I don't know, are you sure we want to do this? Sea level adaptation decisions under uncertainty

T. Thorarinsdottir[1], P. Guttorp[1], M. Drews[2]

Corresponding author: Name, Address. (email)

[1]Norwegian Computing Centere

[2]Technical University of Denmark

[3]Affiliation three

₃ **Abstract.**   ...

1. Introduction

2. Sea level projections (PG)

2.1. Global sea level

Most climate models do not explicitly provide sea level as an output of the calculations. Rather, the IPCC AR5 report [*Stocker et al.*, 2013, ch. 13] combines the heat expansion of the ocean with temperature forced models for glacial melt, Greenland ice melt, and Antarctic ice melt and with land rise due to rebound from the last ice age. Judging from the supplementary material to *Stocker et al.* [2013, ch. 13], the uncertainty assessment is only based on the spread of the ensemble of temperature projections, not on the additional uncertainty in the ice models used.

We will instead use the empirical approach of Rahmstorf and collaborators [*Rahmstorf*, 2007; *Rahmstorf et al.*, 2011], employing the statistical modeling of *Bolin et al.* [2014] to relate global annual mean temperature anomalies [*Hansen et al.*, 2001] to global mean sea level anomalies [*Church and White*, 2011].

We then apply the estimated historical relationship to projected temperatures from the CMIP5 experiment [*Taylor et al.*, 2012] to obtain projected global annual mean sea level, taking into account the uncertainty in the statistical model as well as the spread of the temperature projection ensemble (see subsection 2.3). For the i'th temperature projection T_t^i we estimate the corresponding global mean sea level as

$$H_t^{gl,i} = \int\limits_{t_0}^{t} \hat{a}(T_u^i - \hat{T}_0)du + \varsigma_t$$

20 where $\hat{a}$ and $\hat{T}_0$ are regression parameters of observed global sea level on observed global

21 temperature and ς_t the integrated time series regression error.

2.2. Local sea level

22   In order to get from global sea level projections to local ones, it is important to note

23 that sea level rise not is uniform over the globe. Glacial and land ice melting affect the

24 local sea level differently depending on where the melted ice is located. Another major

25 effect in Fennoskandia is the land rise due to isostatic rebound from the glaciers of the

26 last ice age. Again, we will use historical data to relate global sea level to isostatically

27 corrected local sea level using a time series regression model. Figure 1 shows uncorrected

28 and corrected Bergen sea level data, and the relationship between the corrected Bergen

29 data and the global sea level data. The time series regression uses an ARMA(1,1)-model

30 [*Box and Jenkins*, 1970].

31   The local sea level projections are then obtained by first relating projected temperature

32 to global sea level, and then relating the global sea level to the local one. Each climate

33 model temperature projection yields a different local sea level projection. The local sea

34 level projection based on the i'th climate model for years beyond 2000 is estimated as

$$H_t^{loc,i} + \gamma(t - 2000) = \hat{b}H_t^{gl,i} + \varepsilon_t$$

35 where γ ie the annual land rise rate, t and $\hat{b}$ is the regression coefficient relating global to

36 local sea level.

2.3. Uncertainty assessment

Following the approach of *Guttorp et al.* [2014] we assess the uncertainty in the local sea level projections taking into account the variability between the climate projections used, the uncertainties in the regressions of global mean temperature on global mean sea level and of global on local sea level. We express the sea level projection uncertainty in terms of a confidence band that is simultaneously of the intended level for all projection years. This allows us, for example, to get a confidence band for the years when a given sea level rise is obtained.

2.4. Limitations of the sea level projections

The main assumption is using historical relationships in statistical projections of the type used in this paper is that there is no major change in how temperature relates to sea level, globally and locally. Among the factors that may invalidate this approach are changes in water storage on land (in essence removing water from the oceans), excessive siphoning of groundwater (resulting in land subsidence), changes in the rates of glacial and land ice melt, and changes in Earth's gravitational field due to transfer of mass from land ice to ocean water. For example, the rate of ice melt on Greenland may suddenly increase substantially due to intense warming of both air and sea water. Our current climate models are not able to resolve the ice processes sufficiently to include such so called tipping points into the projections. Also, the IPCC scenarios [*van Vuuren et al.*, 2011] do not include changes in water usage.

3. Decision tools (KdB, MD, TT)

3.1. Timing of adaptation measures

We consider adaptation decision making related to the timing of proactive adaptation measures. That is, the goal is to adapt to sea level rise before major damages occur. In a cost-benefit framework, an investment should be delayed as long as the benefits of delay (avoided investment costs) are greater than the associated costs (higher climate change damages) [*Fankhauser et al.*, 1999].

Fankhauser et al. [1999] describe a deterministic framework where an adaptation investment of C^0 now (at time $n = 0$) leads to unmitigated damage of d_0^0 in period 0, and a stream of partially mitigated damages d_t^0 in periods $t = 1, 2, \ldots$. If r is the discount rate, the net present value damage, D^0, associated with this investment is

$$D^0 = C^0 + d_0^0 + \frac{d_1^0}{1 + r} + \frac{d_2^0}{(1 + r)^2} + \cdots \tag{1}$$

In comparison, postponing the adaptation investment to time period $n = 1$ would lead to unmitigated damages in periods 0 and 1, and partially mitigated damages, d_t^1, thereafter. The delay would be preferable if

$$C^0 - \frac{C^1}{(1 + r)} > (d_0^1 - d_0^0) + \frac{d_1^1 - d_1^0}{1 + r} + \frac{d_2^1 - d_2^0}{(1 + r)^2} + \cdots$$

Here, the expression on the left describes the benefits of the delay while the expression on the right describes the cost of the delay. In the simplest case, there is no change in investment costs ($C^0 = C^1 = C$) and the delay has no lasting effects beyond period 1 ($d_t^1 = d_t^0$ for $t > 1$). In this case, the comparison is between the expected return r earned on the captial while implementation is delayed and one addtional time period of

74 unmitigated damage,

75
$$rC > d_1^1 - d_1^0.$$

3.2. Limitations of the decision framework

4. Case studies

4.1. Data (PG)

76 We use local tide gauge data from the Permanent Service for Mean Sea Level, UK,

77 which is the worldwide repository for national sea level data. Climate projections are

78 from the fifth climate model intercomparison project, CMIP5.

4.2. Timing of adaptation measures (KdB, TT)

79 A case study focusing on and comparing different cities in Norway.

4.3. Selection of adaptation measures(?) (MD)

80 A case study focusing on Denmark.

5. Conclusions

References

Bolin, D., P. Guttorp, A. Januzzi, M. Novak, H. Podschwit, L. Richardson, C. Sowder, A. Särkkä, and A. Zimmerman (2014), Statistical prediction of global sea level from global temperature, *Statistica Sinica*, *25*, 351–367.

Box, G., and G. Jenkins (1970), *Time series analysis: Forecasting and control*, Holden-Day.

Church, J., and N. White (2011), Sea-level rise from the late 19th to the early 21st century, *Surveys in Geophysics*, *32*, 585–602.

Fankhauser, S., J. Smith, and R. S. J. Tol (1999), Weathering climate change: some simple rules to guide adaptation decisions, *Ecological Economics*, *30*, 67–78.

Guttorp, P., D. Bolin, A. Januzzi, D. Jones, M. Novak, H. Podschwit, L. Richardson, A. Särkkä, C. Sowder, and A. Zimmerman (2014), Assessing the uncertainty in projecting local mean sea level from global temperature, *Journal of Applied Meteorology and Climatology*, *53*, 2163–2170.

Hansen, J., R. Rued, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl (2001), A closer look at United States and global surface temperature change, *J. Geophys. Res.*, *106*, 23,947–23,963.

Rahmstorf, S. (2007), A semi-empirical approach to projecting future sea-level rise, *Science*, *315*, 368–370.

Rahmstorf, S., M. Perrette, and M. Vermeer (2011), Testing the robustness of semi-empirical sea level projections, *Climate Dynamics*, *39*, 861–875.

Stocker, T., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley (2013), *Climate Change 2013: The Physical Science*

109   *Basis. Contribution of Working Group I to the Fifth Assessment Report of the Iinter-*

110   *governmental Pabel on Climate Chang*, Cambridge University Press.

111   Taylor, K., R. Stouffer, and G. Meehl (2012), An overview of CMIP5 and the experiment

112   design, *Bull. Amer. Meteor. Soc.*, *93*, 485–498.

113   van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C.

114   Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic,

115   S. J. Smith, and S. K. Rose (2011), The representative concentration pathways: an
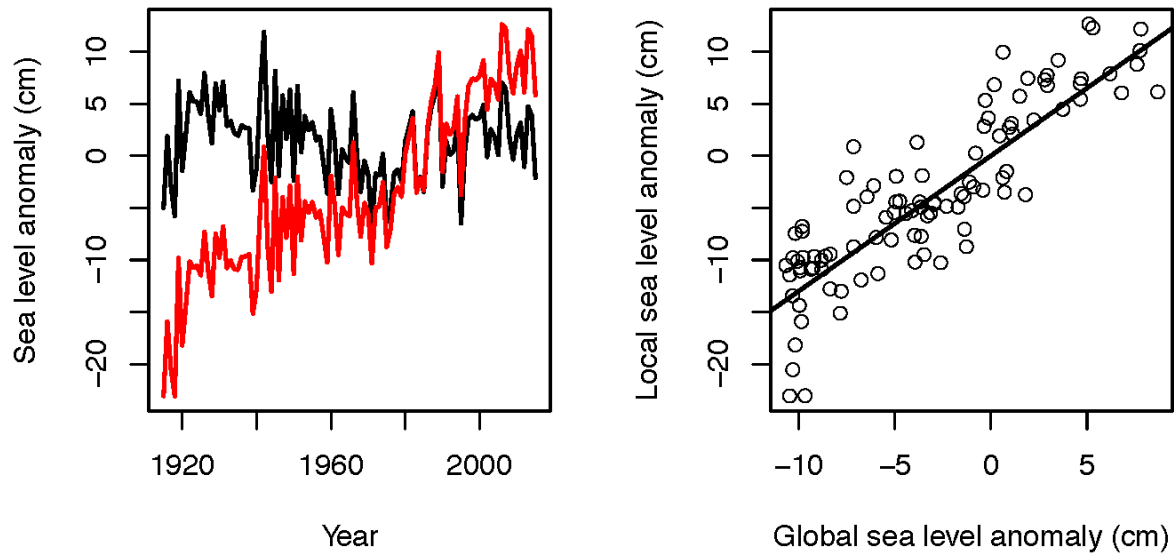
116   overview, *Clim. Change*, *109*, 5–31.

Figure 1. The left figure shows raw (black)and gia-corrected (red) sea level data from Bergen, The right figure relates the gia-corrected Bergen sea level to the global sea level series of *Church and White* [2011]. The straight line is the time series regression line.
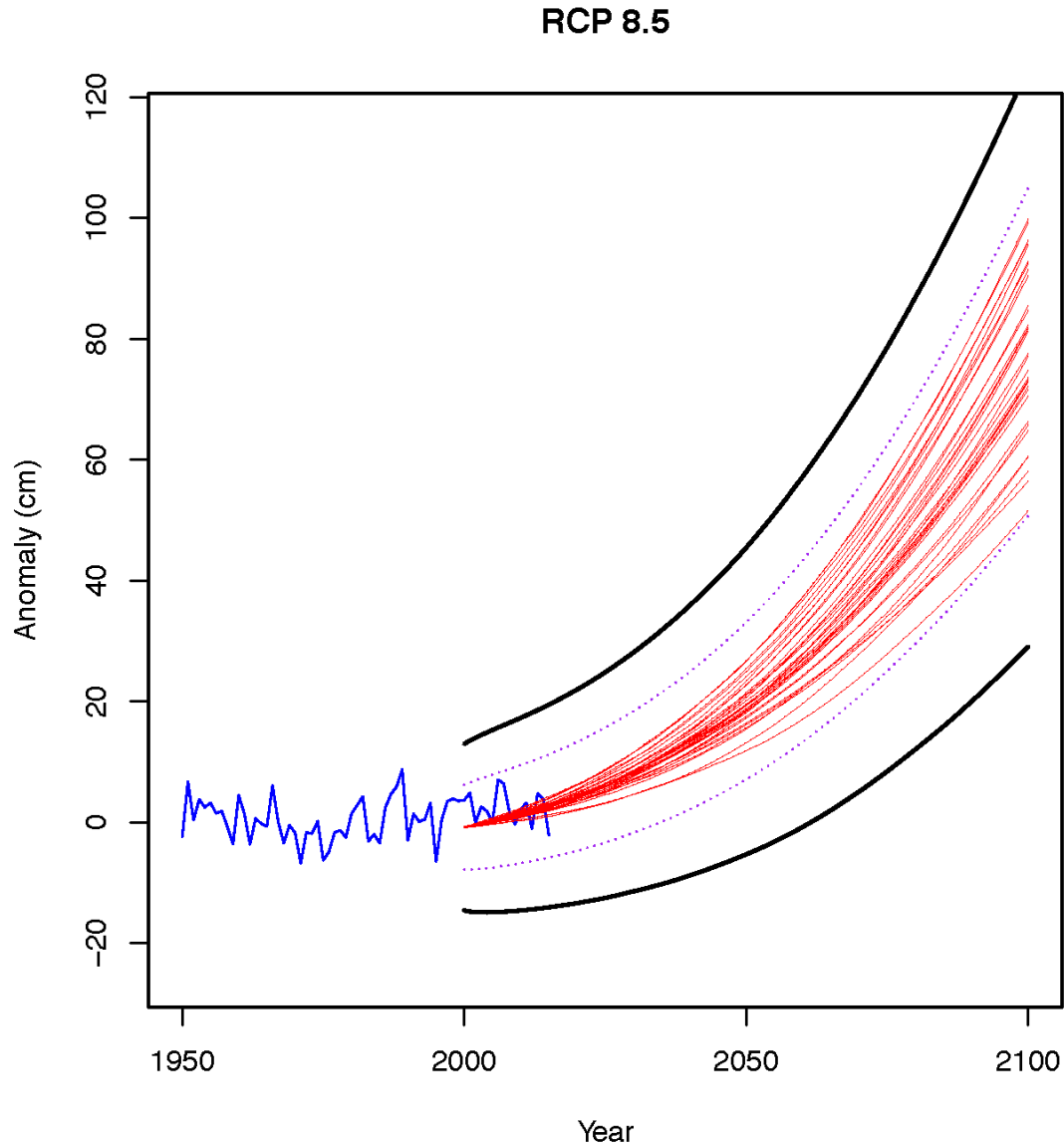
RCP 8.5

Figure 2. Simultaneous 90% confidence set (thick black lines) for Bergen sea level

projections for the years 2000-2100 using RCP8.5. The sea level data are shown in blue

and end in 2015. The thin red lines are the projections without uncertainty based on each

of the climate models. The dashed purple lines connect pointwise confidence intervals for

each year.