UNDERSTANDING MEASURED SEA LEVEL RISE BY DATA ASSIMILATION

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ABSTRACT

Sea surface elevations as measured by the satellite altimeter together with hydrographic measurements are assimilated into a global OGCM that has a free surface, i.e. that conserves mass rather than volume. The combination of both types of measurements appeared to be necessary to get a reasonable estimate of the oceanic circulation. Furthermore referencing the altimeter data to the GRACE geoid improves the modelling of anomalies. Further improvement in estimating sea level change was achieved by including the steric effects (thermosteric and halosteric) into the modelled sea surface elevation, because local sea level trends vary substantially in space and time. They are closely associated to heat and salt anomalies in the ocean.

The evolution of global mean sea level for the period 1993--2003 with annual and interannual variations can be reproduced to 1.74 mm RMS difference. Its trend has been measured as 3.37 mm/year while the constrained model gives 3.45 mm/year considering only the area covered by measurements (3.53 mm/year for the total ocean). We estimate a steric rise of 2.47 mm/year in this period and a gain in the ocean mass which is equivalent to an eustatic rise of 1.07 mm/year. While the corresponding halosteric trend (0.02 mm/year) is of minor importance on global scale, it must not be ignored locally or even regionally. It shows the same order of magnitude as the thermosteric but opposite sign in many places of the ocean. Furthermore, the analysis of the model results shows, that the deep ocean (below 500 m) contributes about as much to the global thermosteric sea level rise as the top layers (above 500 m).

1. INTRODUCTION

Since the launch of the TOPEX/POSEIDON satellite in 1992 the changes in sea level can be measured with high spatial and temporal resolution and a nearly global coverage. The aim of this paper is to find a dynamically consistent interpretation of the measured sea level changes, i.e. to determine whether they are caused by steric effects or by mass changes within the ocean.

To find a consistent reanalysis of the changes and their regional distribution it is insufficient to apply local corrections in temperature or sea surface height or vertical adjustment (heave). Only an optimization of the forcing of the ocean that leads to sustained circulation changes and thus indirectly to sea level changes can be successfull. In the present paper the ocean state estimation technique is applied that constrains an ocean general circulation model (OGCM) by data. The utilized global OGCM has a free surface, i.e. it conserves mass rather than volume. This offers the possibility to combine altimeric measurements with hydrographic data in a dynamically consistent manner and to look at the oceans sea level change in more detail, in space as well as in time. Using altimetric and hydrographic data for the period 1993-2003 mainly the regional and global trends in the sea level will be discussed.

2. MODEL AND DATA

For our purpose we use the Hamburg Large Scale Geostrophic model (LSG, [1]). In conjunction with its adjoint this model has been used successfully for ocean state estimation (e.g. [2], [3], [4]). It has 2 x 2 degree horizontal resolution, 23 vertical layers (varying from 20 m thickness for the top layer to 750 m for the deepest ones) and the implicit formulation in time allows for a time step of ten days. The datasets used in the assimilation experiment are:

- monthly sea surface temperatures (SST) for the period 1993-2003 [5]
- gridded fields of ten day averages of sea surface height anomalies (SSHA) as measured by the TOPEX/Poseidon altimetric mission for the period 1993-2003, provided by Geoforschungszentrum Potsdam (GfZ; S. Esselborn, pers. Communication). These anomalies are combined with the SHOM98.2 mean sea surface height (MSSH; [6]) referenced to the EIGEN-GRACE01S geoid [7] to give absolute dynamic height values.
- temporal mean transports of mass, freshwater and heat as obtained by different authors and as they are summarized e.g. by [8] and [9]. Transport constraints are not applied for the Antarctic Circumpolar Current (ACC).
- the climatological mean temperatures and salinities from the WOCE Global Hydrological Climatology (WGHC; [10]) in combination with the mean annual cycle from the most recent World Ocean Atlas (WOA01; [11]). These data are supplied to the assimilation procedure with small weights thus serving only as background information.
- the mean annual cycle of temperatures, salinities and horizontal velocities on two sections in the Weddell Sea area and on four sections in the Ross Sea. These data are taken from high resolution model experiments of the Weddell Sea [12] and the Ross Sea [13] whose water mass characteristics and circulation are in good agreement with local observations. These

sections are marked in Fig. 1 by straight red lines. Thus the experiment **roWE** as analysed in this paper is an extension of the experiment **WEDD** described in [14], which utilizes the Weddell Sea data only.

To adjust the model to the data the adjoint method is employed, which is a variational optimization method. 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), whereat the first guess forcing is taken from the monthly NCEP re-analysis fields. A more detailed desription of the assimilation procedure can be found in [4].

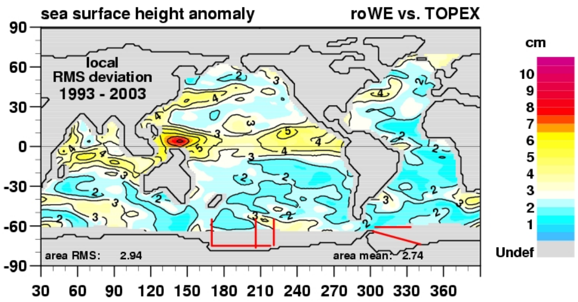

Figure 1: Local temporal RMS of the difference between modeled SSHA and the TOPEX/Poseidon data. The contour intervall is 1 cm. The models coastline is given by the thick black line and the grey shading within the ocean indicate areas with no SSHA data used. The red lines within the Weddell Sea and the Ross Sea mark the sections with data from the fine resolution model runs (from [12] and [13] respectively).

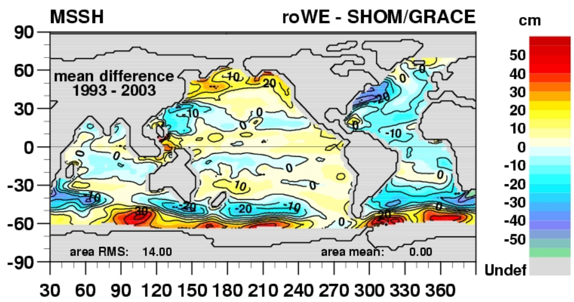

Figure 2: Local difference between the models mean SSH and the corresponding data mean. The contour intervall is 10 cm.

3. RESULTS

The temporal RMS differences between the modeled SSHA and the data is shown in Fig.1. The global RMS value, which is the measure of success in the assimilation, is 2.9 cm although locally we find higher RMS values (up to 7 cm) 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 5 cm in most part of the ocean giving a global RMS value of 14 cm (Fig.2). As for the anomalies the largest deviations (up to ~30 cm) are found in the regions with strong currents, i.e. the western boundary currents as well as the Antarctic Circumpolar Current (ACC). Especially the signature in the ACC region implies that these currents are represented too broadly by the model. For the surface temperature the corresponding RMS differences between the model and the data are 0.30 K for the temporal mean and 0.51 K for the anomalies (not shown).

Another possibility to judge the model results is e.g. to compare the upper oceans heat content anomalies to independent data. Fig.3 shows the modeled heat content anomaly for the upper 700 m of the global ocean. The resulting trend of the model (estimated by fitting a straight line to the curve) corresponds to a mean heat gain of 1.0 W/m^2. Though this value is somewhat higher than the values estimated from the analysis of [15] or from [16] it compares well, although no explicit subsurface temperature data are given in the assimilation.

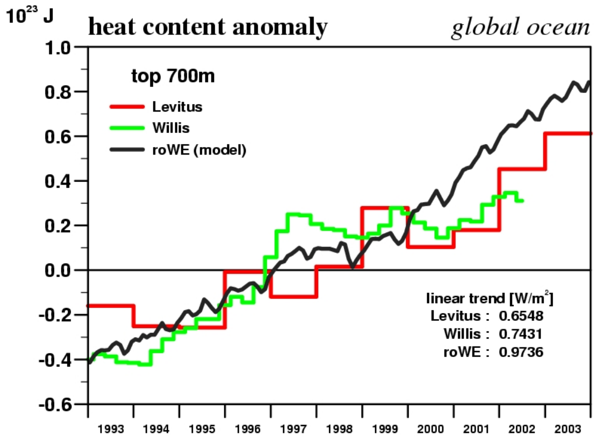

Figure 3: Modeled upper ocean (top 700m) global heat content anomaly compared to the results from [15] and [16] respectively.

Fig.4a shows that the optimized model reproduces the global mean sea level data well (RMS of difference: 0.15 cm). This is true especially for the interannual variability, while the amplitude of the annual cycle is slightly underestimated by the model. The latter becomes even more apparent on local scale (not shown) and appears to be a general deficit of the OGCM used which leads to the high RMS values apparent in Fig.1. Fig.4a also shows that the linear trend in the modelled global sea level change (3.53 mm/year) originates mainly from the steric (2.47 mm/year) while the eustatic contribution (1.07 mm/year) is smaller but as essential. Its value corresponds well to the 0.87 mm/year that can be derived by adding together the estimates reported in [17]: 0.25 mm/year sea level rise from land water and snow mass, 0.1 mm/year from mountain glaciers, 0.13 mm/year from Greenland and 0.22 mm/year from Antarctica.. Furthermore, the global eustatic sea level resamples nearly all the 'short term' temporal variability of the global mean sea level, while the steric contribution appears more or less as a straight line. Nevertheless we find a small annual cycle in the steric part too, which appears to be in anti-phase with the eustatic.

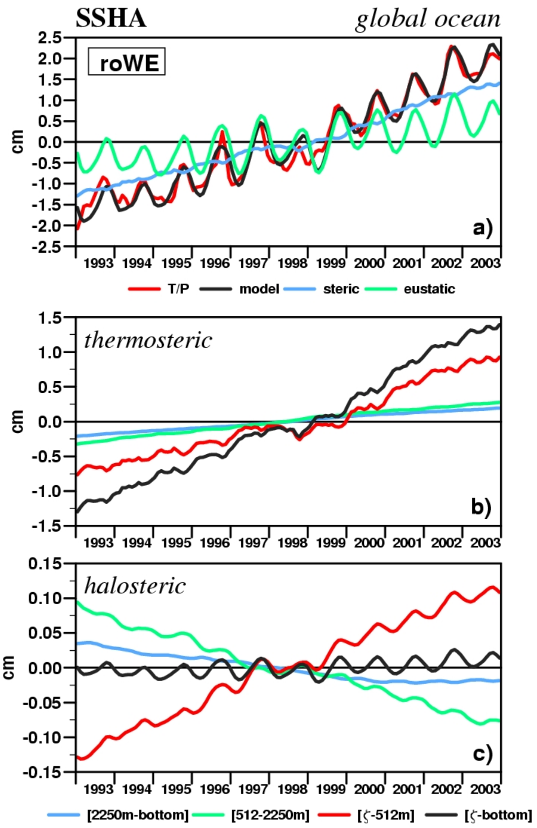

*Figure 4: (a) Global mean sea level anomaly from the assimilation experiment **roWE** as compared to the TOPEX/Poseidon data. Additionally the modeled steric and eustatic parts are shown.The thermosteric and the halosteric contributions from different depth ranges are shown in (b) and (c) respectively.*

On global scale the steric contribution to the sea level rise is mainly caused by the thermosteric effect (Fig.4b) with a positive trend (2.45 mm/year) steming from all layers. Fig.4b also shows that the deeper layers (below 500 m) contribute as much to the thermosteric sea level rise as the top 500 m, which is confirmed e.g. by the results shown in [16]. Thus, the deep layers should not be neglegted when estimating the oceans water mass budget from sea level change and temperature measurements especially on long timescales. The negligence might be justified when investigating the mean annual cycle only, like e.g. [18], [19], [20] or [21]. Looking on longer periods temperature and salinity changes might be small in the deep layers but they are related to a large volume that amplifies their influence on the sea level.

The halosteric part (Fig.4c) implies a redistribution of salt from the top layers to the deeper ones. But this is not a unique result from all our assimilation experiments performed so far. Anyhow, for the total volume the halosteric sea level trend reflects the global freshwater balance from precipitation, evaporation and run-off (see e.g. [22]) but it is of minor importance (0.02 mm/year). However, it cannot be neglegted locally neither regionally as can be seen from Fig.4.

In Fig.5 the modelled total local sea level trend is splitted into its thermosteric, halosteric and eustatic part. The spatial distribution of the trend as estimated from the altimeter data is well reproduced by the model (Fig.5a). Much of its spatial structure is already due to the local changes in heat content (thermosteric trend, Fig.5b), but there are large regions, where the halosteric part (Fig.5c) becomes essential. Here both steric components have the same order of magnitude for the trend (~5 mm/year global 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 (see also [23] or [3]).

On local or regional scale the eustatic sea level changes (Fig.5d) are the residual of the horizontal mass transport divergence and the surface freshwater fluxes. Compared to the steric changes (Fig.5b,c) 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, except for the Pacific sector of the ACC, but this rise is not evenly distributed: throughout the Atlantic and the Indian Ocean the eustatic trends are positive (~2 mm/year) on a fairly constant level while they are well below 1 mm/year in most parts of the Pacific. The most conspicuous feature in Fig.5d are the negative trends in the area of the ACC, especially the one west of Drake Passage (down to –4 mm/year) leaking into the Scotia Sea. This unequal distribution of eustatic sea level change in the single ocean basins appears to be caused mainly by an internal redistribution of mass [14].

These results are only one step on our way to fully understand the present day sea level change. Although global analyses like in [15] or [16] have their own deficiencies, the next step will be to include more subsurface information directly into the assimilation scheme to improve the modeled steric sea level change and by this to upgrade the eustatic estimates. Furthermore, once the GRACE data have been improved, the alternate approach will be possible too: to better the ocean heat content estimates, steric sea level variations by constraining the bottom pressure variations. This route was proposed e.g. by [24] and appears to be necessary to follow because direct hydrographic measurements are sparse in space and time.

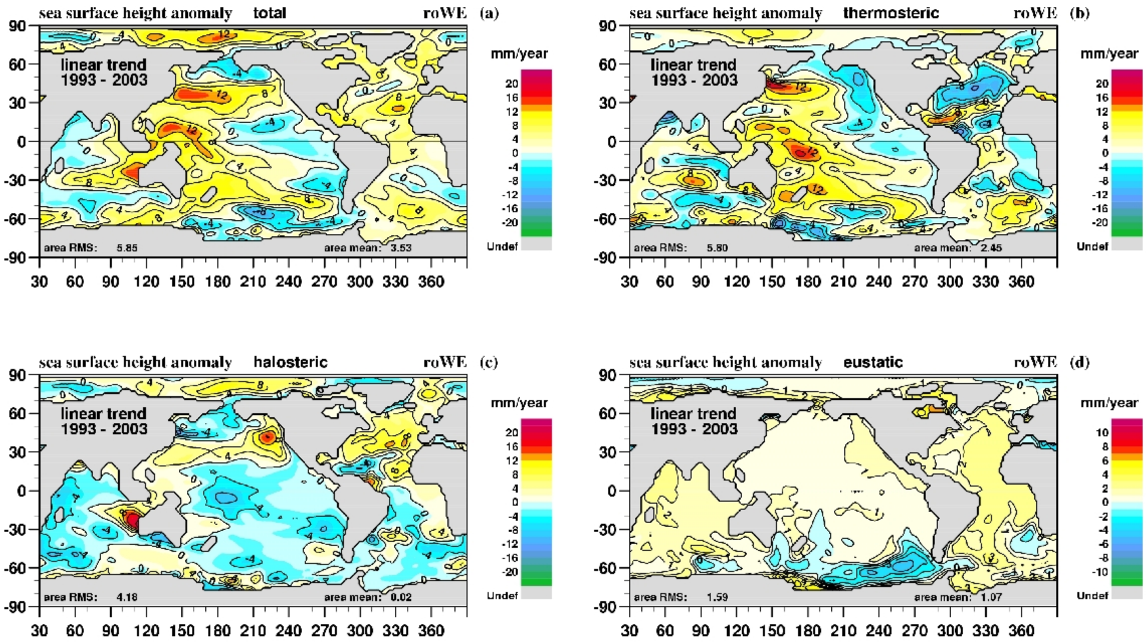

Figure 5: (a) Modeled local sea level trends and its (b) thermosteric, (c) halosteric and (d) eustatic component. The contour intervalls are 4 mm/year in (a)-(c) and 1 mm/year in (d)

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