',...
       'Mass+steric height','Location','northwest');
xlabel('Time [year]','FontSize',13);ylabel('Variation in global mean sea level [cm]','FontSize',13);
title('Global sea level variation','FontSize',16);
hold off

figure(4)
hold on
plot(alt_t,alt_h(2,:),'r',grace_t,grace_h(2,:),'b',argo_t,argo_h(2:),'g',...
     argo_t,argo_h(2:)+grace_h(2:),'y')
legend('Altimetry','Mass component from GRACE','Steric component from Argo',...
       'Mass+steric height','Location','northwest');
xlabel('Time [year]','FontSize',13);ylabel('Variation in mean sea level [cm]','...
       'FontSize',13);
title('Atlantic ocean sea level variation','FontSize',16);
hold off

figure(5)
hold on
plot(alt_t,alt_h(3,:),'r',grace_t,grace_h(3:),'b',argo_t,argo_h(3:),'g',...
     argo_t,argo_h(3:)+grace_h(3:),'y')
legend('Altimetry','Mass component from GRACE','Steric component from Argo',...
       'Mass+steric height','Location','northwest');
xlabel('Time [year]','FontSize',13);ylabel('Variation in mean sea level [cm]','...

```

```

    'FontSize',13);
title('Indian ocean sea level variation','FontSize',16);
hold off

figure(6)
hold on
plot(alt_t,alt_h(4,:), 'r',grace_t,grace_h(4,:), 'b',argo_t,argo_h(4,:), 'g',...
     argo_t,argo_h(4,)+grace_h(4,:), 'y')
legend('Altimetry','Mass component from GRACE','Steric component from Argo','Mass+steric height','Location','n',...
       'FontSize',13);ylabel('Variation in mean sea level [cm]','FontSize',13);
title('Pacific ocean sea level variation','FontSize',16);
hold off

figure(7)
hold on
plot(alt_t,alt_h(5,:), 'r',grace_t,grace_h(5,:), 'b',argo_t,argo_h(5,:), 'g',...
     argo_t,argo_h(5,)+grace_h(5,:), 'y')
legend('Altimetry','Mass component from GRACE','Steric component from Argo',...
       'Mass+steric height','Location','northwest');
xlabel('Time [year]','FontSize',13);ylabel('Variation in mean sea level [cm]','...
       'FontSize',13);
title('South pole sea level variation','FontSize',16);
hold off

figure(8)
hold on
plot(alt_t,alt_h(1,:), 'r')
plot(argo_t,argo_h(1,)+grace_h(1,:), 'y')
legend('Altimetry','Argo+GRACE')
xlabel('Time [year]','FontSize',13);ylabel('Variation in global mean sea level [cm]','...
       'FontSize',13);
title('Altimetry','FontSize',16);
hold off

figure(9)
hold on
plot(grace_t,grace_h(1,:), 'r')
plot(grace_t,alt_h(1,)-argo_h(1,),'y')
legend('GRACE','Altimetry-Argo')
xlabel('Time [year]','FontSize',13);ylabel('Variation in global mean sea level [cm]','...
       'FontSize',13);
title('Mass-induced height variations','FontSize',16);
hold off

figure(10)
hold on
plot(argo_t,argo_h(1,),'r')
plot(argo_t,alt_h(1,)-grace_h(1,),'y')
legend('Argo','Altimetry-GRACE')
xlabel('Time [year]','FontSize',13);ylabel('Variation in global mean sea level [cm]','...
       'FontSize',13);
title('Steric height variations','FontSize',16);
hold off

```

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