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# Analysis of sea-level reconstruction techniques for the Arctic Ocean

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## Introduction

For reconstructing historical sea levels in the Arctic area, lack of data presents a major challenge. We attempt to adapt the model by Church et al. (2004), examining inclusion criteria for tide gauges in the area. The tide gauge records are taken from the PSMSL database.

The reconstruction model is based upon spatial, stationary patterns of variability extracted from a calibration period, usually satellite data; however, for this exercise, we are using data from the Drakkar ocean model, covering the period 1958–2008 with monthly data. These patterns are determined as empirical orthogonal functions (EOFs). The model determines, for each point in time, an appropriately weighted sum of these, constrained locally by tide gauge records and regularized per Kaplan et al. (1997).

The *leverage* of each tide gauge is a statistical measure of its influence on the result. This way, we can readily identify possible outliers among the tide gauge records in a procedural, objective way.

## Model

We use the model described by Kaplan et al. (1997), i.e. minimizing the cost function

$$(\mathbf{H}\mathbf{E}\boldsymbol{\alpha} - \mathbf{G})^{\mathsf{T}}\,\mathbf{R}^{-1}\,(\mathbf{H}\mathbf{E}\boldsymbol{\alpha} - \mathbf{G}) + \boldsymbol{\alpha}^{\mathsf{T}}\boldsymbol{\Lambda}^{-1}\boldsymbol{\alpha}$$

where $\mathbf{E}$ are the retained eigenfunctions from a calibration period, $\mathbf{G}$ are the tide gauge records, $\mathbf{H}$ an indicator matrix, $\mathbf{R}$ describes the error covariance, and $\boldsymbol{\Lambda}$ contains the retained eigenvalues. We solve for $\boldsymbol{\alpha}$, giving coefficients for the eigenfunctions at each time step.

To capture any overall trend in the data, the eigenfunction basis is augmented with an "EOF0" (a spatially uniform pattern).

As in Church et al. (2004), we use first differences of the tide gauge time series, avoiding the need for a consistent vertical datum for the tide gauges, something that is hard to provide in the Arctic.

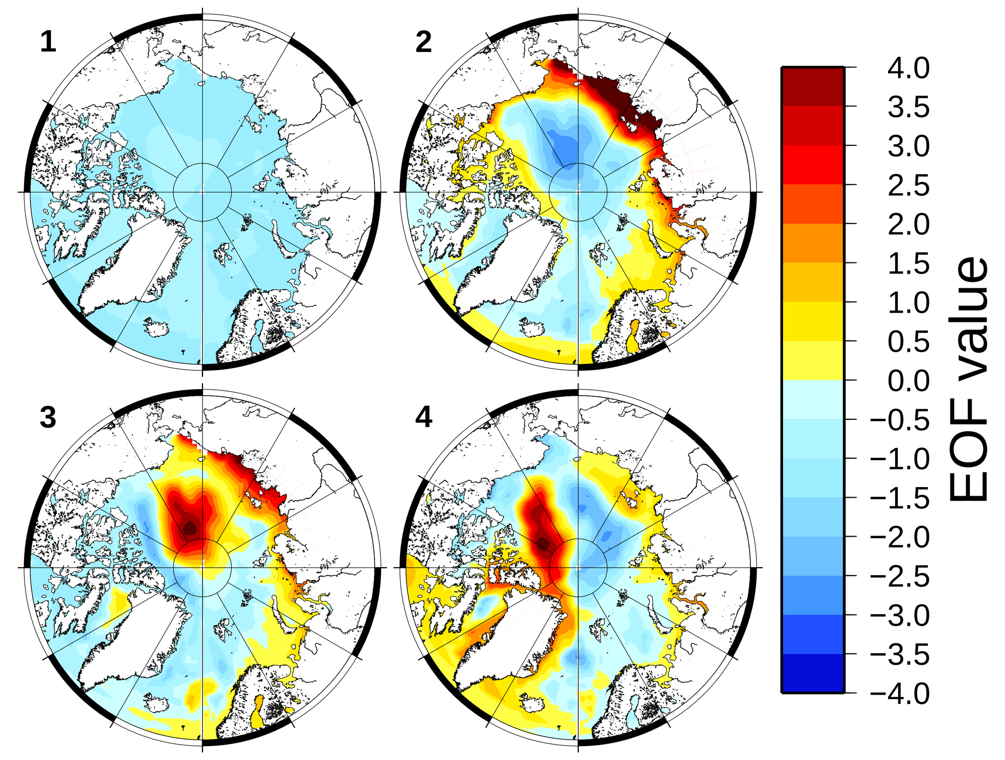
## Data

For this reconstruction, only PSMSL tide gauges above 68°N have been included. The differenced time series have had glacial isostatic adjustment (GIA) relative sea level predictions (Peltier ICE-5G) removed. The time series do not have inverse barometric (IB) correction applied in this case. All data are preprocessed to remove a constant term, a 12-month oscillation and a 6-month oscillation.

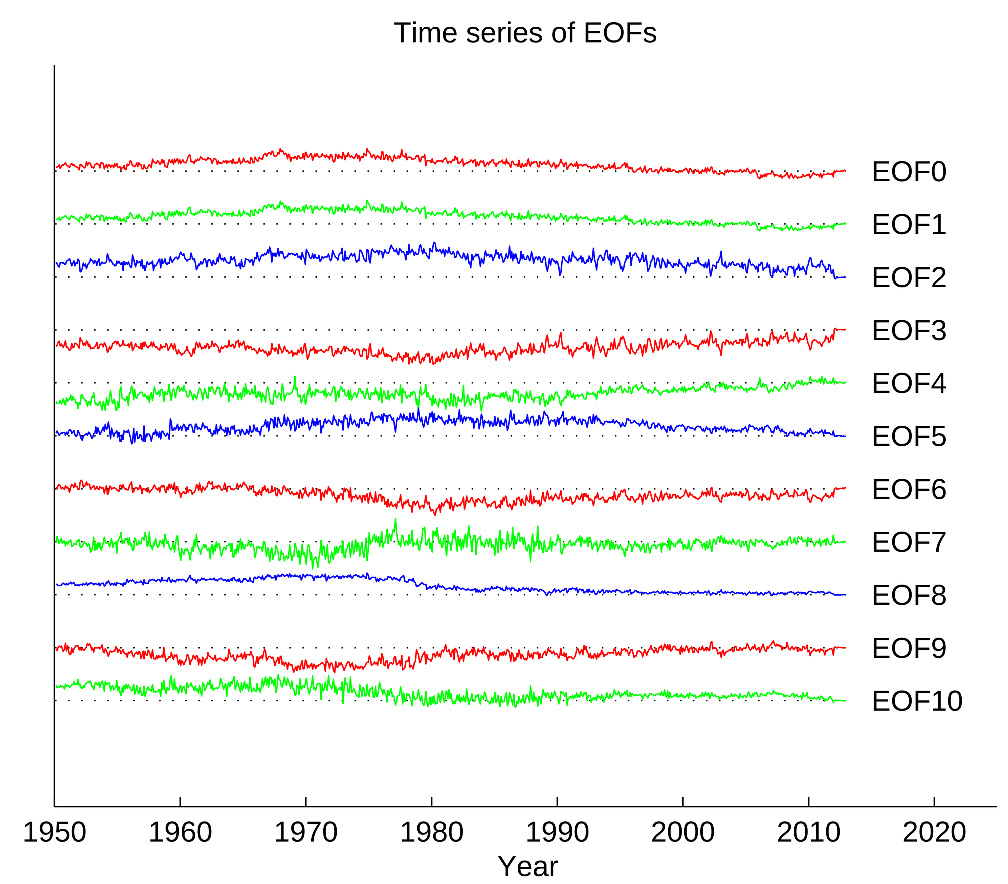
Only tide gauges with more than 5 years of data are included. At any point in time, the solution is enforced by the gauges with available data; this varies from 13 to 69 gauges over the period considered (out of the 106 gauges located at above 68°N). We reconstruct the period 1950–2010 as this is the only period where a reasonable amount of tide gauge data seems available.

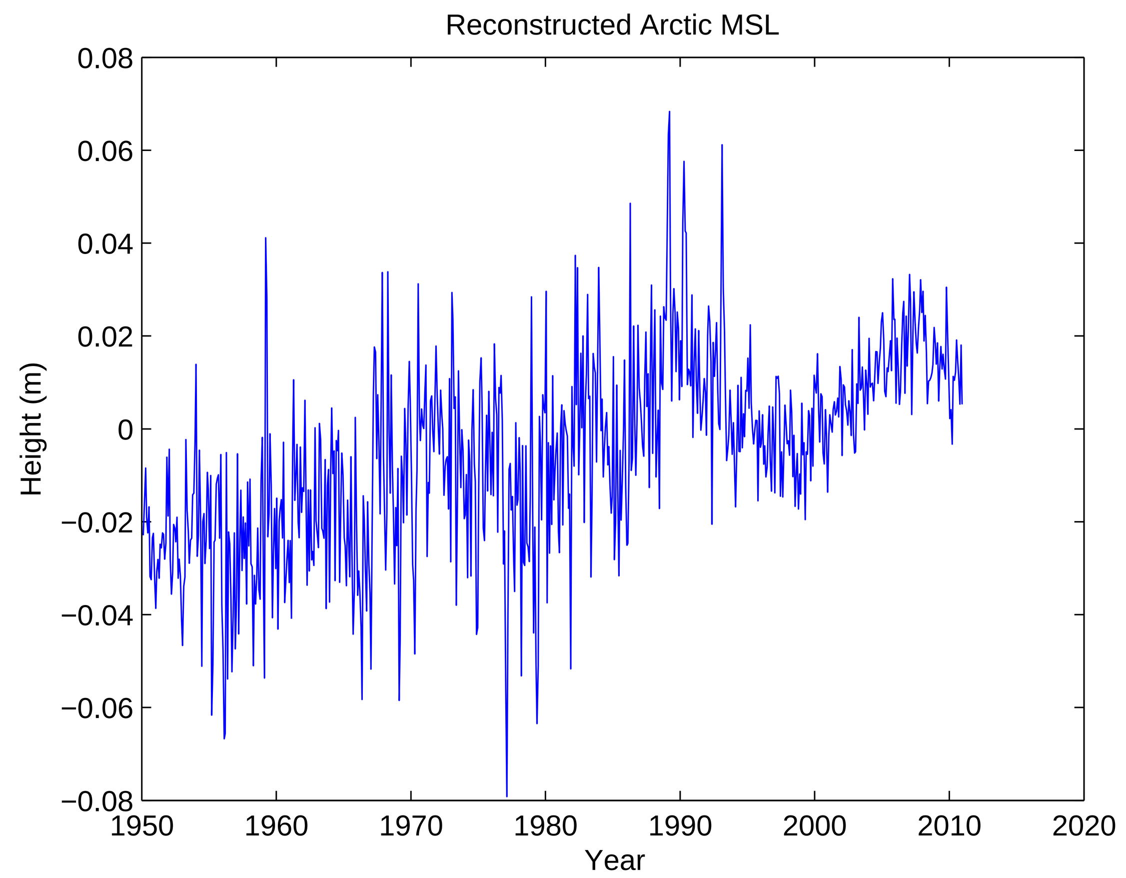
The calibration sea-level dataset is from the Drakkar ocean model (Barnier et al., 2006); it is intended to replace this with satellite altimetry in the long run.

## Reconstruction




EOF1 is clearly near-uniform, and therefore the augmentation with "EOF0" may thus be superfluous; the corresponding solution time series are also virtually identical.

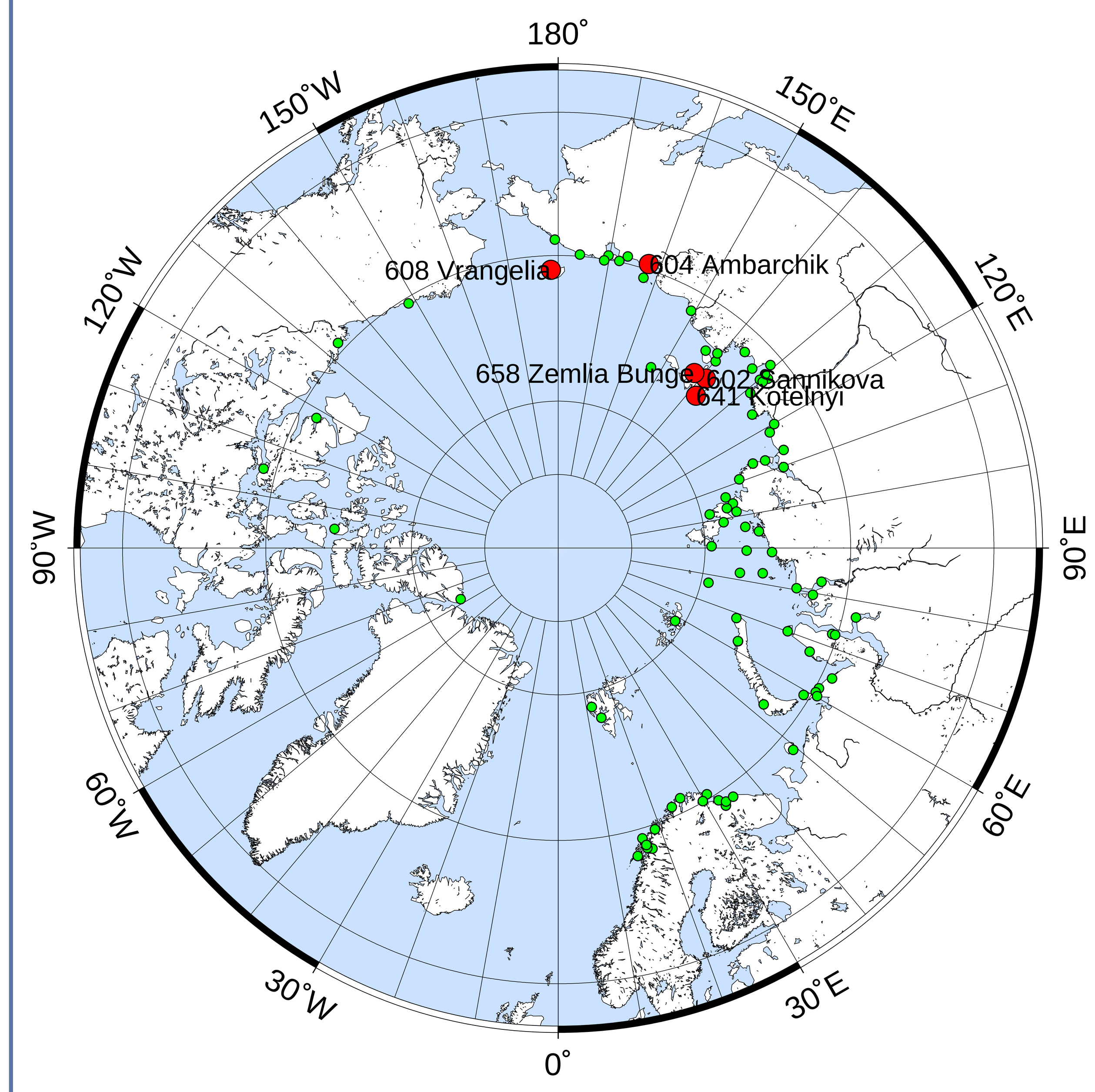


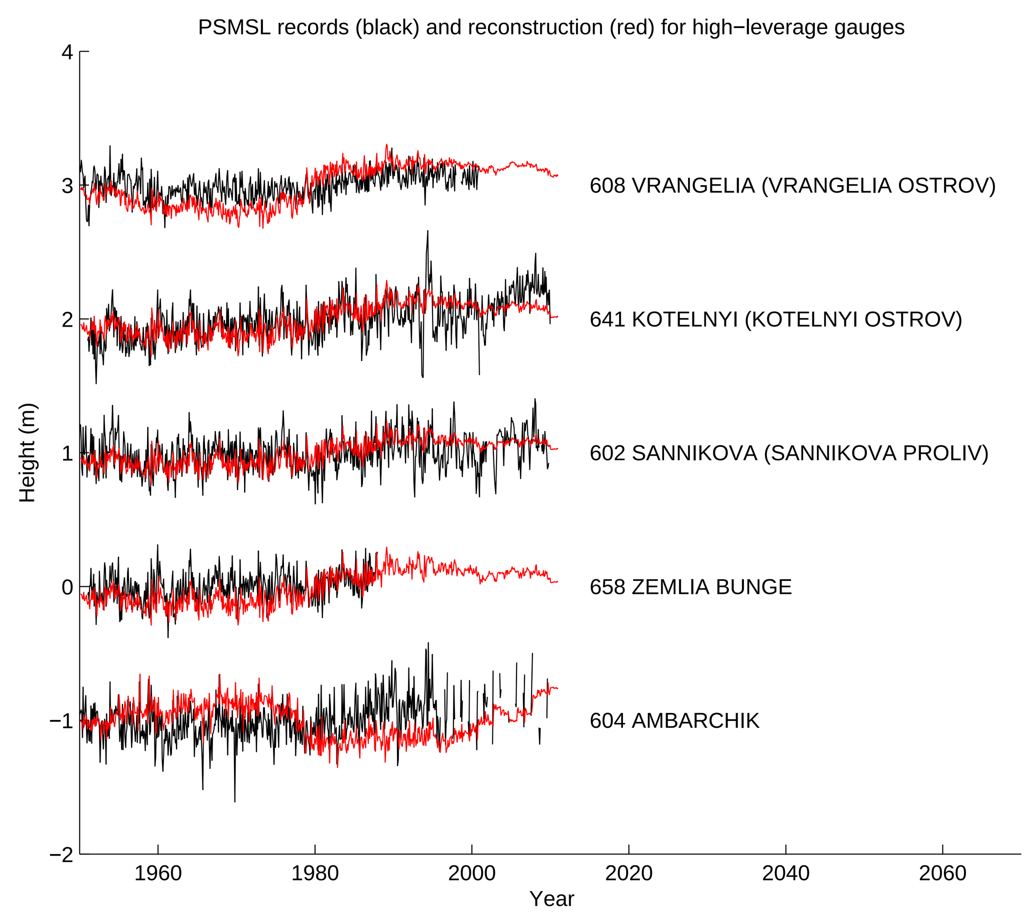




Reconstructed mean sea level for the entire Arctic Ocean above 68°N, using only tide gauges above 68°N, yielding a trend of approx. 0.8 to 1 mm/yr for the entire period. From 1995 to 2010, we obtain > 3 mm/yr.

## Leverages

Among the tide gauges above 68°N (green), our analysis identifies five gauges (red) as having a leverage more than three times the mean leverage of all gauges.




The three gauges exhibit some of the highest leverages, statistically suggesting a large influence on the reconstruction. This may suggest removal could be appropriate, though they could also represent an important subpattern in the data. In this case, it seems that the high-leverage gauges may be singled out due to being the primary driver of the positive MSL trend. Some of the reconstructed time series have rather sudden vertical shifts, or the EOFs may not correspond very well with the tide gauge records, which could also play a role.

## Conclusions

The reconstructed development in Arctic mean sea level (above 68°N) shows an increasing trend of about 0.9 mm/yr for the 1950–2010 period. Although this is somewhat lower coastal MSL findings by Henry et al. (2012) (1.6 ± 0.11 mm/yr for the Norwegian and Russian sectors), the qualitative development is very similar, with a positive trend of about 4 mm/yr between 1998 and 2010. Also, the lack of IB correction in our reconstruction (on the order of 0.3 mm/yr) may affect the results.

While leverage is often used to identify dubious observations and outliers, in this case they might indicate appropriately influential gauges; by far the most variance in the area is explained by the uniform EOF0 and the practically uniform EOF1, and forcing these will introduce large changes to the reconstruction.

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