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Arctic Sea Level Change over the altimetry era and reconstructed over the last 60 years

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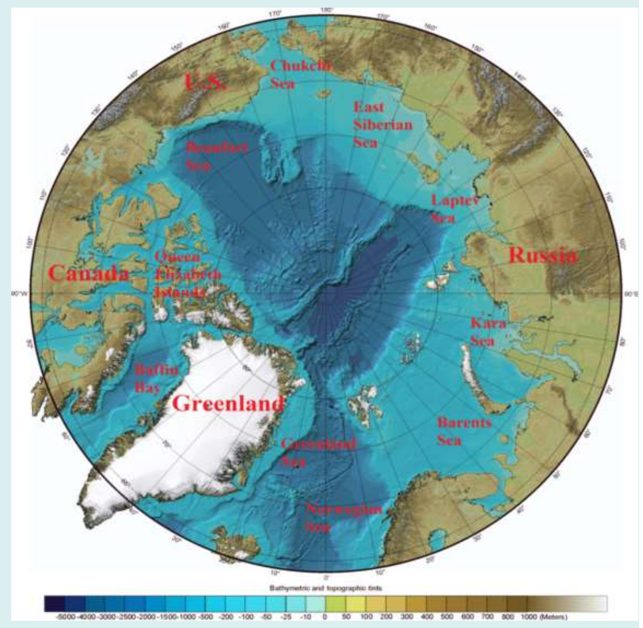
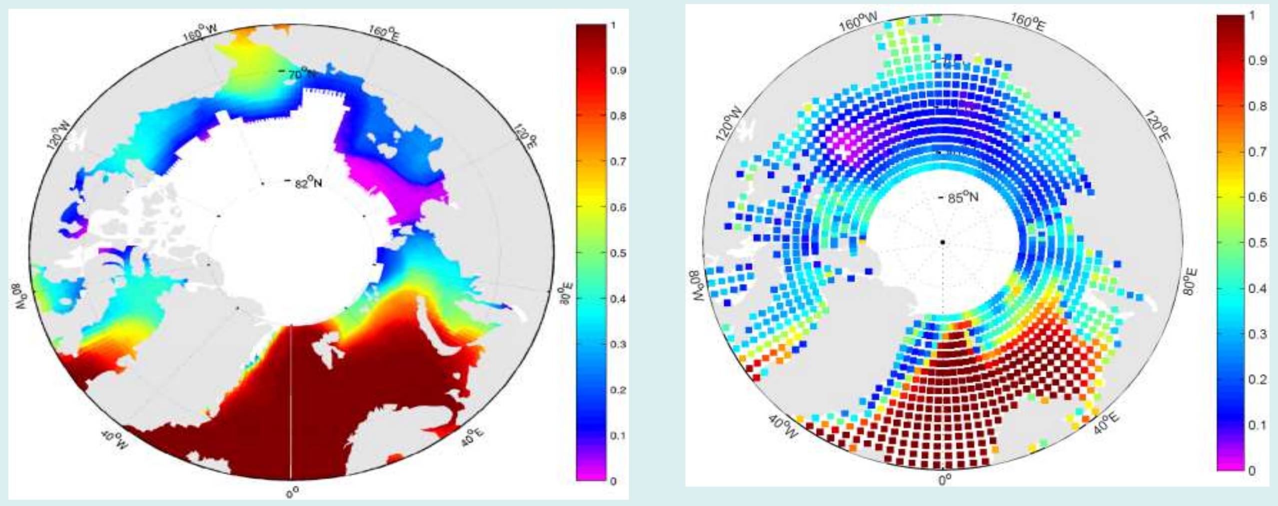
Abstract



The Arctic Ocean process severe limitations on the use of altimetry and tide gauge data for sea level studies and prediction due to the presence of seasonal or permanent sea ice. In order to overcome this issue we reprocessed all altimetry data with editing tailored to Arctic conditions, hereby more than doubling the amount of altimetry in the Arctic Ocean with up to 10 times the amount of data in regions like the Beaufort Gyre region compared with AVISO and RADS datasets. With recent data from the Cryosat-2 SAR altimetry the time-series now runs from 1991-2015 a total of nearly 25 years.

Good altimetric data is seen to crucial for sea level studies and profoundly for sea level reconstruction where we present a 60 years sea level reconstruction based on this new data set. We here present a new multi-decade altimetric dataset and a 60 year reconstruction of sea level based on this together with tide gauge information. From our reconstruction, we found that the Arctic mean sea level trend is around 1.5 mm +/- 0.3 mm/y for the period 1950 to 2010, between 68ºN and 82ºN. This value is in good agreement with the global mean trend of 1.8 +/- 0.3 mm/y over the same period as found by Church and White (2004). We also find significant higher trend in the Beaufort Gyre region showing an increase in sea level over the last decade up to 2011.

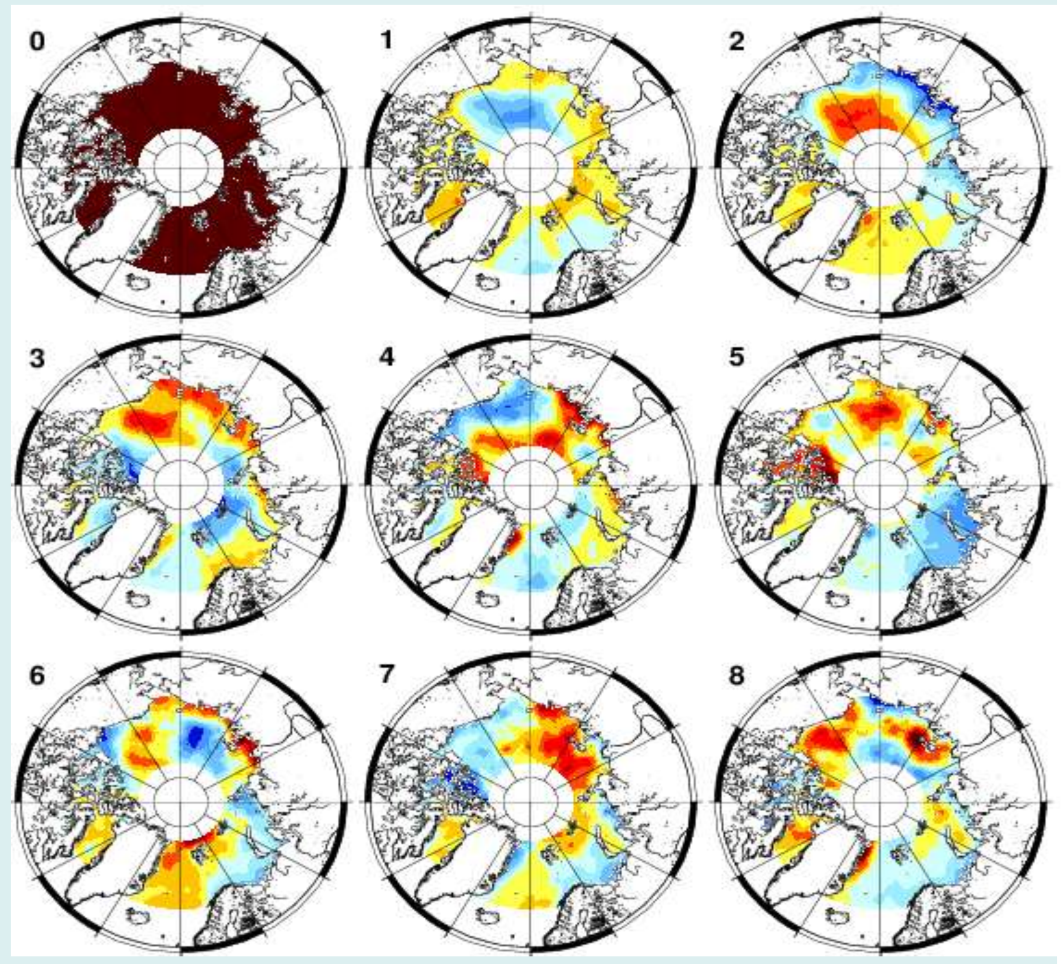
The DTU Arctic Sea level dataset.



The fraction of all possible data over 20 years (1992-2012) is shown. Left the fraction of all data (weekly basis) from AVISO. Right: The fraction of all data in the DTU Arctic Sea Level data set.

In the North Atlantic, this fractions is close to 1 (all data available) whereas in the Beaufort region in the interior of the Arctic the fraction is close to 0 (no data) for the AVISO datasets due to the editing relative to the old CLS01 MSS. For the DTU dataset the fraction is some 10-20 % indicating important Recovery of data.

Below the The leading eight EOFs (EOF1-EOF8) derived from satellite altimetry data between 68 ºN and 82 º N Besides these eight EOF's, an additional EOF0 was introduced as a constant for the region. The scaling for the EOF's is arbitrarily so not given.



Stable Arctic Sea level reconstruction

Sea level reconstruction is usually carried out using an ordinary least squares regression (OLS). Assuming two datasets to be related by a linear equation, one may obtain the parameters for that linear equation through regression. Defining a response variable y, a multivariate predictor X and model parameters α the regression equation becomes

$$y = X\alpha + e \qquad (1)$$

where e are the residuals, we want to obtain the "best" estimate for α. The canonical technique for satellite- and tide gauge-based sea level reconstruction was established in Church et al. (2004)

In the canonical reconstruction we shall solve for sea level coefficients α(l x M), that is, a scalar coefficient for each eigenfunction per timestep or temporal points M of the (tide gauge) dataset, while spatially covering the l leading eigenfunctions in the dataset.
Minimizing the cost function, one obtains the solution for α :

$$\alpha = P E^T H^T R^{-1} G \qquad (2)$$

where

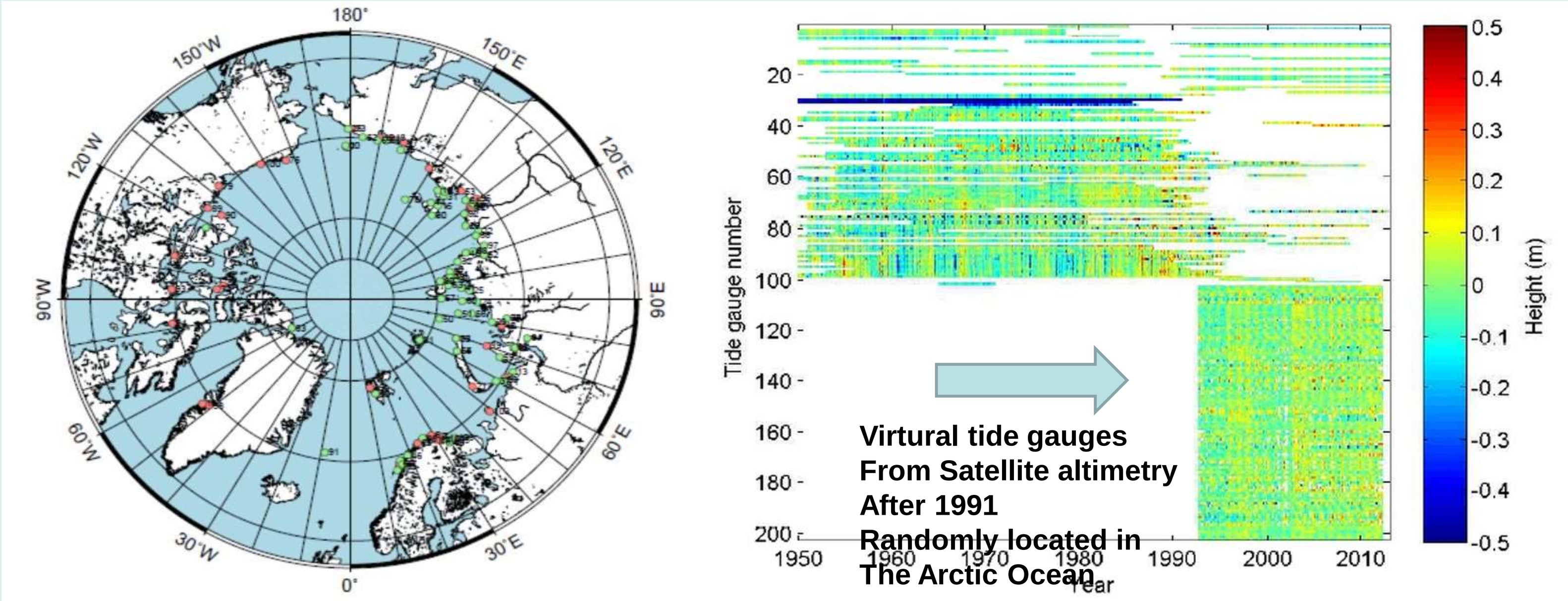
$$P = (E^T H^T R^{-1} H E + \Lambda^{-1})^{-1} \qquad (3)$$

G is the data-matrix, R is the error covariance matrix, H(N x n) is the indicator matrix which is zero everywhere, except at H(j,k) = 1 where j is the tide gauge index, and k is the index of its closest pixel in the calibration grid. Λ is the selected eigenvalues. A detailed description of the reconstruction technique using ridge regression and its adaptation to the Arctic Ocean is available online from (Svendsen, 2015)
A significant adaptation of the technique from Church et al. (2004) is necessary when reconstructing Arctic sea level, as the tide gauge records are too short and scattered for the reconstruction which in the approach by Church et al. (2004) demanded continuous time series throughout the period 1950 to today. Consequently the technique had to be adapted to allow for sparse and incomplete datamatrices as input to the reconstruction. Estimation of the covariance matrix has to be adapted so that was computed from available (incomplete) data. To extract as much information as possible from the tide gauge dataset, we solve for the α coefficents once per timestep (rather than all at once), with a time-variable H matrix that selects the available tide gauges at that point in time.

A different reconstruction approach is discussed in Ray and Douglas (2011), where no differencing is used, and instead one uses the original tide gauge records and solves for the vertical datum of each individual tide gauge as part of the solution. This is done to address the integration error that can accumulate as one moves back in time, as nothing forces the reconstruction back to reality when errors appear in Equation 2.

Arctic Tide Gauges

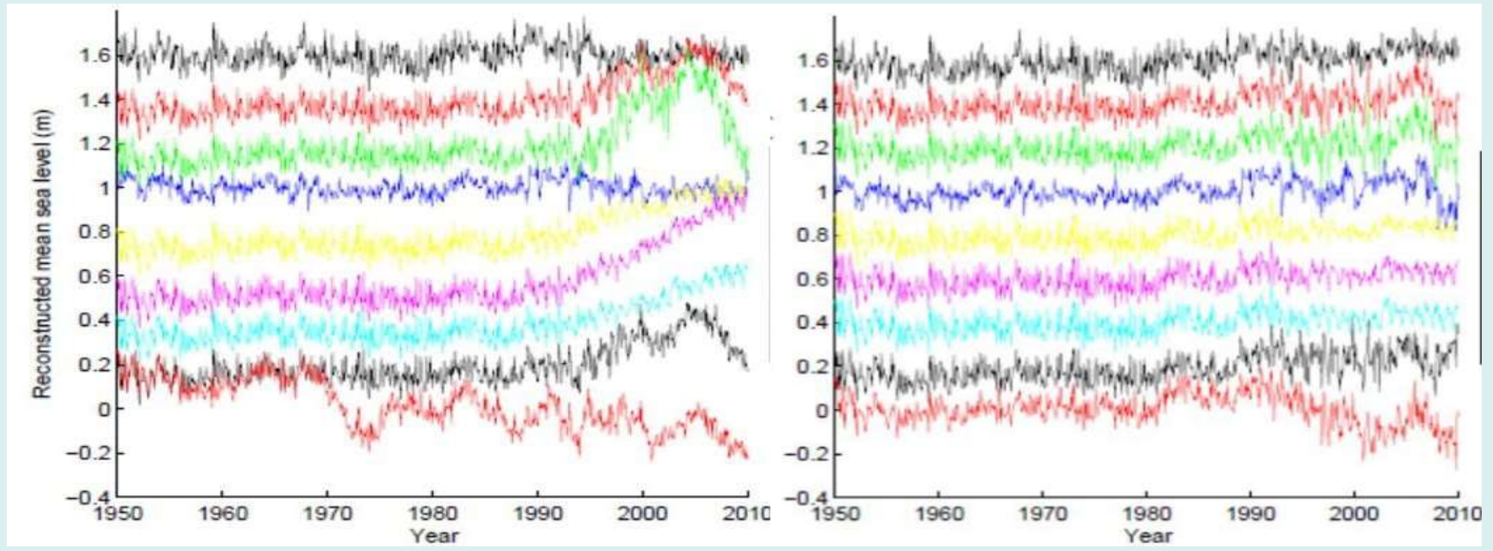
The 102 tide gauges from the Permanent Service of mean sea level (PSMSL, Woodworth and Player, 2003; Holgate et al., 2013) around the Arctic Ocean are plotted in Figure 1 along with four addition "metric-only" data without a historical datum mainly around Greenland. Both set of tide gauges can still be used in the reconstruction



Temporal outages in the tide gauges or vertical datum shifts in the time series generally needs careful handling in both methods. A straight forward method is to split the affected tide gauge in two if temporal outages larger than a certain time and vertical offset larger than a certain amount is encountered. Here we included a study of the effect on the sea level reconstruction accounting for vertical outages longer than 6 month and vertical jumps larger than +/- 25 cm.

Reconstruction results.

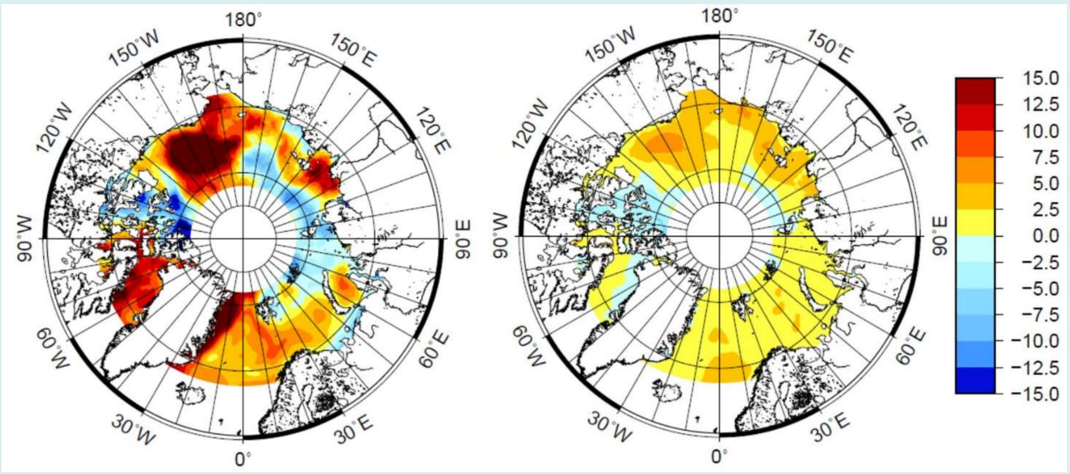
A number of parallel reconstructions were made for the Arctic to compare results using cumulated differences (as Church et al. (2004)) and a reconstruction solving for the tide gauge datums (Ray and Douglas, 2011). In total 8 different reconstructions were implemented.



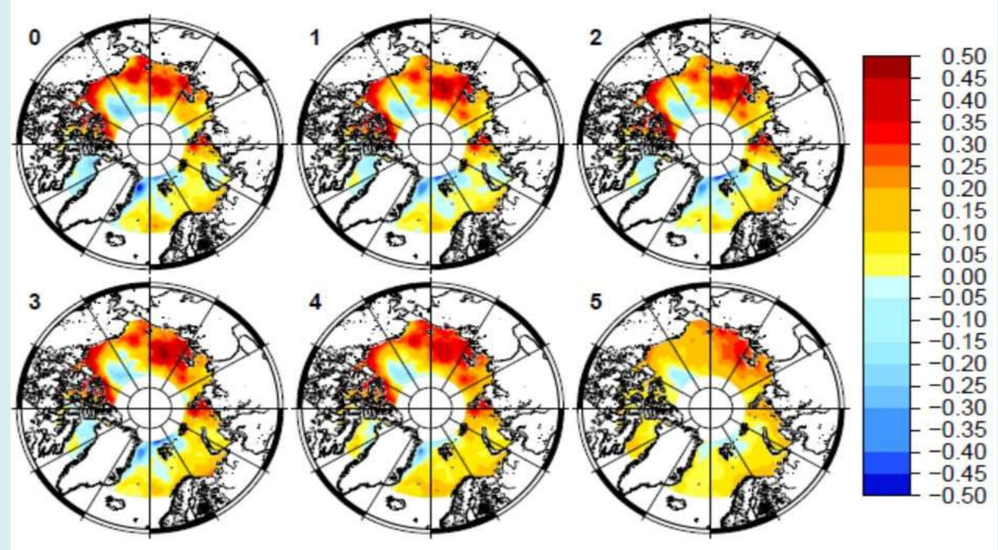
Spatially integrated sea level for eight parallel reconstructions for the Arctic Ocean using the cumulated difference methods by Church and White (left panel) and the datum shift estimation by Ray and Douglas (right panel). From top to bottom they the reconstructions are in black: EOF0 only; red: EOF0-8; green: no regularization applied; blue: using annual tide gauge data; yellow: adding 50 virtual tide gauges; purple: adding 100 virtual tide gauges; cyan: adding 200 virtual tide gauges; dark grey; tide records split at gaps and brown; tide gauge records split at vertical jumps.

	Nb Virtual gauges	Linear Trend (1950-2010) mm/y	Linear Trend (1993-2012) mm/y
Cumulative Differences (Church & White)	0	4.3 +/- 0.4	3.3 +/- 2.1
	50	5.3 +/- 0.4	11.6 +/- 0.9
	100	7.8 +/- 0.4	23.6 +/- 0.8
	200	5.0 +/- 0.4	15.1 +/- 0.8
Datum Fit. (Ray & Douglas)	0	1.5 +/- 0.3	2.3 +/- 2.4
	50	1.5 +/- 0.3	2.0 +/- 1.0
	100	1.5 +/- 0.3	1.8 +/- 1.1
	200	1.5 +/- 0.3	1.8 +/- 1.2

Trend based on Arctic sea level reconstructions using different methods and number of virtual tide gauges during the altimetry era. The first column gives the trend for the past 60 years whereas the second column shows the trend for the altimetry era (20 year).



Spatial pattern of sea level trend for the 1950–2010 period in mm/year and stabilized using 60 virtual tide gauges after 1993. In the left panel the reconstruction based on cumulated differences (Church and White) in the left panel and from the datum shift estimation (Ray/Douglas)



The decadal means for the 1950-2010 period relative to an arbitrary mean. Indeed the decadal means shows i very little variations in the first three decades similar to the work by Prochutinski et al (2009)and Pavlov (2001) which gives good faith in the sea level reconstruction.

References

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