Exploring relationship between global temperatures and global sea levels

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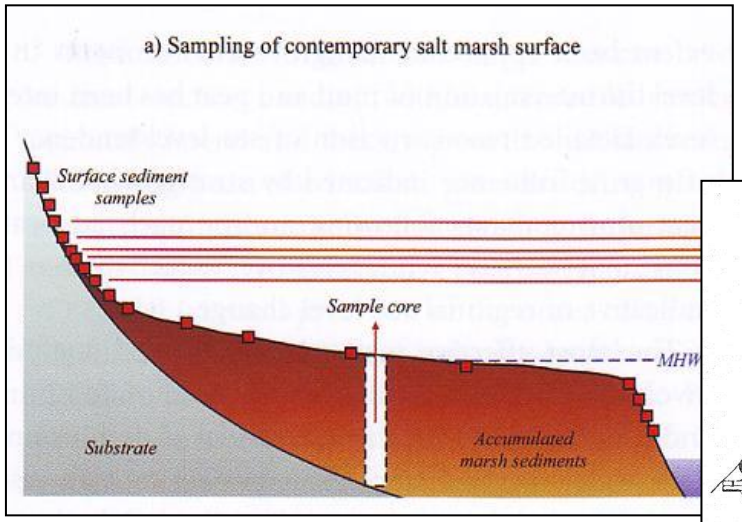
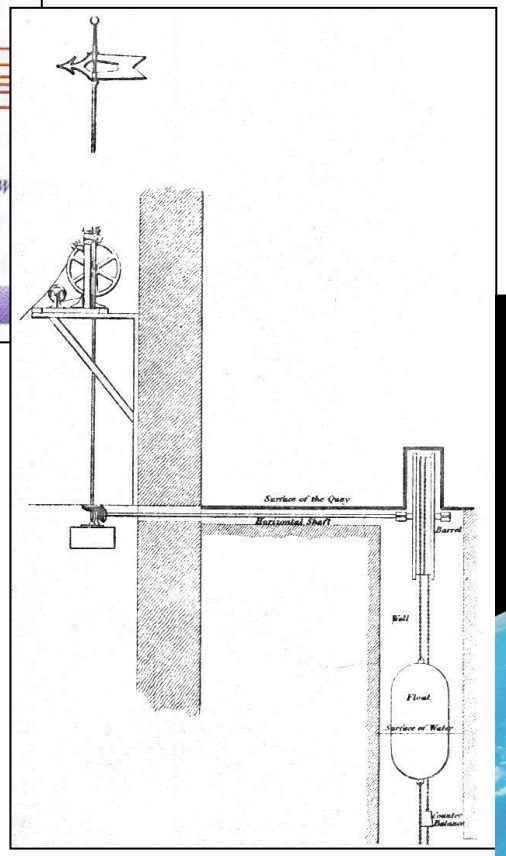
Measurement of sea level height

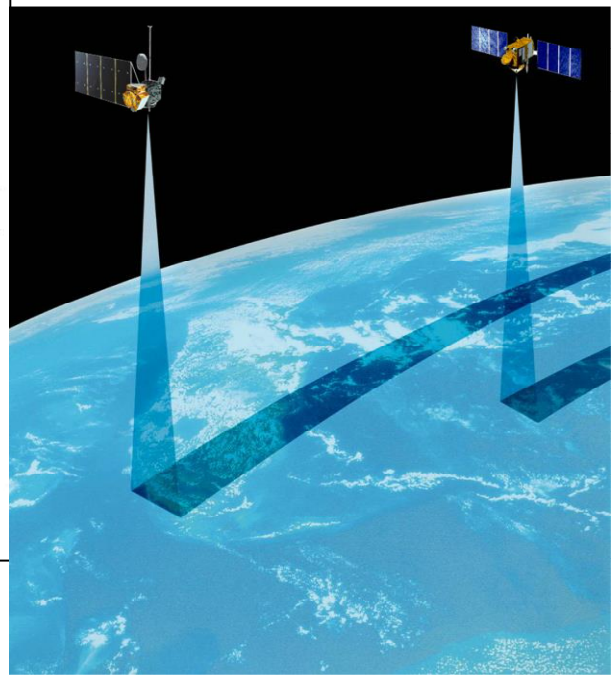


Sediment core

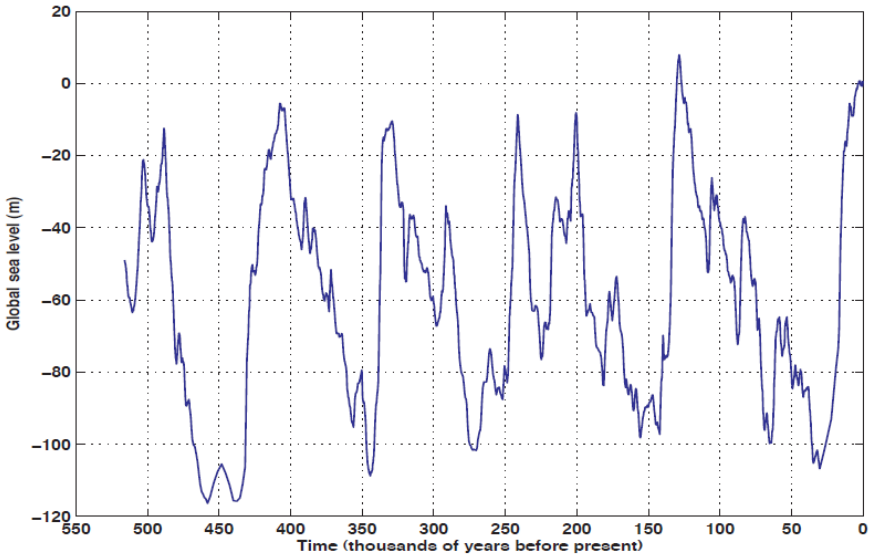


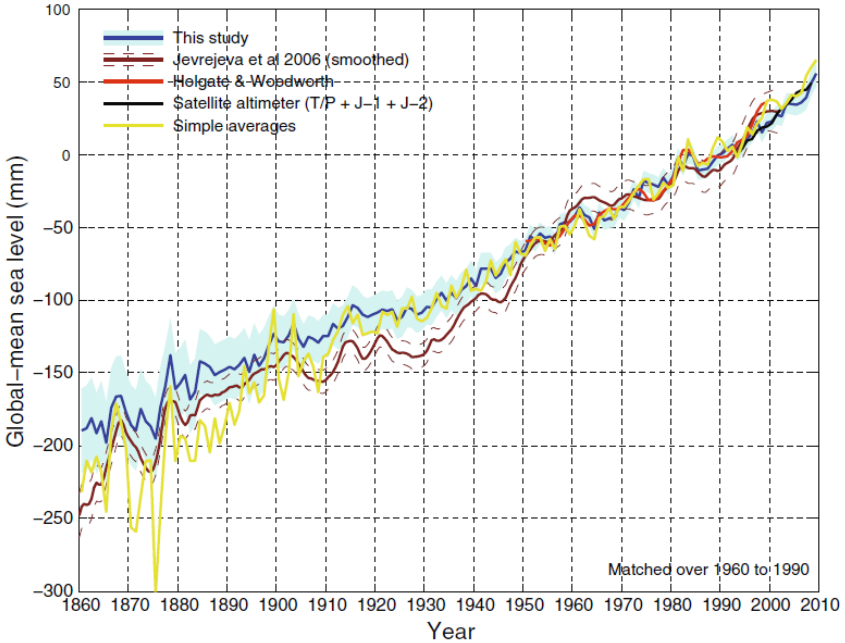
Tide gauge

Satellite altimeter

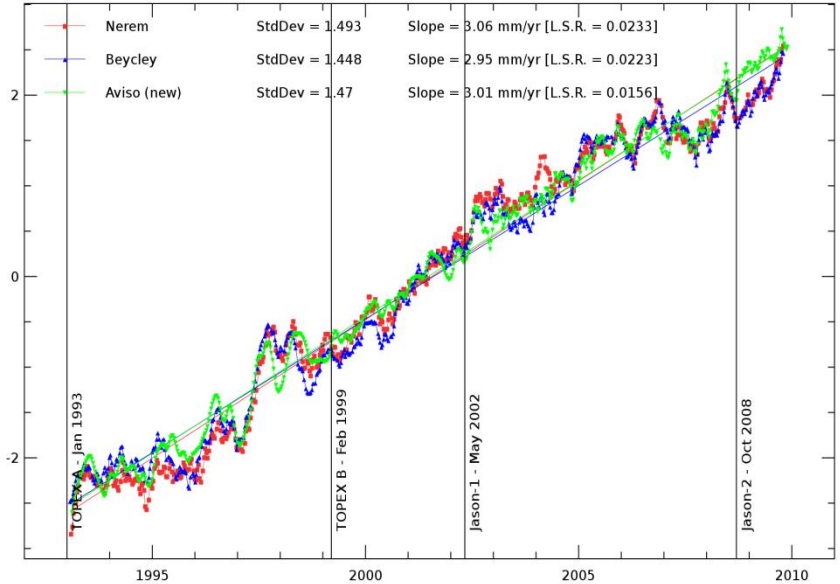


Global sea level variability



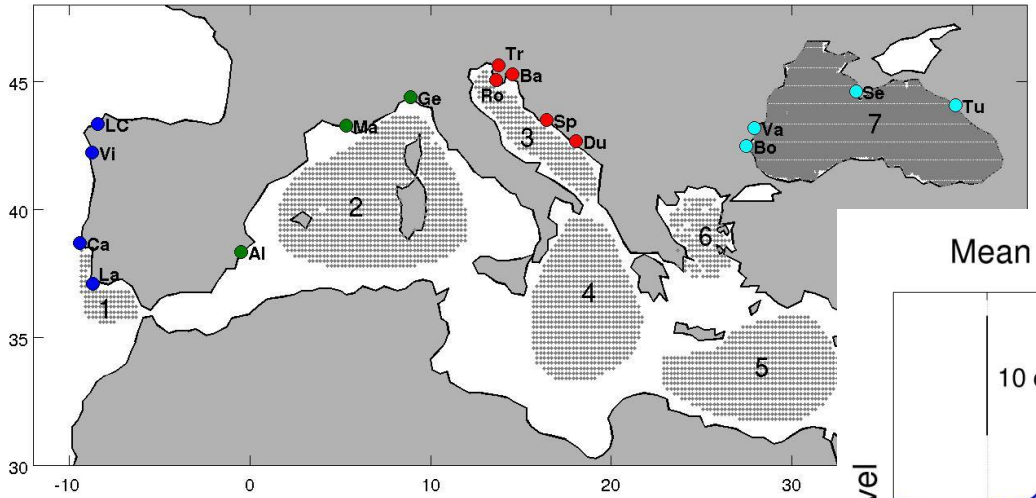


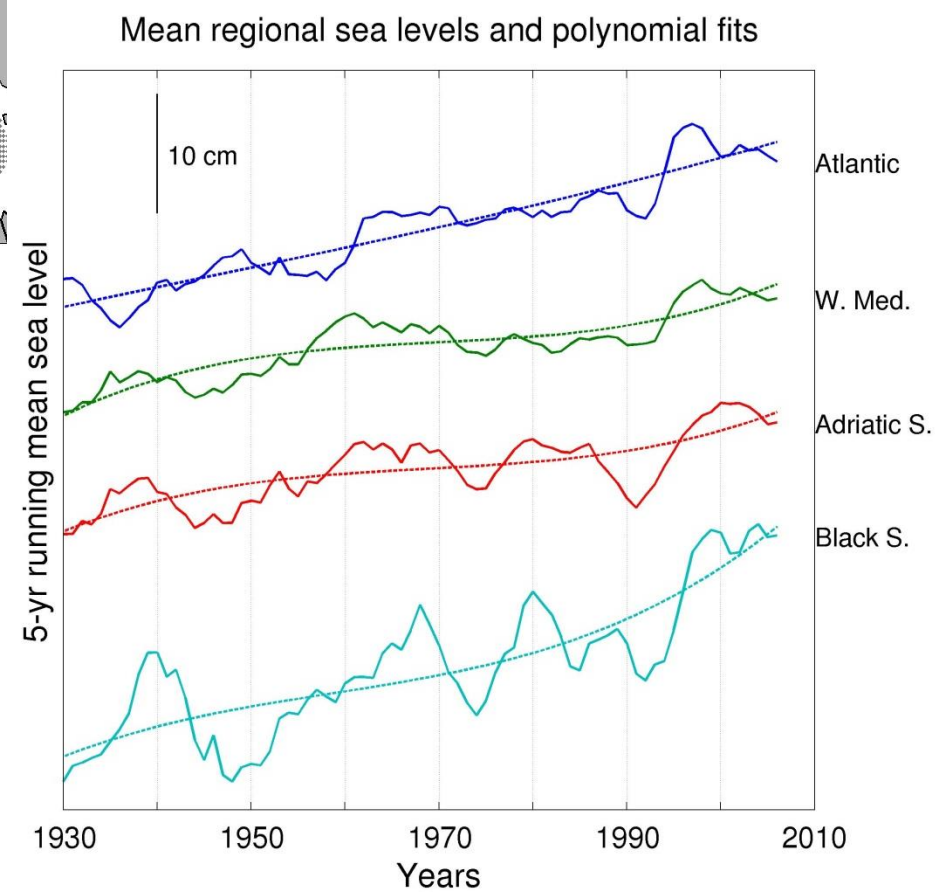
J. A. Church, N. J. White (2011)



A. Cazenave (2010)

Mediterranean sea level





M. Orlić, M. Pasarić (2013)

Storm surge events

Numerical modeling

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial \zeta}{\partial x} - \frac{1}{\rho}\frac{\partial p_a}{\partial x} + \frac{1}{H\rho}(\tau_x - \tau_{dx})$$

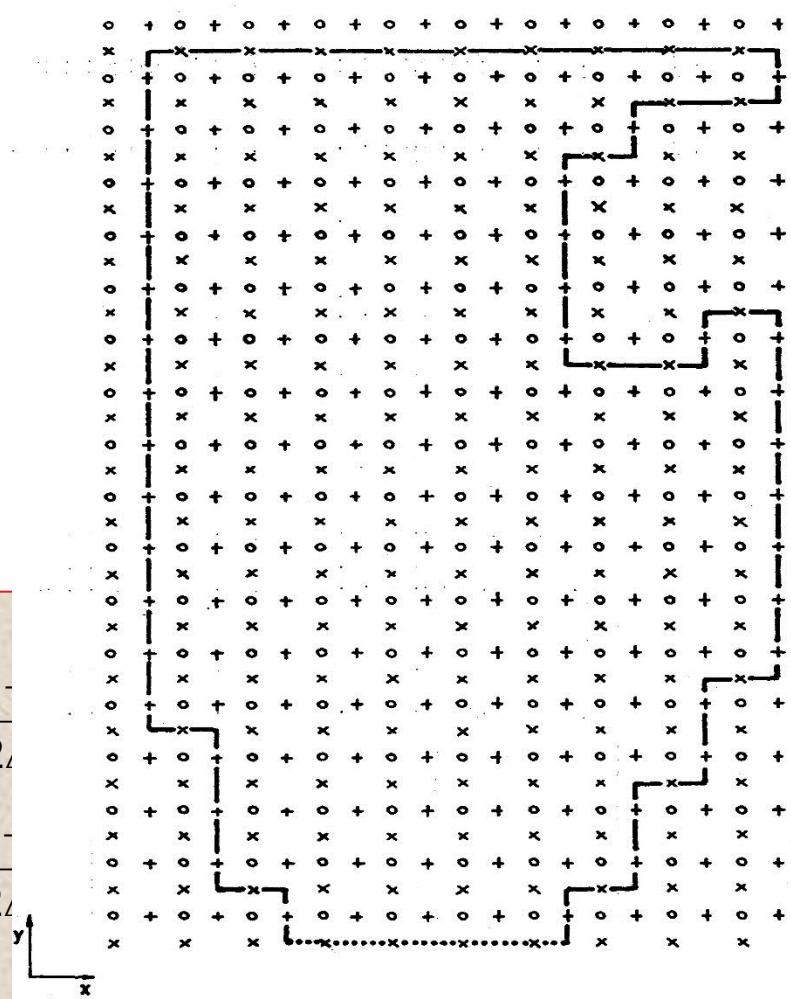
$$\frac{\partial v}{\partial t} + fu = -g\frac{\partial \zeta}{\partial y} - \frac{1}{\rho}\frac{\partial p_a}{\partial y} + \frac{1}{H\rho}(\tau_y - \tau_{dy})$$

$$\frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) + \frac{\partial \zeta}{\partial t} = 0$$

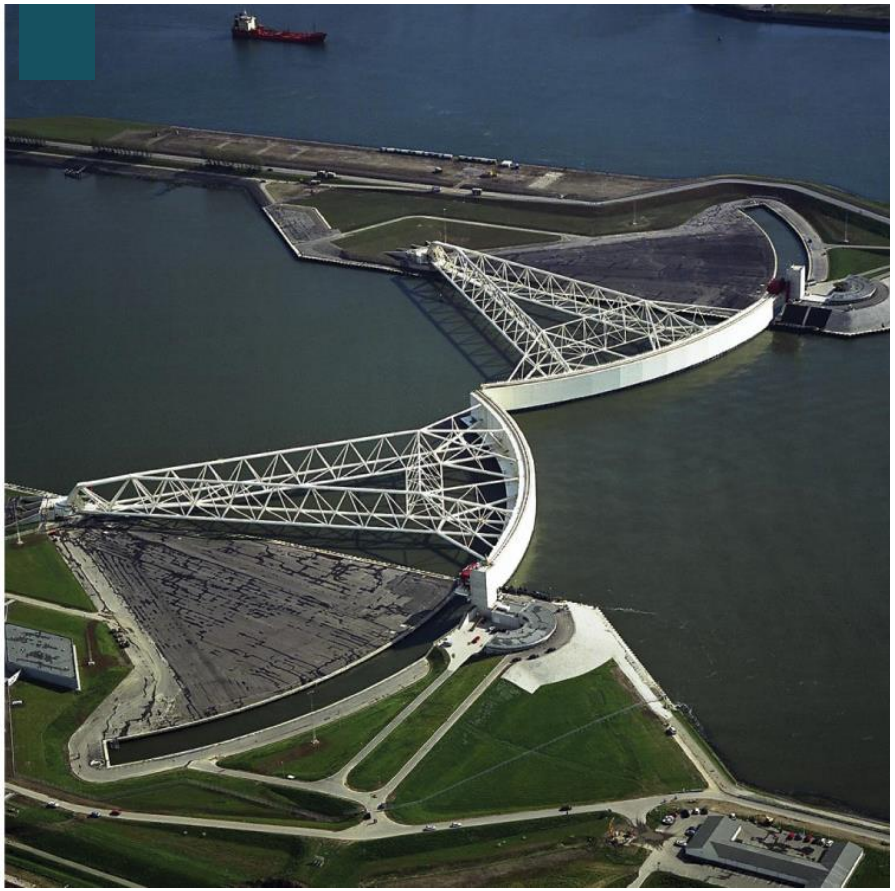
$$\frac{u_{i,j}^{n+1} - u_{i,j}^{n}}{\Delta t} - f\overline{v}_{i,j}^{n} = -g\frac{\zeta_{i+1,j}^{n+1} - \zeta_{i-1,j}^{n+1}}{2\Delta s} - \frac{1}{\rho}\frac{p_{a,i+1,j}^{n}}{2}$$

$$\frac{v_{i,j}^{n+1} - v_{i,j}^{n}}{\Delta t} + f\overline{u}_{i,j} = -g\frac{\zeta_{i,j+1}^{n+1} - \zeta_{i,j-1}^{n+1}}{2\Delta s} - \frac{1}{\rho}\frac{p_{a,i,j+1}^{n}}{2}$$

$$\frac{(Hu^n)_{i+1,j} - (Hu^n)_{i-1,j}}{2\Delta s} + \frac{(Hv^n)_{i,j+1} - (Hv^n)_{i,j-1}}{2\Delta s} + \frac{}{\Delta t} = 0$$



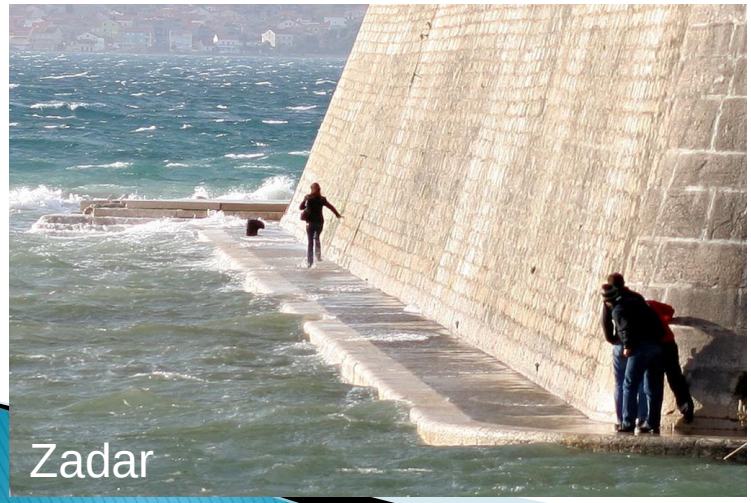
Adaptation: dams off London and Rotterdam



The Adriatic flood of 1 December 2008


Venice


Rijeka

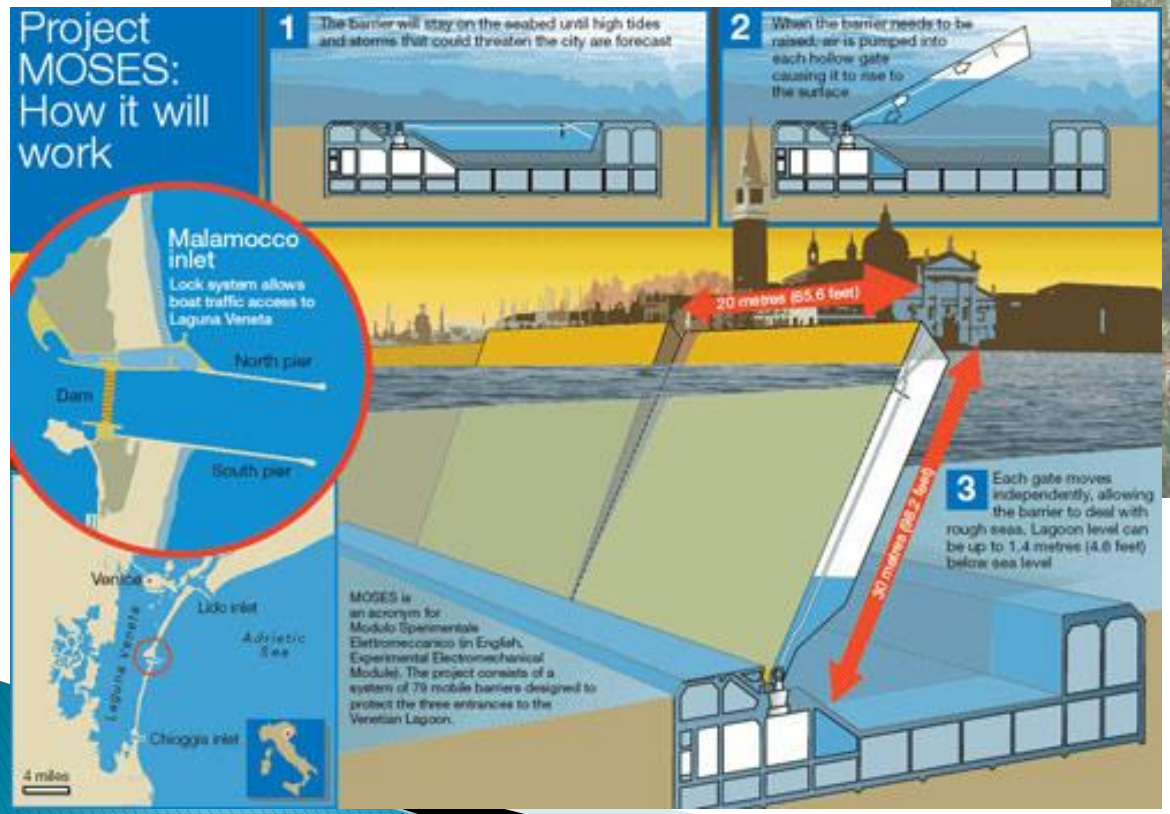

Zadar

Trogir

Records at Bakar (without local seiches)

Date	Time (LT)	Height above MSL (cm)
1 November 2012	7:00	113
1 December 2008	9:00	105
25 December 2009	2:00	103
23 December 2009	3:00	97
22 December 1979	10:00	97
17 December 1958	3:00	96
Etc.	…	…

Adaptation: dams under construction off Venice



Influence on coastal population

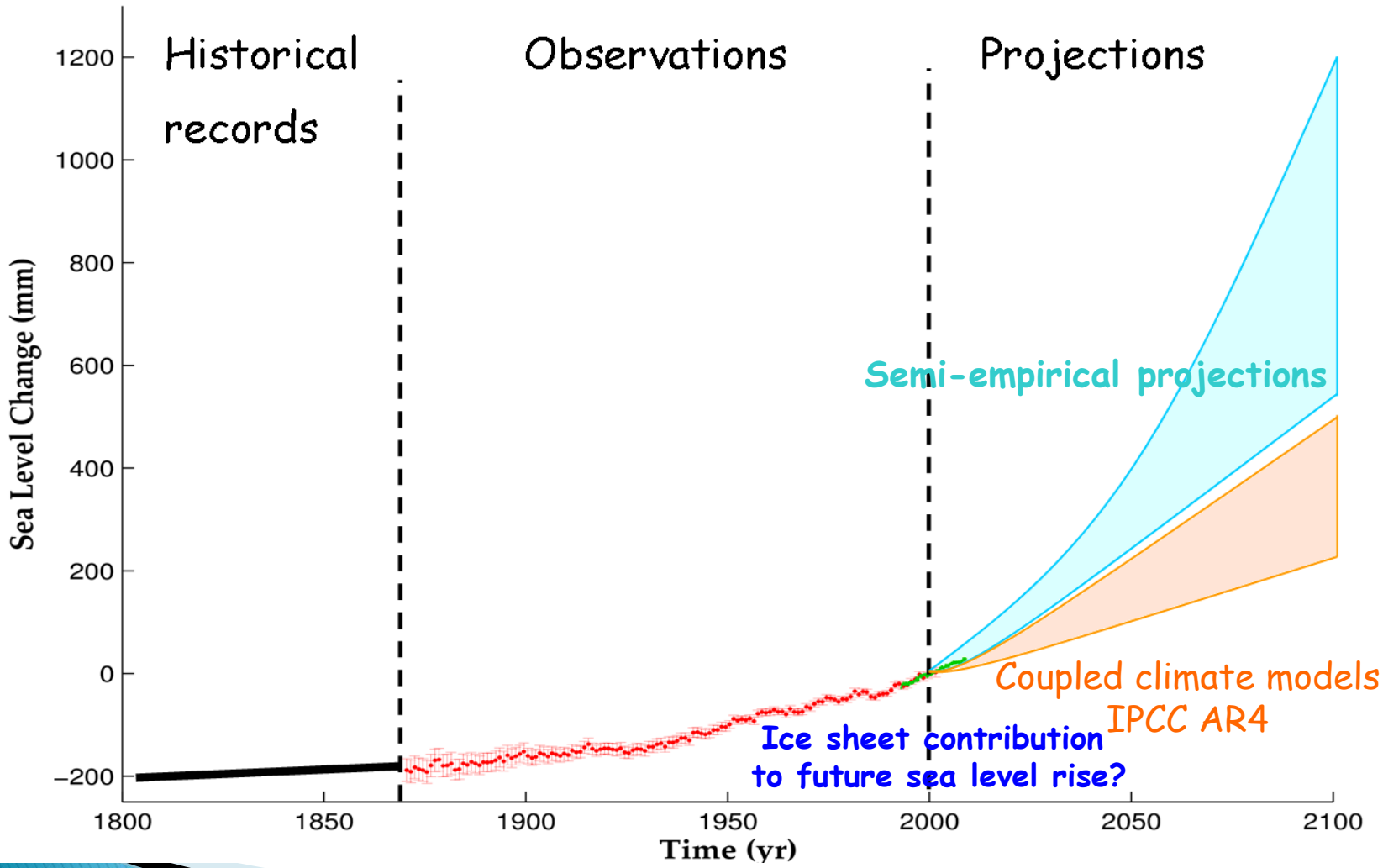
Deltas (R. J. Nicholls, P. P. Wong, 2007)

Islands

Expected damage in Croatia

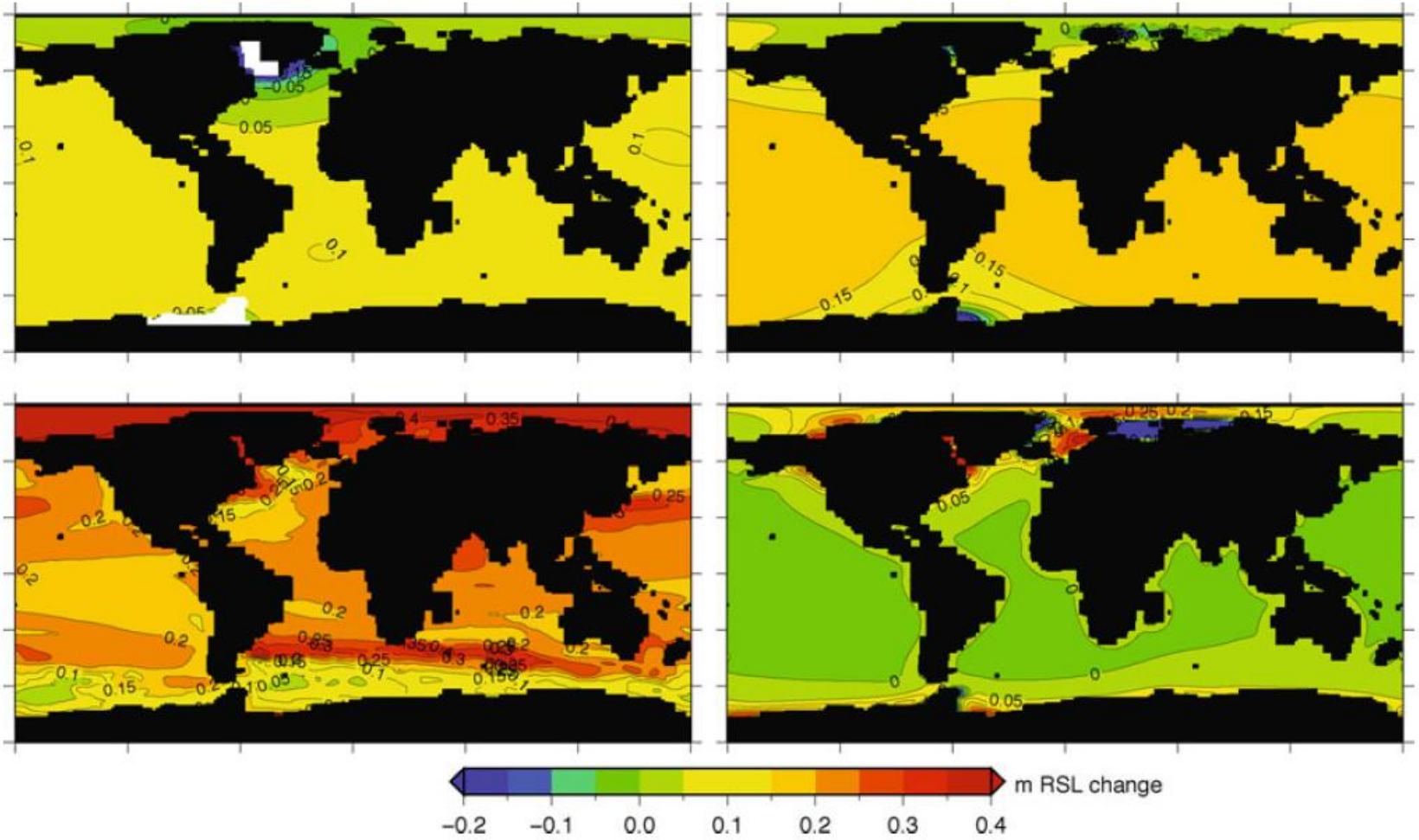
- According to a recent study prepared by researchers from the Global Climate Forum (Berlin) and Christian Albrechts University (Kiel), it is expected that the annual damage due to the coastal flooding events in Croatia will amount to 0.9 – 8.8 billion dollars by the end of 21st century.
- The cost of building and maintenance of the infrastructure needed to prevent the damage would amount to 16 – 23 billion dollars.
- Consequently, the investment would pay off in 2 – 26 years.

Global sea level projections



P. L. Woodworth (2011)

Modeling of relative sea level (change from 1980/1999 to 2090/2099, scenario A1B)

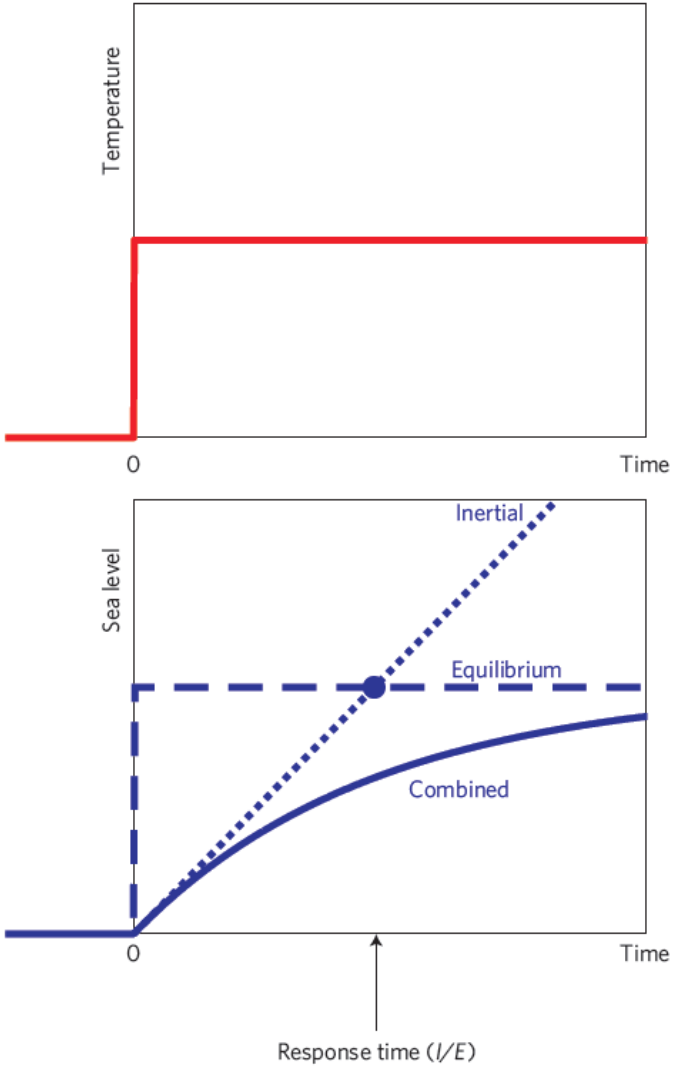


A. B. A. Slangen et al. (2012)

Semi-empirical method (variant A)

$$E\eta = \tau$$

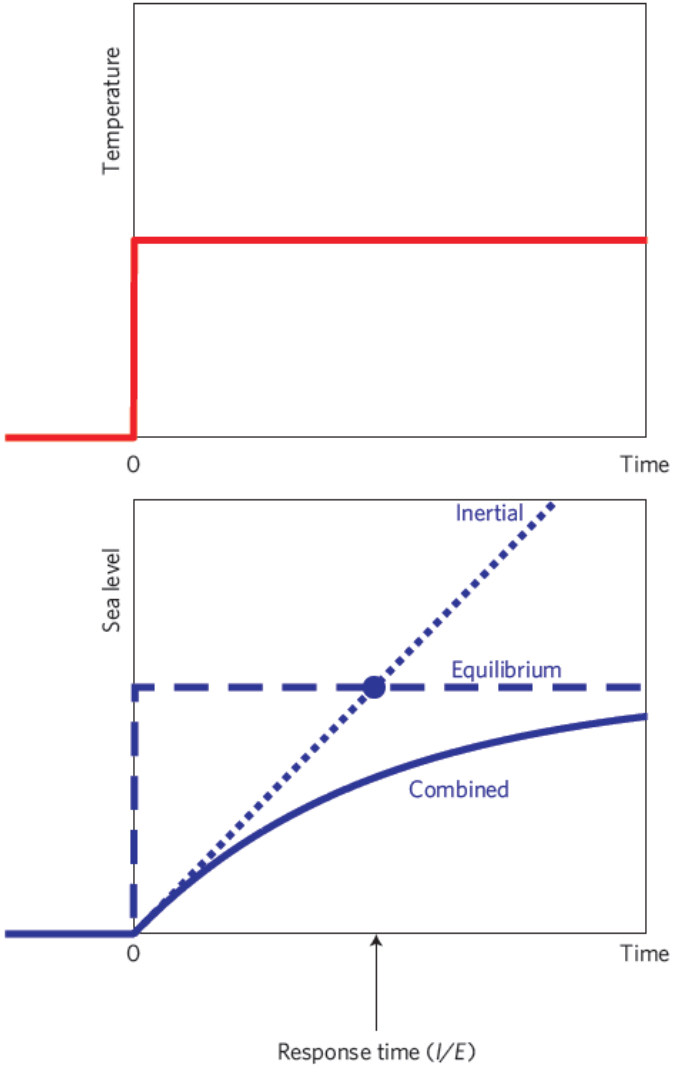
V. Gornitz et al. (1982)



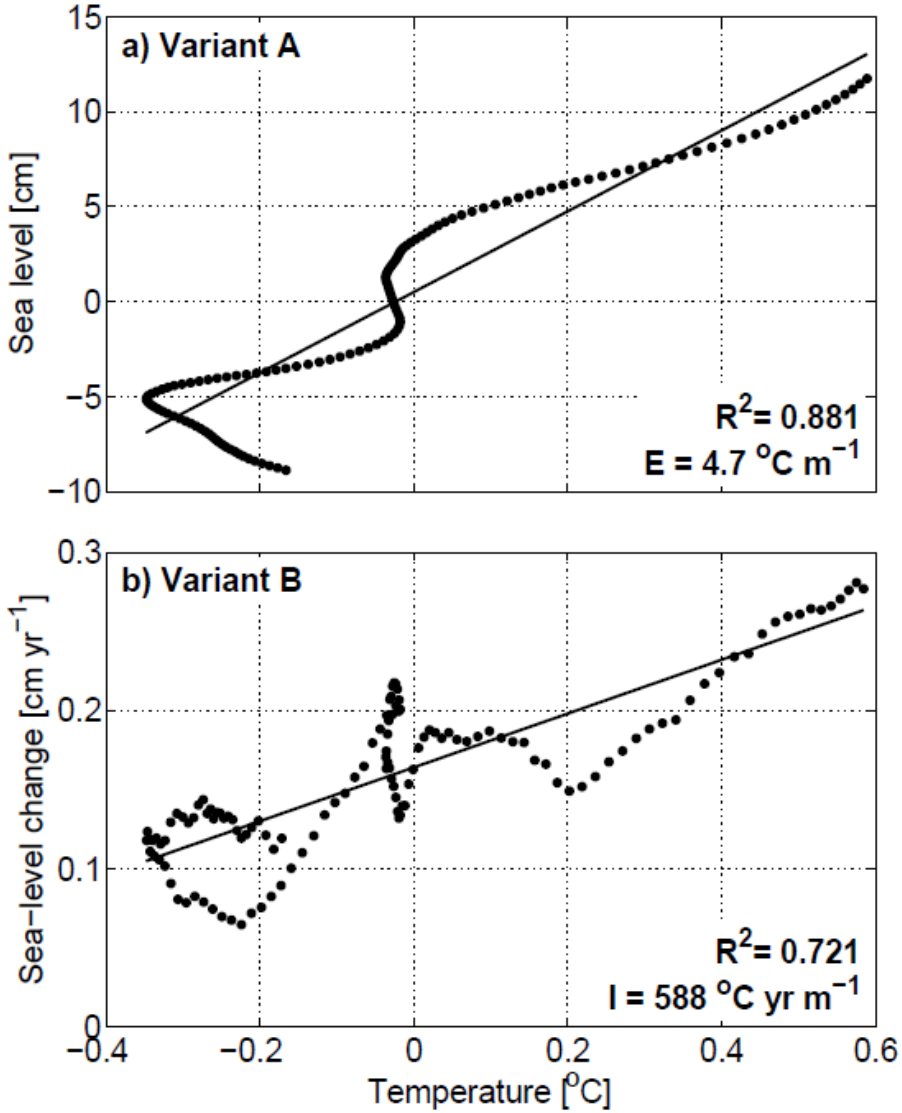
Semi-empirical method (variant B)

$$I\frac{d\eta}{dt}=\tau$$

S. Rahmstorf (2007)



Variants A and B applied to the data

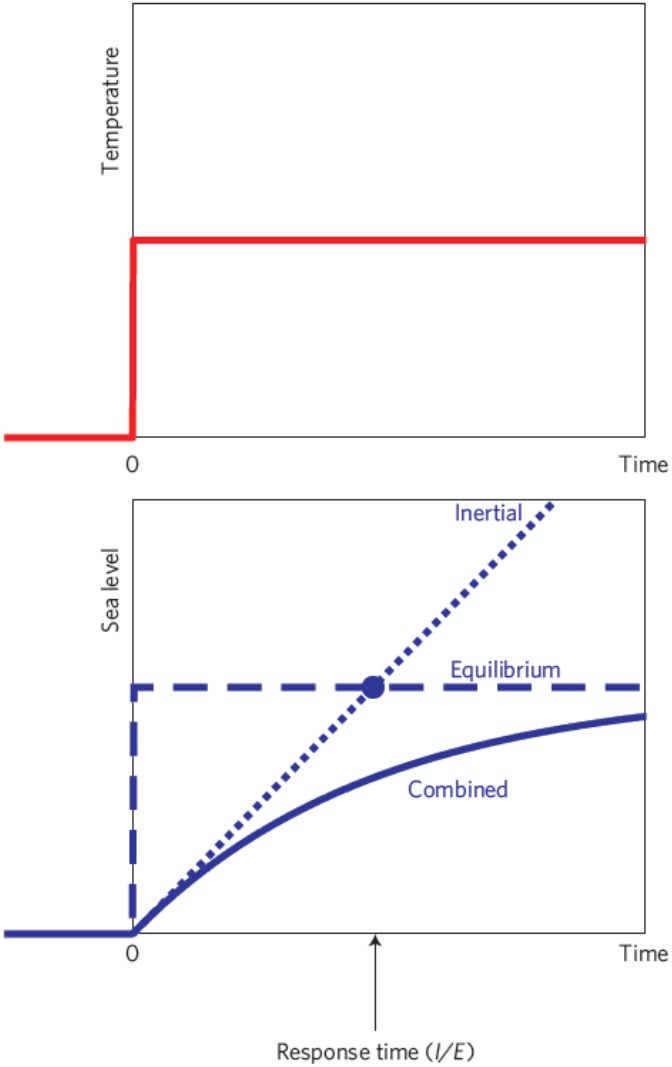


M. Orlić, Z. Pasarić (2015)

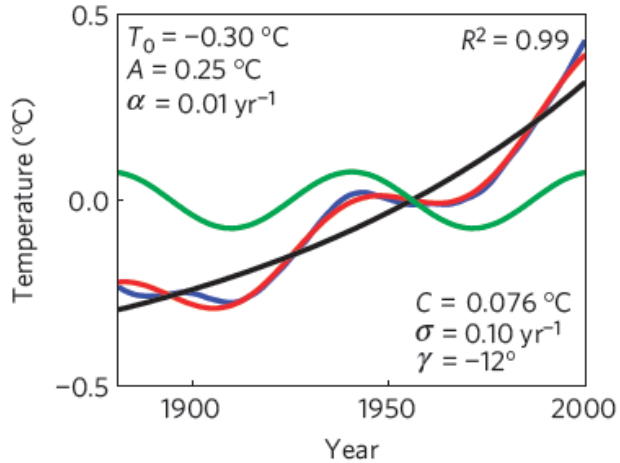
Semi-empirical method (variant C)

$$I\frac{d\eta}{dt}+E\eta=\tau$$

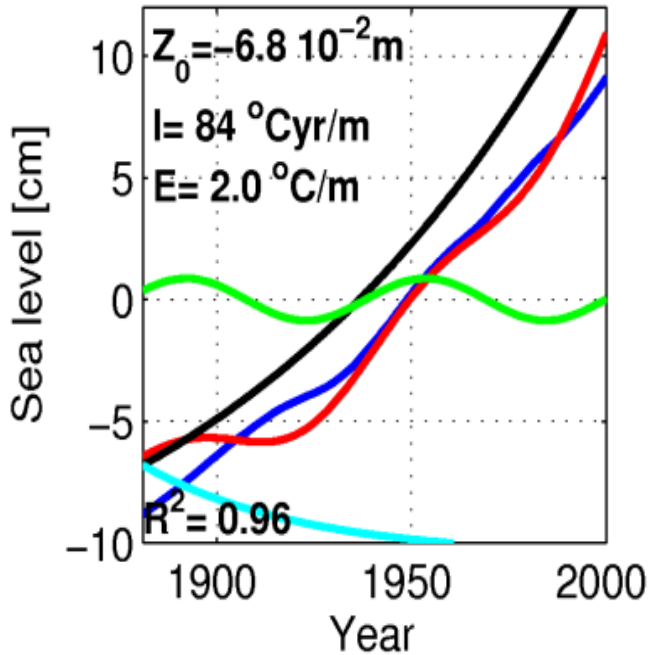
M. Orlić, Z. Pasarić (2013)



Variant C applied to the data (first approach, C1)



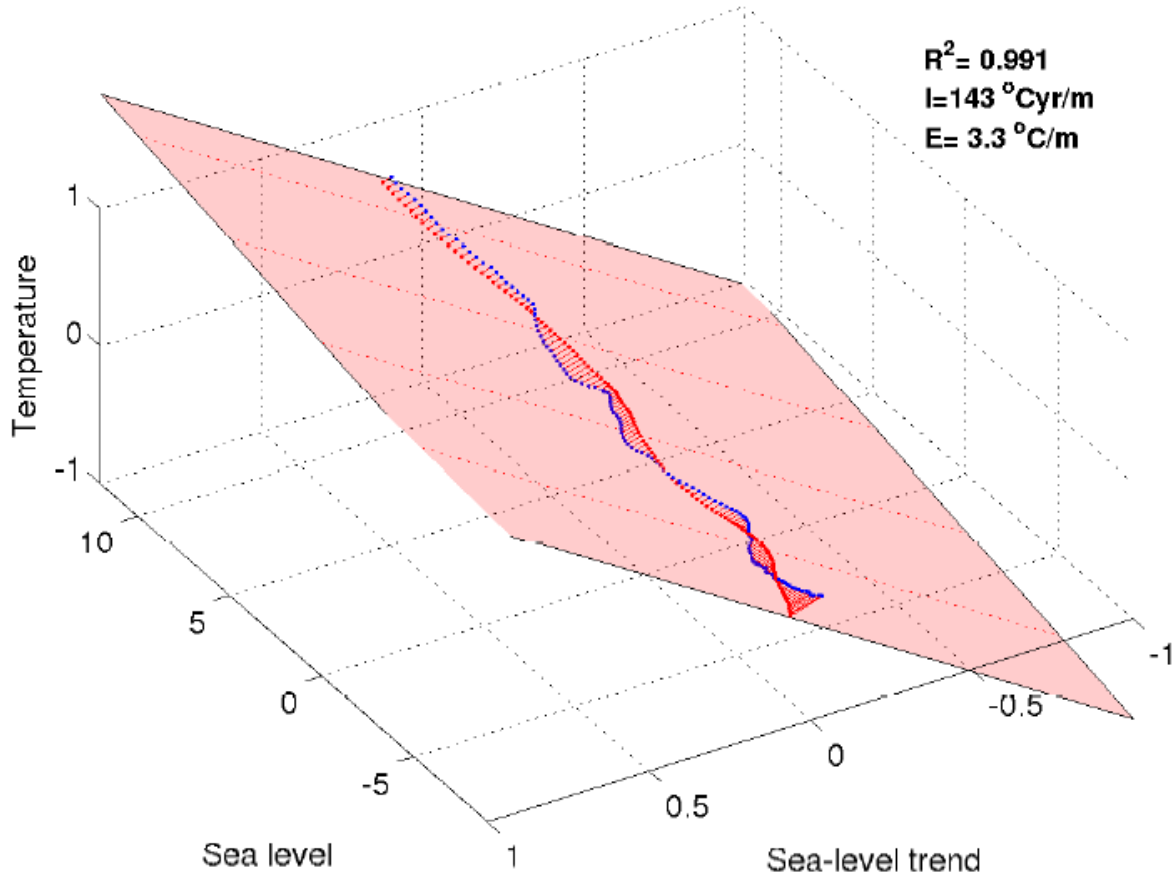
$$\tau = A\left(e^{\alpha t} - 1\right) + C\cos(\sigma t - \gamma)$$



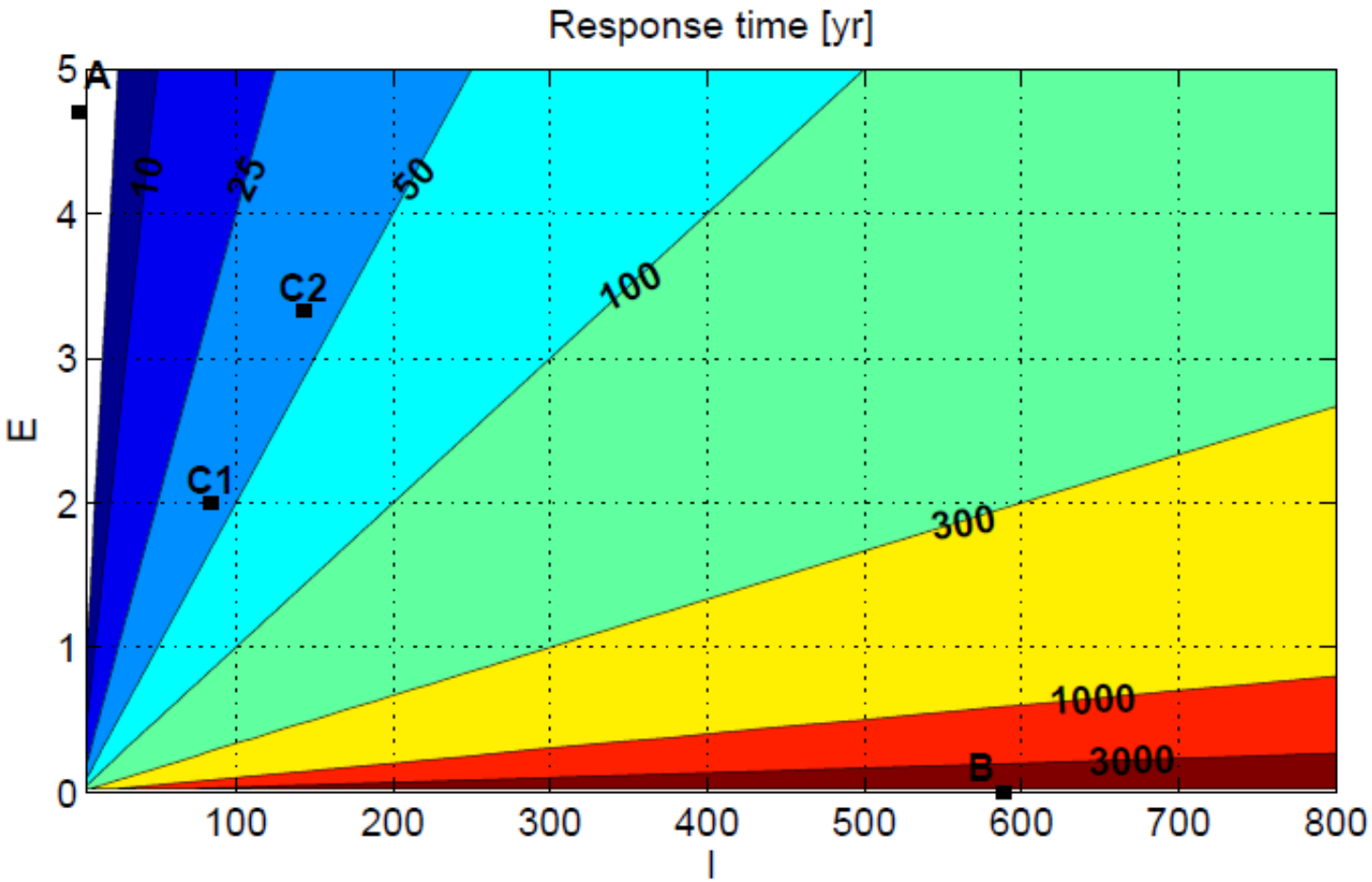
$$I\frac{d\eta}{dt} + E\eta = \tau \Rightarrow$$

$$\eta = B\beta\left(e^{\alpha t} - 1\right) + B\alpha\left(e^{-\beta t} - 1\right) + D\cos(\sigma t - \delta)$$

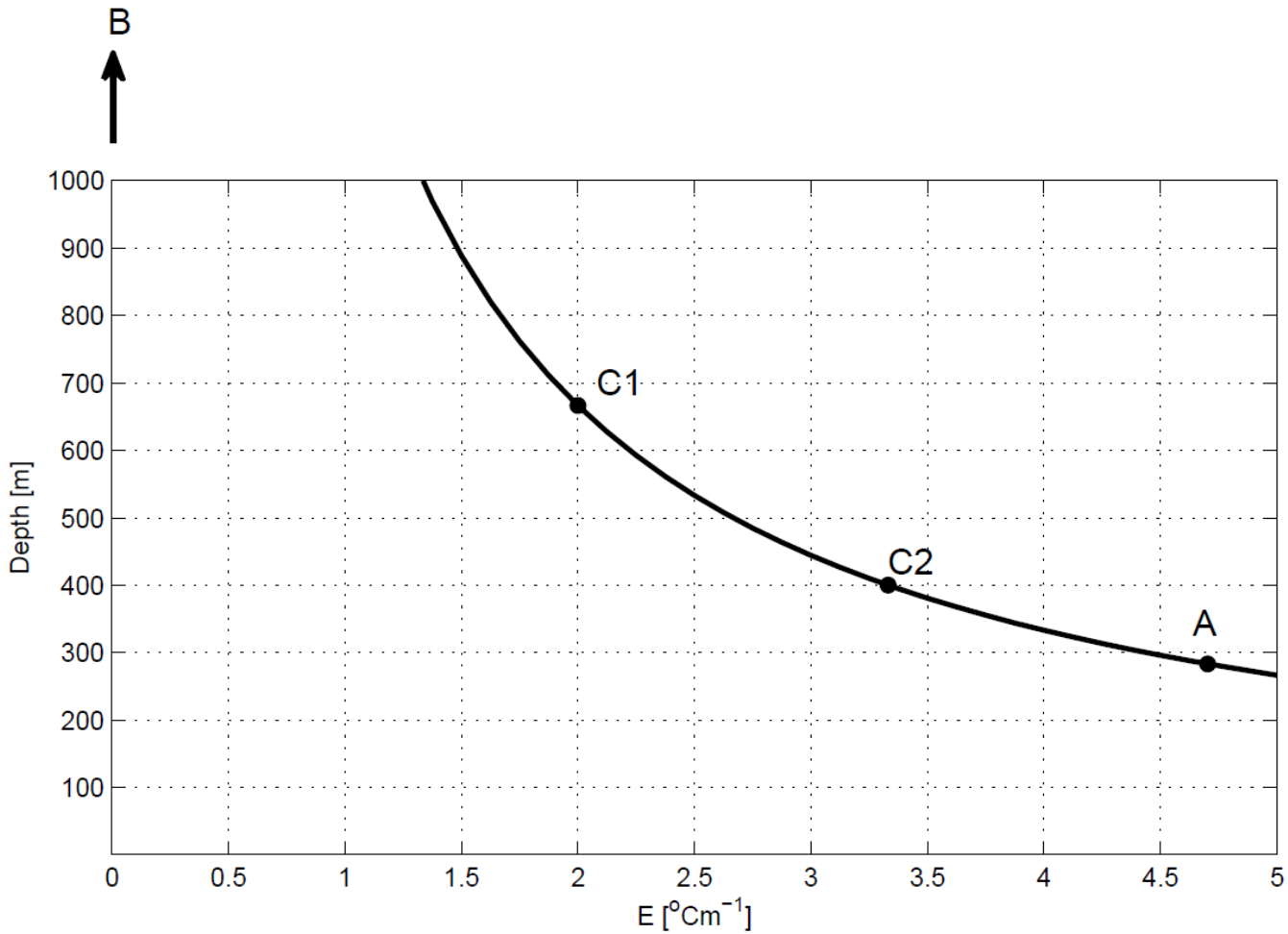
Variant C applied to the data (second approach, C2)



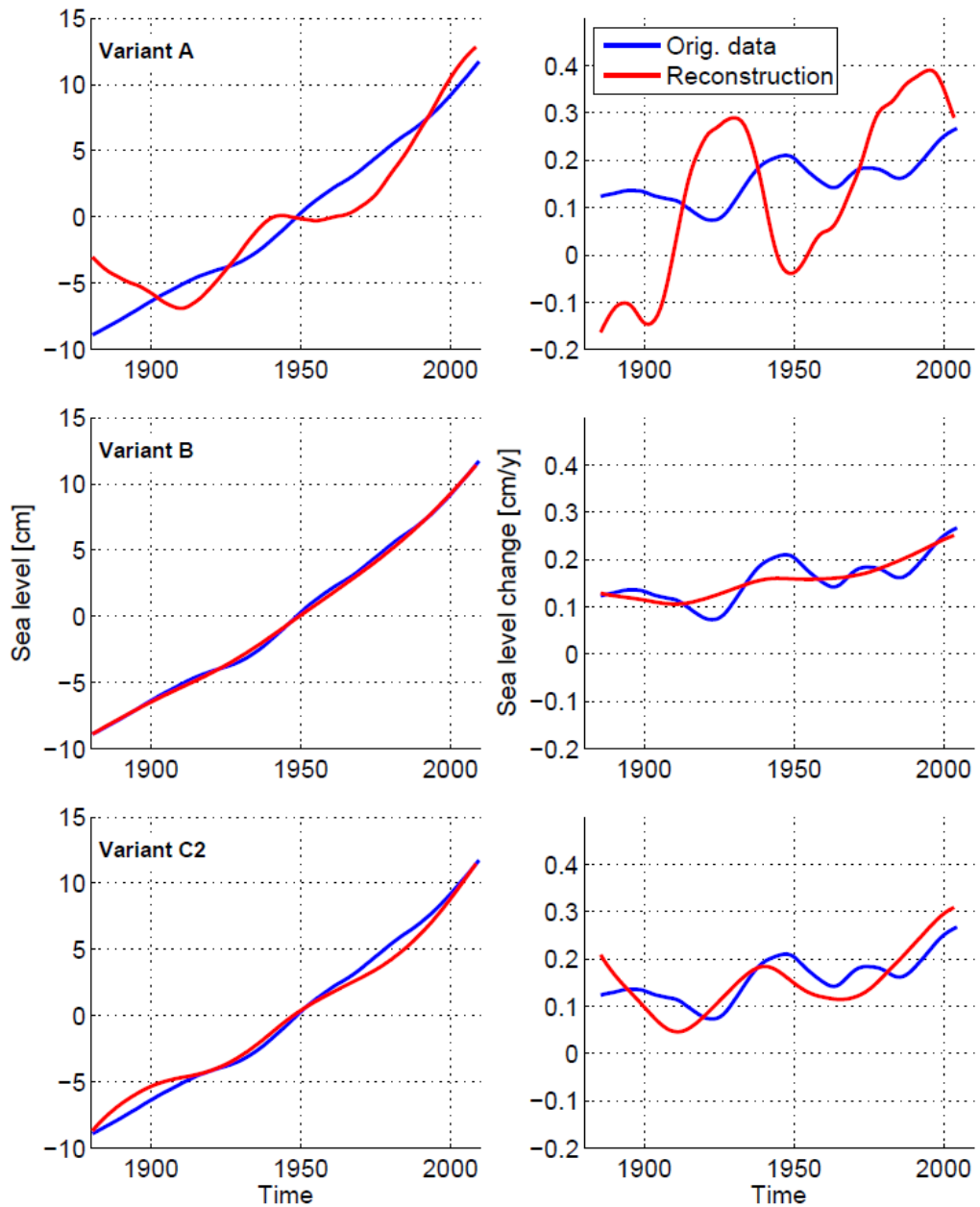
Response time



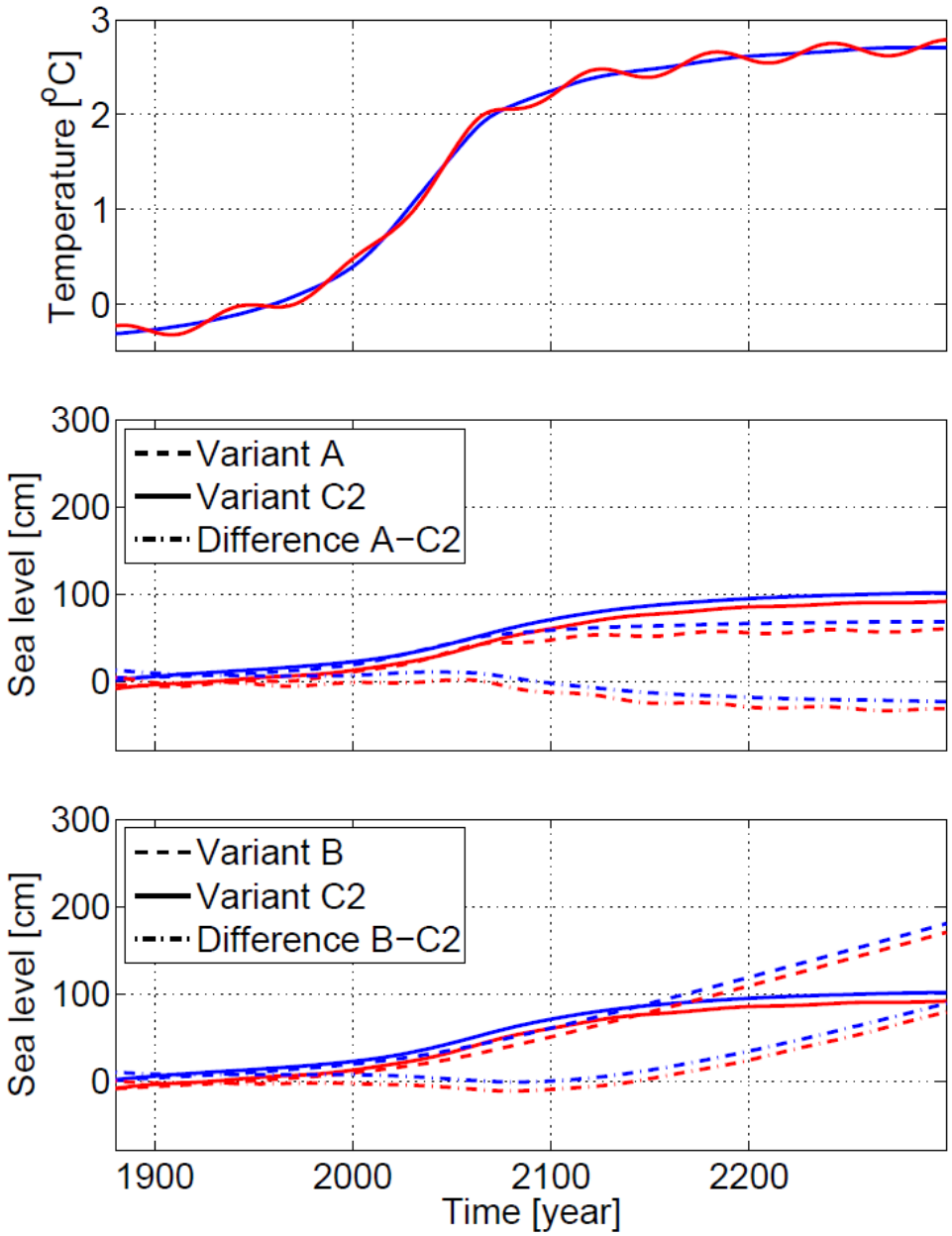
Extension of heat-content change



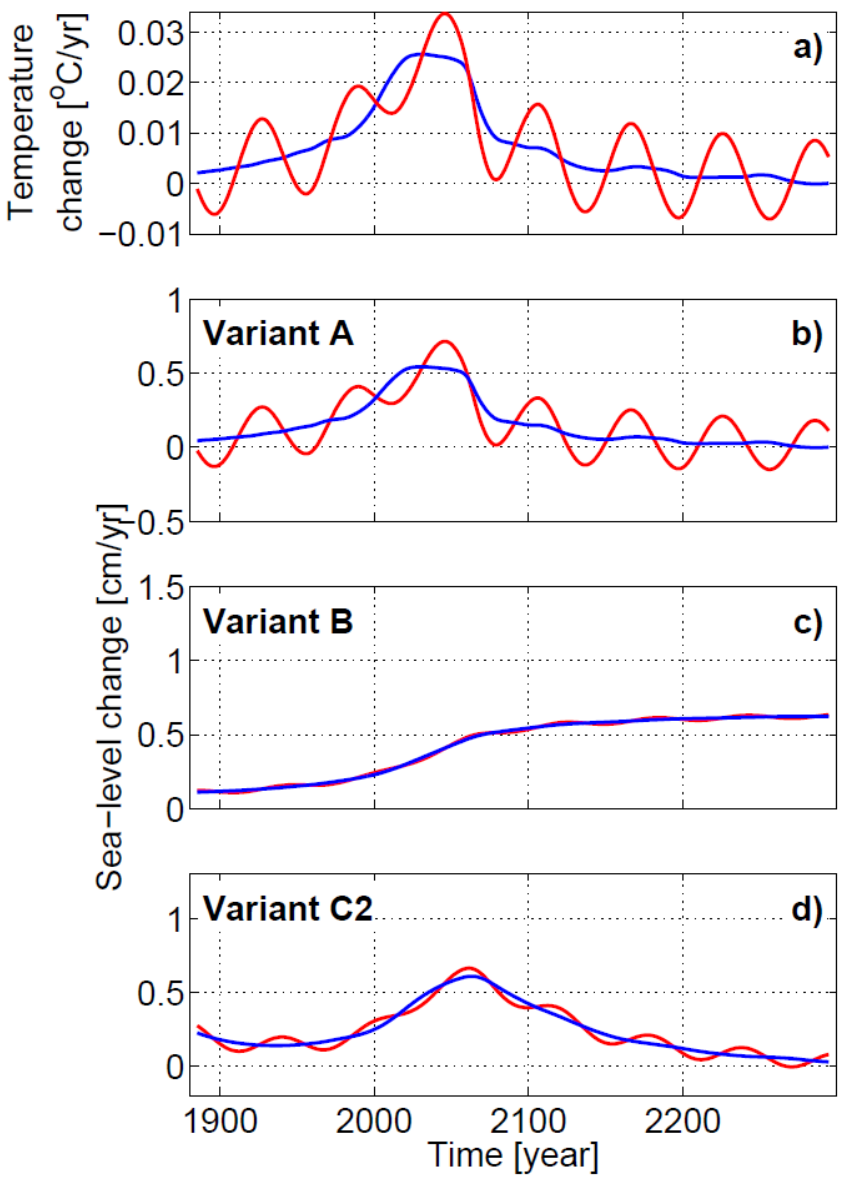
Comparison of measured and modeled sea levels and sea level trends



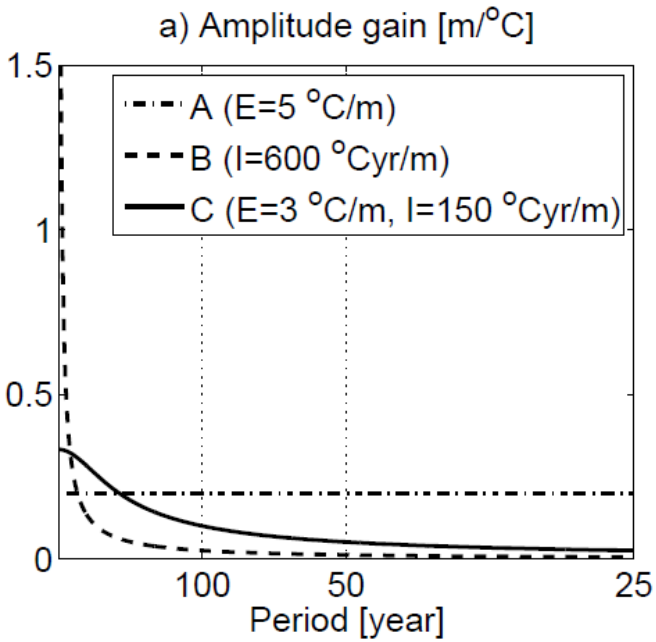
Reconstruction of sea levels and projections under the RCP4.5 scenario



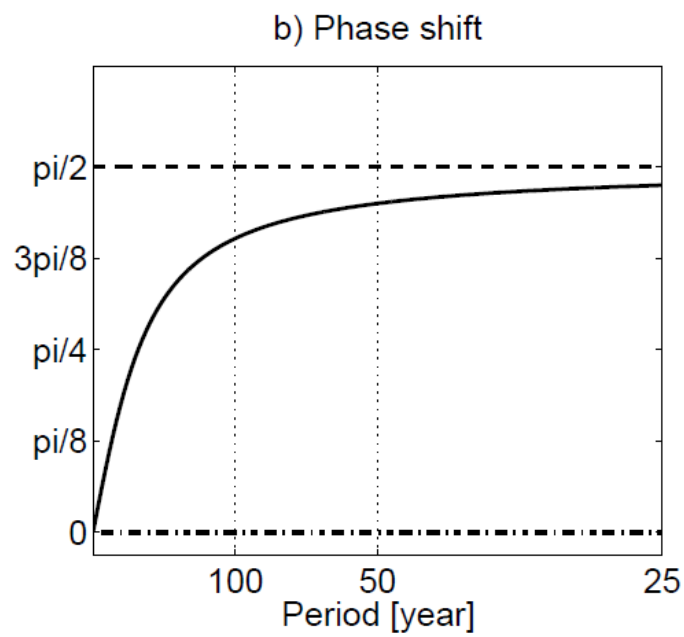
Reconstruction of sea level trends and projections under the RCP4.5 scenario



Interpretation using transfer functions



$$\Gamma(\sigma) = \frac{1}{\sqrt{E^2 + I^2\sigma^2}}$$



$$\Phi(\sigma) = \arctan\left(\frac{I\sigma}{E}\right)$$

Conclusion

- When considering sea level, it is helpful to pay attention not only to the time series of heights but also to related derivatives
- This enables one to take into account a broader part of the spectrum of sea level variability
- The extension is useful, because the methods utilized in analysis and projection have to be calibrated on the data having a specific spectral content and are then used to prepare projections under the forcing having different spectral characteristics

Supporting papers

nature climate change

LETTERS

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Semi-empirical versus process-based sea-level projections for the twenty-first century

Mirko Orlić* and Zoran Pasarić

Two dynamical methods are presently used to project sea-level changes during the next century. The process-based method relies on coupled atmosphere–ocean models to estimate the effects of thermal expansion and on sea-level models combined with certain empirical relationships to determine the influence of land-ice mass changes[1,2]. The semi-empirical method uses various physically motivated relationships between temperature and sea level, with parameters determined from the data, to project total sea level[3–7]. However, semi-empirical projections far exceed process-based projections. Here, we test the robustness of semi-empirical projections to the underlying assumptions about the inertial and equilibrium responses of sea level to temperature forcing and the impacts of groundwater depletion and dam retention during the twentieth century. Our results show that these projections are sensitive to the dynamics considered and the terrestrial-water corrections applied. For B1, which is a moderate climate-change scenario[1], the lowest semi-empirical projection of sea-level rise over the twenty-first century equals 62 ± 14 cm. The average value is substantially smaller than previously published semi-empirical projections and is therefore closer to the corresponding process-based values. The standard deviation is larger than the uncertainties of process-based estimates.

Global sea-level change is influenced by three important processes[1]: increasing ocean volume due to heat absorption, increasing ocean mass caused by the melting of glaciers and ice sheets, and changing ocean mass related to varying water storage on land. The first two processes may be linked to global warming, whether natural or anthropogenic. The third process, however, is not necessarily correlated with the global temperature because it may be strongly influenced by certain population-driven activities, such as groundwater depletion and water impoundment behind dams. In the present paper, all processes are taken into account when analysing data collected over the past century or so, whereas only the combined effect of the first two processes is considered when deriving projections for the next century.

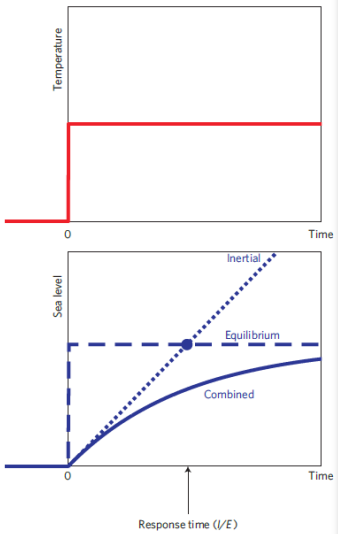

Figure 1 | Different types of sea-level response to a step temperature increase. Top: temperature forcing. Bottom: inertial (dotted line), equilibrium (dashed line), and combined (solid line) sea-level response the forcing. Other forms of forcing can be understood as series of small step changes, and the resulting responses can be constructed according

Some Pitfalls of the Semiempirical Method Used to Project Sea Level

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ABSTRACT

Three variants of the semiempirical method for sea level projection are considered. They differ in assuming that the response of sea level to temperature forcing is equilibrium, inertial, or a combination of the two. All variants produce a successful regression of the temperature and sea level data, albeit with controlling parameters that differ among the cases. The related response times vary considerably, with a realistic value (~50 yr) obtained only if both the equilibrium and the inertial dynamics are taken into account. A comparison of sea levels projected by using the three variants shows that the time series are similar through the middle of the twenty-first century but they radically diverge by the end of the twenty-third century. This result is interpreted with the aid of the underlying transfer functions. It suggests that one should be cautious when using the semiempirical method to project sea level beyond the twenty-first century.

1. Introduction

Sea level rise is one of the most worrisome consequences of expected climate change, and it has therefore attracted considerable attention from researchers (e.g., Stocker et al. 2014). In projecting sea level change during the next century and beyond, two dynamic methods are commonly used. The process-based method addresses the contribution of thermal expansion to sea level rise by using coupled atmosphere–ocean models and allows for the contribution of land-ice mass changes by using sea level models combined with some empirical relationships. The semiempirical method does not distinguish between the two contributions to sea level change, but it reproduces the response of total sea level to temperature increase via a set of physically motivated relationships and relies on available data to determine the controlling parameters.

presently tend to exceed process-based projections even if uncertainties are taken into account. Some researchers favor the results obtained by the semiempirical method (Rahmstorf et al. 2012; Bittermann et al. 2013), and a larger group prefers the outcome of the process-based method (Church et al. 2013; Stocker et al. 2014). A smaller group of investigators advocate a reconciliation of the two methods (Moore et al. 2013; Orlić and Pasarić 2013), which would enable the projections to be issued with more confidence than if based on a single method.

We believe that the gap between the two methods could be narrowed considerably if the assumptions and procedures on which they rest are analyzed in detail. As is well known, the process-based method has considerable difficulties with the ice sheets, especially when it comes to calving and migration of grounding line, and with the hundreds of thousands of glaciers