Steric and Eustatic Effects:
Understandig measured sea level rise by data assimilation

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Model Setup

Eleven years (1993-2003) of TOPEX/Poseidon sea surface height anomalies, provided by GfZ Potsdam, are assimilated into a global OGCM. In addition the SHOM98.2 mean sea surface relative to the EIGEN-GRACE01S geoid (GfZ) as well as sea surface temperatures and ice cover information from Reynolds (2002) are assimilated into the model. The WGHC climatology combined with the monthly anomalies from WOA01 is used as background information for temperature and salinity. Furthermore data from high resolution regional model runs are supplied in the Ross Sea and in the Weddell Sea.

The OGCM that is used in this study is based on the Hamburg Large Scale Geostrophic model LSG. The model has a $2^\circ \times 2^\circ$ horizontal resolution, 23 vertical layers and a ten day timestep. Furthermore the model is able to estimate the single contributions to sea level change, the steric (thermosteric, halosteric) and the non-steric effects (local freshwater balance, mass redistribution) seperately.

To adjust the model to the data the adjoint method is employed. The control parameters of this optimization are the models initial temperature and salinity state as well as the forcing fields (windstress, air temperature and surface freshwater flux). The forcing is optimized via an empirical orthogonal function (EOF) decomposition, with the first guess taken from the NCEP reanalysis.

Conclusion

In contrast to other studies we find no significant seasonal signal for the global steric expansion. In addition, we estimate a strong expansion from the ocean below 500m. Seemingly our analysis is not falsified by GRACE.

Validation

The temporal RMS differences between the modeled SSHA and the data is shown in Fig. 1.1 The global RMS value, which is the measure of success in the assimilation, is 2.9cm although locally we find higher RMS values (up to 7cm) especially in the tropical Pacific and in the western boundary currents. For the temporal mean SSH the deviations between the model and the data are well below 5cm in many parts of the ocean giving a global RMS value of 14cm. For the surface temperature the corresponding RMS differences between the model and the data are 0.30K for the temporal mean and 0.51K for the anomalies.

Using information in the Weddell Sea and the Ross Sea areas leads to an improved evolution of the global upper ocean heat content. The trend now fits well to the estimates derived analysing the WOA01 and the Willis data respectively (Fig. 1.2). Further independent data are e.g. global ocean mass changes as derived from the GRACE mission. The modelled annual cycle for 2003 fits well to these data in amplitude while the phase of the models signal seems to be about one month early (Fig. 1.3).

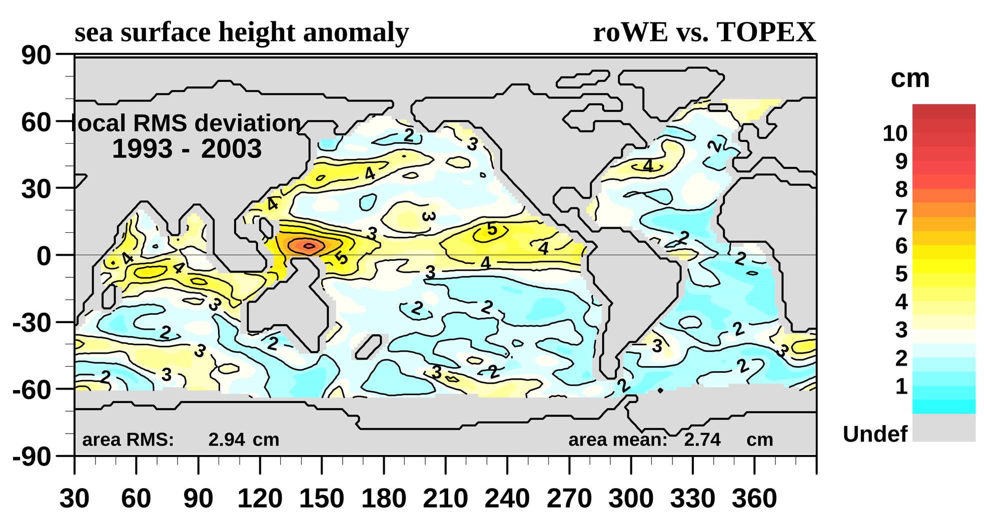

Fig. 1.1: *Local temporal RMS difference between the modeled SSHA and the TOPEX/Poseidon data*

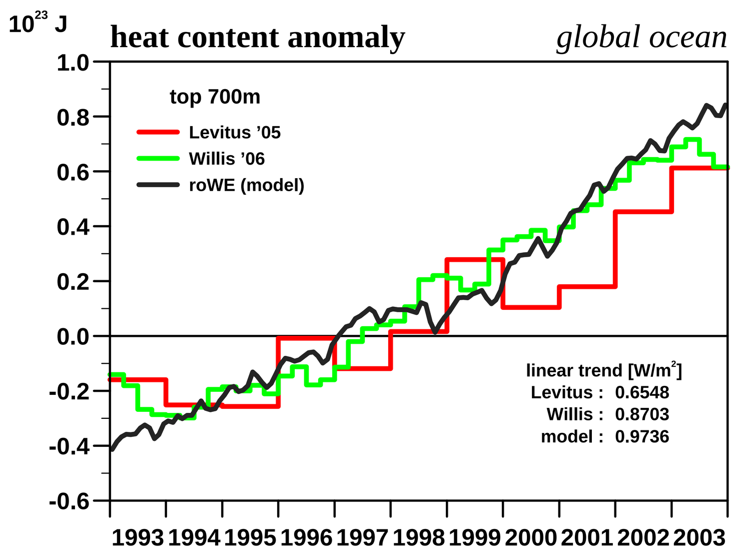

Fig. 1.2: *Global ocean heat content anomaly for the depth range [ζ-700m] compared to the WOA01 annual anomaly data (Levitus, red line) and to the Willis data (2006 update, green line)*

Levitus S. et al.: Warming of the world ocean 1955–2003, *Geophysical Research Letters*, Vol. 32, L02604, doi: 10.1029/2004GL021592, 2005
Willis J. K. et al: Interannual variability in the upper ocean heat content, temperature and thermosteric expansion on global scales, *Journal of Geophysical Research*, Vol. 109, C12036, doi: 10.1029/2003JC002260, 2004

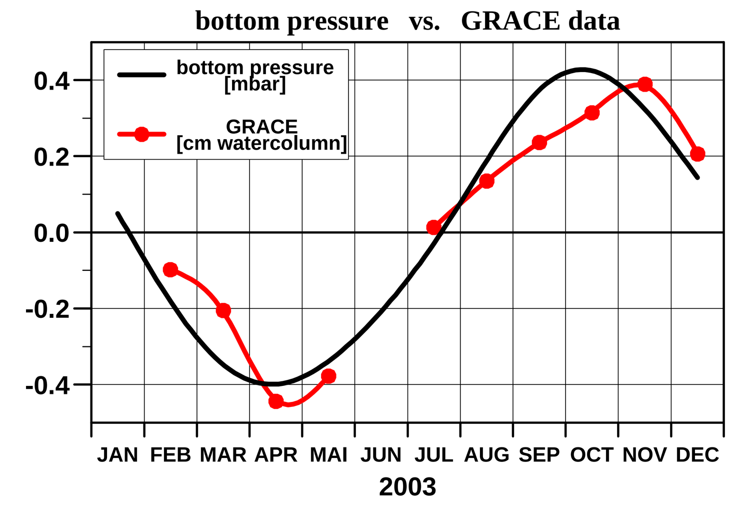

Fig. 1.3: *Global bottom pressure anomaly [mbar] for the year 2003 as compared to the latest GRACE data analysis [cm watercolumn equivalent] from GFZ (red line).*

Local Sea Level Trends

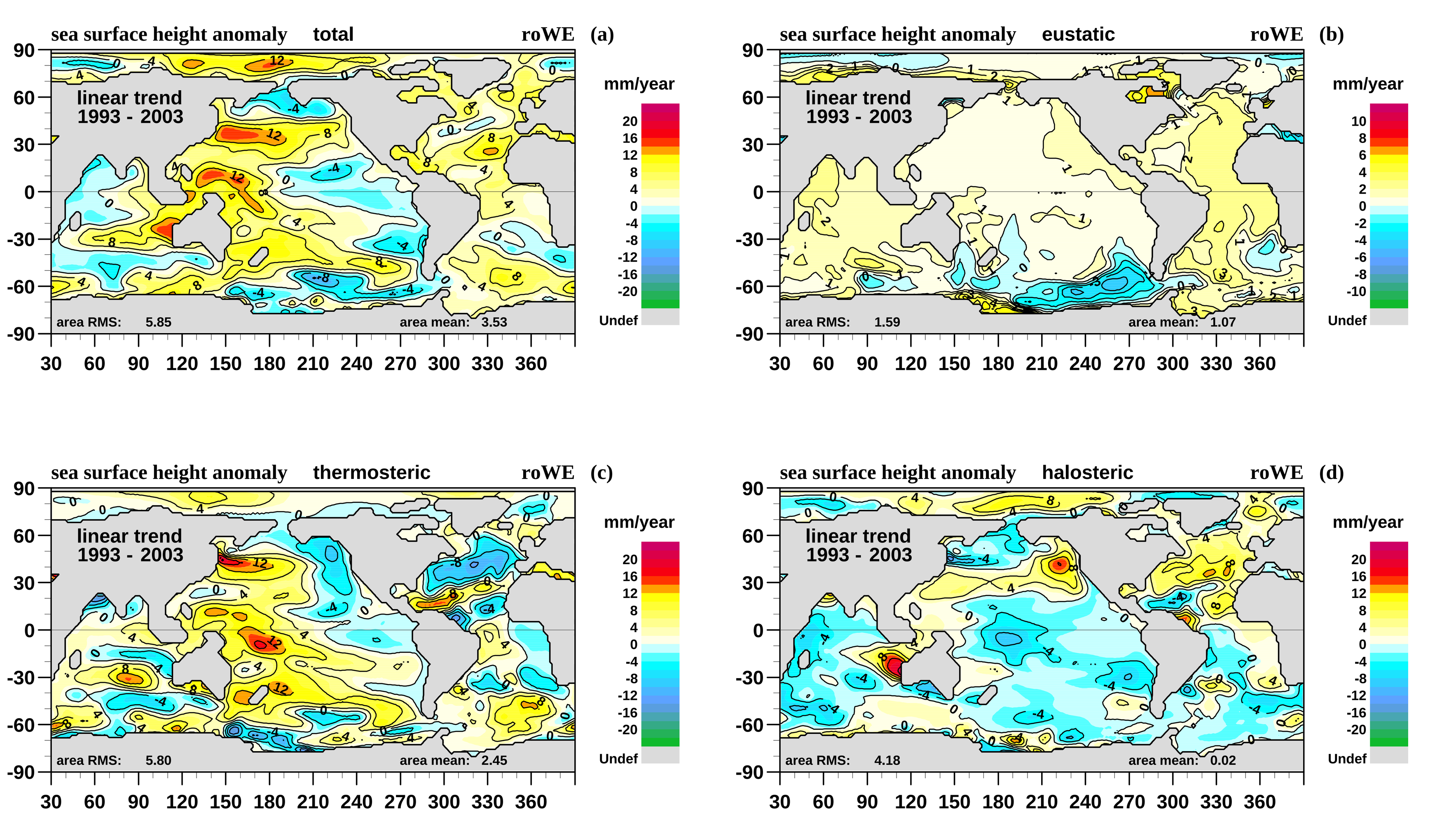

Fig. 2: *(a) Modeled local sea level trends and its (b) eustatic, (c) thermosteric and (d) halosteric component. The contour intervalls are 4 mm/year in (a),(c) (d) and 1 mm/year in (b)*

In Fig.2 the modelled total local sea level trend is splitted into its eustatic, thermosteric and halosteric part. The spatial distribution of the trend as estimated from the altimeter data is well reproduced by the model (Fig.2a). Much of its spatial structure is already due to the local changes in heat content (thermosteric trend, Fig.2c), but there are large regions, where the halosteric part (Fig.2d) becomes essential. Here both steric components have the same order of magnitude for the trend ($\sim$5mm/year global area RMS), but in many regions of the world ocean, especially in the Atlantic, they are opposite in sign thus compensating each other at least by part. On local or regional scale the eustatic sea level changes (Fig.2b) are the residual of the horizontal mass transport divergence and the surface freshwater fluxes. Compared to the steric changes (Fig.2c,d) the eustatic changes are about five times smaller and they vary on very large scales. In summary there is net eustatic sea level rise in all basins. But this rise is not evenly distributed: throughout the Atlantic and the Indian Ocean the eustatic trends are positive ($\sim$2mm/year) on a fairly constant level while they are well below 1mm/year in most parts of the Pacific.

Figure 3.1a shows that the model reproduces the global mean sea level data well. This is true especially for the interannual variability, while the amplitude of the annual cycle is slightly underestimated by the model. The latter appears to be a general deficit of the OGCM used that leads to the high RMS values apparent in Fig. 1.1. Figure 3.1a also shows that the linear trend in the modelled global sea level change originates mainly from the steric while the eustatic contribution is smaller but as essential. Furthermore, the global eustatic sea level resamples nearly all the 'short term' temporal variability (annual cycle) of the global mean sea level.

On regional scale, e.g. for the North Atlantic (Fig. 3.2a) the annual amplitude of the steric and the eustatic part are comparable in size. Figures 3.1b and c show that the deep layers contribute as much to the global thermosteric sea level change as the upper 500m, while the halosteric part is of minor importance on this scale. For the North Atlantic (Fig. 3.2) the halosteric changes are as important as the thermosteric: in the upper ocean they have the same sign and magnitude, while in the deeper ocean they nearly compensate.

Regional Sea Level Evolution

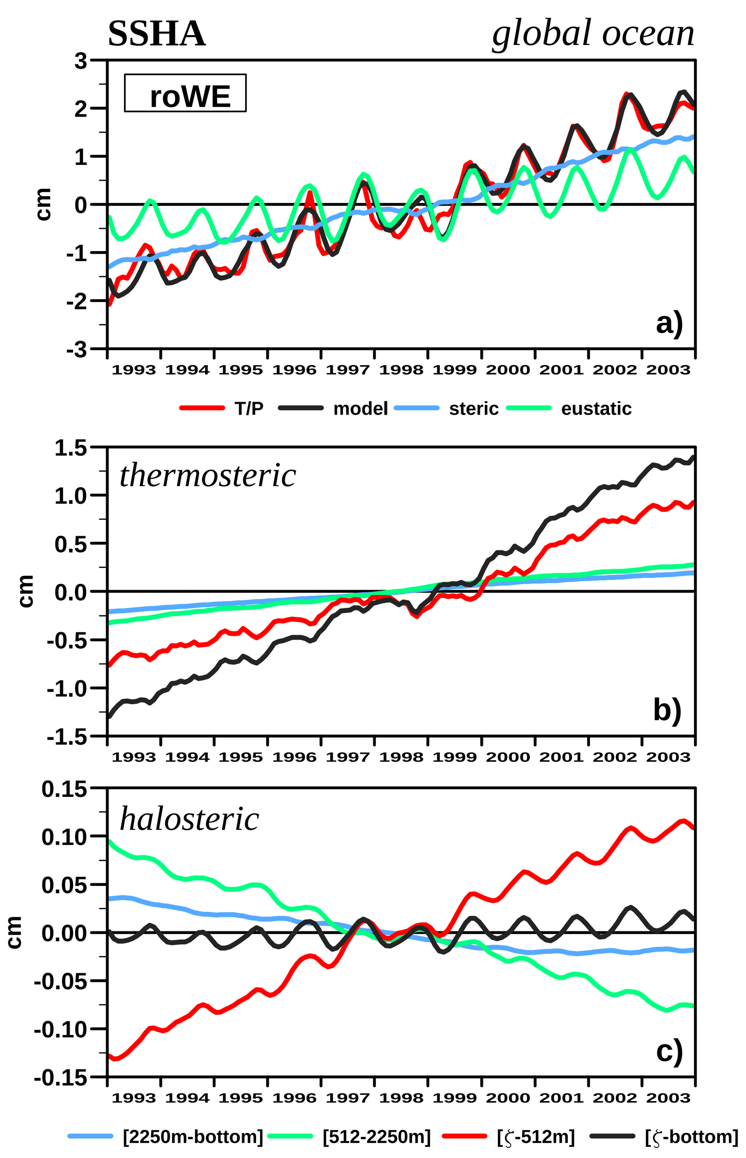

Fig. 3.1: *Temporal evolution of the global mean sea level anomaly as compared to the TOPEX/Poseidon data (a). The evolution of the total steric and the eustatic component is also included in (a). The contributions to the thermosteric and the halosteric component from different depth ranges are shown in (b) and (c) respectively.*

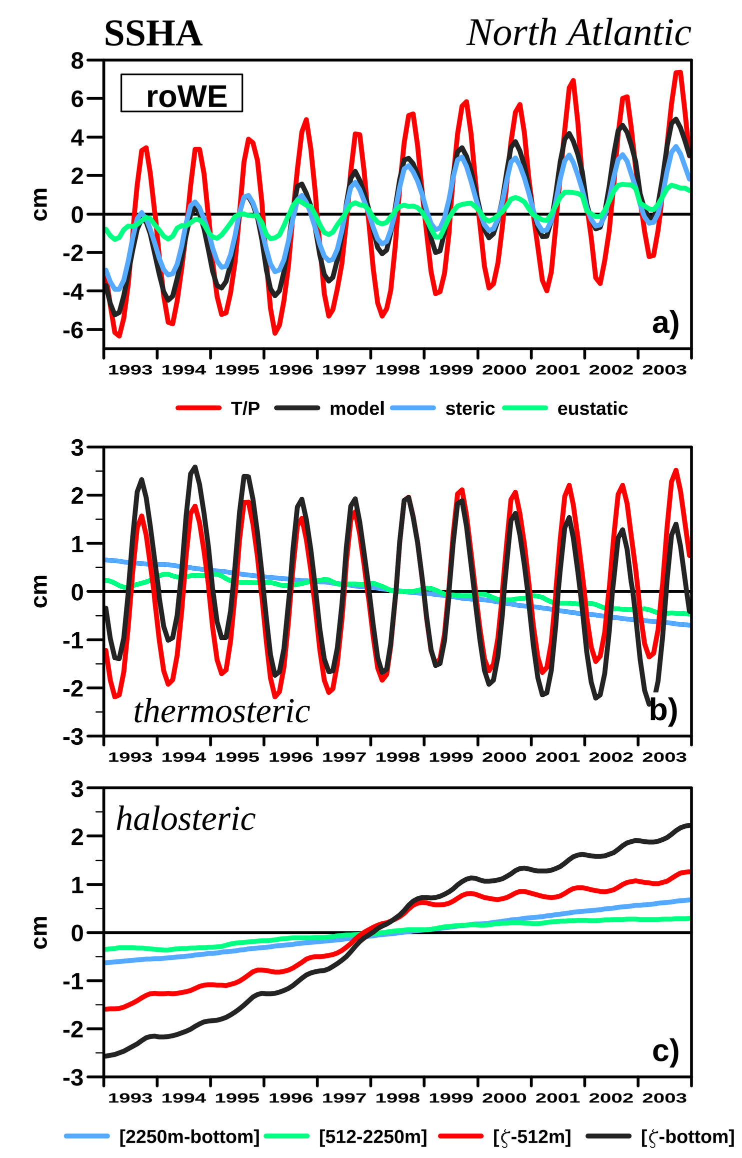

Fig. 3.2: *same as Fig. 3.1 but for the North Atlantic [20N-65N]*

Sea Level Trends [mm/year]
Global Ocean

	0m – bottom	0m – 512m	512m – 2250m	2250m – bottom
TOPEX	+3.37			
model	+3.53			
(Topex area)	(3.45)			
eustatic	+1.07			
total steric	+2.47	+1.74	+0.40	+0.32
thermosteric	+2.45	+1.52	+0.55	+0.38
halosteric	+0.02	+0.22	–0.15	–0.06

Sea Level Trends [mm/year]
North Atlantic

	0m – bottom	0m – 512m	512m – 2250m	2250m – bottom
TOPEX	+4.43			
model	+5.50			
(Topex area)	(5.18)			
eustatic	+1.75			
total steric	+3.75	+3.81	–0.02	–0.04
thermosteric	–0.96	+1.02	–0.71	–1.27
halosteric	+4.71	+2.79	+0.69	+1.23

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