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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, thereby more than doubling the amount of available data 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 new 60 year sea level reconstruction based on this new data set. We here present a new multi-decadal altimetric data and a 60 year reconstruction of sea level based on this new data set along with tide gauge information. From our reconstruction, we found that the Arctic mean sea level trend is around 1.5 mm +/- 0.3 mm/yr 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/yr over the same period as found by Church and White (2004). We also find significant higher trends 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 fraction 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 CLS/1 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 1991 and 2012. Besides these eight EOFs, an additional EOF was introduced as a constant for the region.

The scaling for the EOFs is arbitrarily 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

\[ y = Xα + e \]

where α 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(j,k) that is, a scalar coefficient for each eigenfunction per timescale or temporal points M of the tide gauge dataset, while spatially covering the 1 leading eigenfunctions in the dataset.

Minimizing the cost function, one obtains the solution for α:

\[ α = (E†F†HE + A†)⁻¹E†Y \]

where \( E \) is the data matrix, \( R \) is the error covariance matrix, \( H \) is the indicator matrix which is zero everywhere, except at (HL), where \( L \) is the index of its closest pixel in the calibration grid. A is the selected eigenvectors.

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 datamatrixes 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 coefficients once per timescale (rather than all at once), with a 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 "virtual gauges" that are linked to tide gauges in Greenland. Both set of tide gauges can still be used in the reconstruction

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.

Spatial pattern of sea level trend for the 1950-2010 period in m/yr/ and stabilized using 60 virtual tide gauge after 1993. In the left panel the reconstruction based on cumulated differences (Church and White) in the left panel and from the mean sea level trend (Ray/Douglas)

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

References