Decadal Sea Level Changes in the 50-Year GECCO Ocean Synthesis

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Abstract

An estimate of the time-varying ocean circulation, obtained over the period 1952-2001 is analyzed here with respect to its decadal and longer term changes in sea level. The estimate results from a synthesis of most of the ocean data sets available during this 50-year period with the ECCO/MIT ocean circulation model. Estimated over the top 750 m depth, the increase in thermosteric sea level rise amounts to 1.3 mm/yr on average over the period 1992 through 2001. This corresponds to an increase in upper ocean heat content of $1.5 \times 10^{22}$ J/yr and is in agreement with estimates of Willis et al. (2004). However, over the period 1962 through 2001 the global net thermosteric sea level rise is estimated as 0.92 mm/yr from top to bottom, which is three times the recent estimate from Antonov et al. (2005) (0.33 mm/yr). For the last decade, the corresponding global heat flux into the ocean of 1.5 W/m is twice as large as the recent estimate by Willis et al. (2004) due to the heat content change in deeper layers. Regional changes in sea level are predominantly associated with an intensification of the subtropical gyre circulation and a corresponding redistribution of heat. The horizontal advection of heat due to an increase in wind stress curl is found to explain a major fraction of the estimated regional sea level trends over the last 40 years. However, the mechanisms appear different during the last decade when changes in surface heat flux may explain as much as 50% of the sea level changes.
1 Introduction

During the past 20 years, substantial progress has been made in analyzing and understanding decadal variability and multi-decadal trends in global ocean heat content and thermosteric sea level. Church et al. (2001) documented the widespread results of early thermal expansion estimates of the order of 1 mm/y. In particular, there exists a significant disparity (Munk, 2002; Cabanes et al., 2001; Cazenave and Nerem, 2004; Miller and Douglas, 2004) between estimates of global sea level rise and its thermosteric component in the second half of the 20th century. Church et al. (2004) attempted to provide an improved estimate of sea level change over the last 50 years by extending the unprecedented data coverage available since the launch of Topex/Poseidon backward in time using EOFs jointly with long tide gauge records. Tide gauge data suggest an increase of about 1.8 mm/y (Douglas, 1991, 1997; Church et al., 2004). However, this estimate is subject to a large regional variability, which raises serious questions about the adequacy of this global data base for such an investigation.

Investigations of the 50-year ocean data record with respect to ocean heat storage and thermosteric sea level rise have been carried out by Levitus et al. (2000, 2005d,c), Antonov et al. (2002, 2005), and Ishii et al. (2003, 2006). All those studies are based on the same World Ocean Database (Conkright et al., 2002) but differ in their detailed analysis procedures. Ishii et al. (2006) estimated a linear trend of 0.19 x 10^22 ± 0.05 J/yr for heat content in the top 700 m for the period 1955-2003, with a corresponding 0.31 ± 0.07 mm/yr rise in thermosteric sea level. This has to be compared with trend estimates from Levitus et al. (2005c) and Antonov et al. (2005) of 0.23 x 10^22 J/yr for the of heat content trend for the same layer and time period and of 0.33 mm/yr for thermosteric sea level. Considering the deeper layer, 0-3000 m, increased this estimate by 20%, to 0.40 mm/yr for the period 1957-1997.

Contribution of a halosteric component to sea level change was estimated by Ishii et al. (2006) as 0.04 ± 0.01 mm/yr, consistent with the earlier estimate by Antonov et al. (2002). While the halosteric contribution is important in regional patterns of sea level change, it does not contribute much to a global average steric change whereas an eustatic contribution of 1.1-1.3 mm/yr due to the associated freshwater input dominates
the sea level change (Wadhams and Munk, 2004). The lack of historical salinity data, especially in the Southern Hemisphere, however, may preclude an accurate estimate of the global oceanic freshwater budget over the 50-year record. Gregory et al. (2004) tested the sensitivity of estimates of sea level change on different assumptions while filling data-void regions. The authors showed that results of heat content changes are indeed affected by details of the analysis procedure and that resulting errors in the estimate of the heat content can be larger than the trend over the 50-year period. Obtaining estimates of SSH changes over the last 50 years from data alone, therefore, remains to be extremely challenging.

To overcome the inadequate data distribution a promising approach is to synthesize all available data into one dynamically consistent estimate of the evolving ocean by merging them with a circulation model through data dynamically consistent assimilation. The benefit of such an analysis over many years and decades resides in the fact that the ocean model carries the information, obtained by the ocean observing system locally in space and time, over many years and decades forward and backward in time and thus allows, at least hypothetically, the possibility of inferring the ocean state and its changes even in locations remote from direct observation. The consortium for Estimating the Circulation and Climate of the Ocean (ECCO) previously demonstrated the feasibility to obtain such dynamically consistent global ocean state estimates (Stammer et al., 2002, 2003, 2004; Köhl et al., 2007; Wunsch and Heimbach, 2006). Wunsch et al. (2007) studied estimates of regional patterns of global sea level change from a 1° solution obtained over the period 1993-2004. The authors concluded from their solution that for regional patterns on large scales only few individual points have statistically significant signals. They reported a global sea level change of 1.6 mm/yr of which about 70% results from the addition of fresh water to the model. In comparison, Cazenave and Nerem (2004) and Leuliette et al. (2004) have estimated from altimetric data a global average sea level rise of 2.8±0.4 mm/yr during the last decade.

To address climate relevant problems, longer time scales have to be taken into consideration. It was therefore attempted by the German partner of the ECCO effort (GECCO) to estimate the ocean circulation over the 50-year period 1952-2001. The aim of the GECCO effort is to bring the ECCO/MIT adjoint ocean circulation model (Adcroft et al., 2002;
into consistency with all in situ and satellite observations that were collected since the beginning of the 1950s. The GECCO optimization follows essentially the procedure of the previous ECCO optimization over 11 years, described in detail by Köhl et al. (2007). Based on this 50-year optimization, Köhl and Stammer (2007) investigated decadal changes of the meridional overturning (MOC) in the Atlantic Ocean, and also provide details on the optimization set up. This present study will focus on regional and global sea level changes on decadal and longer time scales as they result from the GECCO estimate.

The structure of the remaining paper is as follows: Section 2 describes the method and approach taken here. Estimates of sea level change from the GECCO results are presented in Section 3 for the last 40 years and the associated global heat content changes are presented in Section 4. Section 5 focuses on the period 1992 through 2001. Mechanism for the observed and simulated SSH changes are discussed in Section 6. Concluding remarks follow in Section 7.

2 Methodology

The assimilation approach used in this study is essentially identical to the 11-year ECCO global data synthesis on a 1° horizontal grid described by Köhl et al. (2007). It is based on the ECCO/MIT GCM and its adjoint. As in the 11-year optimization, the adjoint code to GM and KPP was excluded from the adjoint model, but additionally higher viscosity and diffusivity were used in the adjoint. Further details of the optimization procedure are provided by Köhl and Stammer (2007). As in that study, we use results obtained after 23 iterations, which were required to bring the model into agreement with the large-scale data structures, and we also exclude the first decade of estimate from the analysis because of model adjustments during that phase.

To bring the global 1° model into agreement with observations, initial temperature and salinity conditions as well as the time-dependent (10-day averages) surface fluxes of momentum, heat, and freshwater were adjusted by the adjoint method. The data coverage after 1992 is the same data base available during the 11-year estimation. Before 1992 the state is mainly constrained by an extensive data base of subsurface XBT and MBT measurements from the World Ocean Data Base 2001 (WOD01; Conkright et al.,
Some of these XBT data is known to have systematic errors in the drop rate equation. Although a drop rate correction is applied to the WOD01 data, an uncertainty about this bias remains. Additionally, tide gauge data were assimilated which contain an eustatic component of the sea level rise not simulated by our model. However, the weights associated with the tide data were very small and the misfit to the tide gauge data was not reduced during the optimization. More details about the data constraints and the weights are provided by Köhl et al. (2006).

While analyzing the SSH trends from the the ECCO/MIT model which is based on the Boussinesq approximation, one has to keep in mind that the model conserves volume (not mass) and that the globally averaged SSH is therefore not permitted to change with time. However, estimations of the thermosteric and halosteric components of SSH trends are not affected. According to Greatbatch (1994), with the knowledge of the surface freshwater flux, a global correction can be calculated from the steric and the eustatic (the volume flux associated with the freshwater flux) components. However, as will be explained in detail below, we do not use this correction because the imbalances in our globally averaged net surface freshwater fluxes appear to be unrealistically large.

3 SSH Trend 1962 – 2001

In this section we will show estimates of SSH changes on decadal and longer time scales. We will divide this discussion into an estimate of SSH changes over the 40-year period 1962 - 2001 followed by a separate discussion of results representing the decade 1992 - 2001 which is described in Section 5. The first decade is excluded from the analysis as described in the previous section. The trends calculated over the period 1962 - 2001 are shown in Fig. 1. They were calculated here and subsequently by fitting a least-squares line into the time series of monthly mean values including the seasonal cycle at each grid point. The estimation of the trends before 1992 relies, in contrast to the period after 1992 where altimeter data provide an excellent constraint, mainly on SST and upper ocean thermal data (XBTs and MBTs). It is therefore reassuring that the spatial patterns are similar to those estimated by Church et al. (2004) from tide gauge data over the period 1950-2000. Particularly, the east-west asymmetry in the Pacific, together with the positive trend east of Japan and a negative trend at the equator are common patterns. Furthermore, patterns...
of the trend in the Atlantic show comparable gyre structures in both estimates. However, the strong dipole structure in the Indian Ocean estimated by Church et al. (2004), is not reproduced; the GECCO estimate shows, in contrast, a structure in the Southern Ocean that corresponds to the deceleration of the Antarctic Circumpolar Current (ACC) by about 20 Sv over 40 years.

A comparison of the total SSH trend with its steric component (right top panel of the figure) reveals that most of the SSH trends are actually steric in nature and that only a small residual part is associated with mass redistribution (not shown). This is different to a recent estimate by Wenzel and Schröter (2007), who found a large signal of mass displacement mainly from the region near the Drake Passage (more than 10 mm/yr) to most other areas. Globally averaged, the steric trend over the 40 year period amounts to 0.74 mm/yr and was removed from the figure. In the bottom row of the figure, the steric SSH change is further separated into a thermosteric ($\zeta_T$) and a halosteric ($\zeta_S$) part by replacing either the time varying salinity $S$ or temperature $T$ by their time mean values $(\bar{S}, \bar{T})$, according to

$$
\Delta \zeta_T = -\frac{1}{\rho_0} \int_{-H}^{0} \Delta \rho(T, \bar{S}, z) dz, \quad \Delta \zeta_S = -\frac{1}{\rho_0} \int_{-H}^{0} \Delta \rho(T, S, z) dz,
$$

where $\rho_0$ is a reference density and $H$ the water depth. The global mean trends for the thermosteric and halosteric fields are 0.92 mm/yr and -0.18 mm/yr, respectively. The thermosteric expansion is slightly larger in magnitude than the halosteric contribution. However, because both components share many common patterns but with opposite sign, the net steric SSH changes are actually smaller than suggested by each field alone. As will become more obvious below, this close relation between both components indicates that most of the steric changes in the ocean can be explained by a redistribution (advection) of water masses and the opposing patterns result from the fact that, for most of the ocean, high temperatures are associated with high salinities.

For a further analysis of the evolution of steric SSH changes, Fig. 2 shows time series of global as well as regional net steric SSH components for the period 1962 through 2002, which are also split into thermosteric and halosteric contributions. The top panel of the figure reveals a decrease in global thermosteric SSH until about 1975 and an almost steady
increase subsequently, giving rise to an averaged increase in thermosteric SSH over the 40 year period 1962 to 2002 of 0.92 mm/yr. An initially decreasing SSH stands in contrast to other recent estimates and suggests that there might still be some influence of model adjustments present even after the first decade. However, a comparison with the time series of global averaged sea level, which was calculated by Church et al. (2004) from tide gauge records using an optimal interpolation method, reveal a stagnation of the sea level change during the 1960s which is partly compatible with our results except that a notable SSH increase starts about 5 years later in GECCO.

Between 1992 and 2002, the globally averaged rate of steric SSH change increases to 1.84 mm/yr. We note that the enhanced increase in steric sea level during the first 5 years in low latitudes resulting from initial adjustments of the model is mostly compensated by similar but opposite trends south of 15°. We note further that the global halosteric contribution of -0.18 mm/yr results mainly from the Southern Ocean, where a dramatic increase in salt can be found that partly compensates the simultaneous significant warming and associated thermosteric SSH increase there. The thermosteric SSH increase between 60°S and 15°S is 1.95 mm/yr since 1960 in the GECCO solution. Because of the presumably artificial salt effect, the total sea level increase in this latitude band is reduced to 0.95 mm/yr. More and better salt observations would be required in the southern ocean to understand salt changes there. This will not be possible in retrospect. And despite of new unprecedented ARGO measurements there, it will remain difficult to deal with this issue.

The largest discrepancy between our thermosteric estimate and those available from Antonov et al. (2005) and Ishii et al. (2006) lies in the lack of the thermosteric SSH increase during the late 1970s and the early 1980s in the GECCO estimate and the associated heat content increase in the ocean. Although the degree of realism of this feature in the presence of an under-sampled ocean is not entirely clear, this discrepancy is partly due to the decrease in the model’s heat content in low latitudes (±15°latitude) until the mid 70th. An inspection of the GECCO results reveals that the largest contribution to the negative thermosteric trend during the first two decades in the tropics comes from the western half of the basins (especially Pacific and Arabian Sea). Negative heat anomalies are subducted in the eastern part of the basins (close to the coastal areas) and are carried
with the mean circulation of the subtropical gyres westward while the signal deepens from an initial 50 m to 150 m (not shown).

4 Global Heat Content Changes

For a further analysis of the models heat content, we show in Fig. 3 a time series of the global heat content change computed over the top 700 m, and from top to 3000 m. Changes below 3000 m are negligible. A temporal mean was removed from each curve. Also shown are respective estimates inferred from Levitus et al. (2005b) over the top 3000 m and Willis et al. (2004) over the top 750 m. It is clear from the figure that the heat content trend toward lower values until the mid 1970s results from the top 700 m of the model and that a significant increase in heat content can be observed after 1975. Over the last 30 years the heat content increases by about 35x10^{22} J, of which 25x10^{22} J result from the top 700 m, and 10 x 10^{22} J from the depth range 700-3000 m. These numbers are about twice as large as previous estimates reported by Levitus et al. (2005a) and Ishii et al. (2006). Levitus et al. (2005a) reported an increase in global heat content by 14.5x10^{22} J from 1955-1998 for the upper 3000 m which corresponds to a rate of about 0.33x10^{22} J/yr. The heat content change estimated by Ishii et al. (2006) over the top 700 m for the period 1955-2003, is 0.19x10^{22} J/yr. However, our global increase in heat content in the top 750 m over the last decade at 1.5x10^{22} J/yr is very similar to the corresponding estimate of Willis et al. (2004) (shown as blue line). One has to note also for Levitus et al. (2005a) and Ishii et al. (2006) that most of the trend takes place after 1990 but the estimated trend still remains smaller than our value or that of Willis et al. (2004). While before 1990 the heat content increase mainly takes place in the upper 700 m, after 1990 the increase in the depth range 700-3000 m becomes increasingly important. After a slight decrease until the mid 1970s, the heat content change increased until the mid 1980s followed by a primarily linear increase afterwards. The interdecadal variability of the GECCO heat content estimate is somewhat different from Levitus et al. (2005a) who reported an interim maximum due to an accelerated increase in heat content during the 1970s, followed by a decrease in the beginning of the 1980s.

Changes of the globally averaged surface heat flux shown in Fig. 4 are consistent Fig. 4
with the general warming trends. Since the mid 1970s the global net surface heat flux increased, reaching values around $1.5 \pm 0.7 \text{ W/m}^2$ during the 1990s. NCEP values, in comparison, range from $-6 \text{ W/m}^2$ at the beginning of the 1960s to $+6 \text{ W/m}^2$ in the mid 1980s. For the time period 1993 to 2003, Willis et al. (2004) report a heating rate of $0.86 \pm 0.12 \text{ W/m}^2$ which is only 60% of our value. However, given that nearly half of the heat content increase in our estimate results from changes below 700 m and that the increase in the upper 700 m match the value of Willis et al. (2004), the estimate of the heating rate by Willis et al. (2004) is likely to be too low.

Estimates of the global mean freshwater flux through the surface are equivalent to estimating freshwater changes in the model and thus to estimating the eustatic contribution to the global sea level rise. Our estimate reduces the larger bias in the NCEP net surface freshwater flux of $2.6 \pm 1.0 \text{ cm/yr}$ into the ocean to a negative value of $-1.0 \pm 1.3 \text{ cm/yr}$ out of the ocean over the 40 year period 1962 to 2002 and to $-0.75 \pm 1.7 \text{ cm/yr}$ for the 1990s. The associated error bars represent the standard deviation from the interannual variability. Apart from the wrong sign, the values are an order of magnitude larger than recent estimates provided by Antonov et al. (2002) or Ishii et al. (2006), ranging between 1.3 and 1.44 mm/yr into the ocean. The associated error bars indicate that the lack of available salinity data together with the low sensitivity of salinity to the global mean freshwater flux precludes an easy estimation of the eustatic contribution to global sea level. The problem had already become apparent in the shorter run by Köhl et al. (2007) and is discussed in some detail by Wunsch et al. (2007). Because of the large freshwater flux bias in the GECCO result, applying the Greatbatch (1994) corrections is not useful to estimate the global SSH change and only the thermosteric part could be estimated. On the other hand, Wunsch et al. (2007) were able to provide a much smaller net surface freshwater flux of $1.1 \pm 0.04 \text{ mm/yr}$ with unprecedented small error bars, despite their suspicion that large errors will be associated with estimates of fresh water changes from salinity measurements. The difference to our results can be explained by additional global balance constraints on freshwater and enthalpy that they imposed in their optimization. It is therefore likely that these constraints primarily determine the size of their global trend estimates and that the available salinity data is not enough to constrain the freshwater fluxes.
5 SSH Trends 1992 — 2002

The period after 1990 is marked by an unprecedented sampling of ocean sea surface and hydrography, especially through Repeat Hydrography and the ARGO network and through the advent of high-precision satellite altimetry. The impact of altimetry is especially large because of its ability to provide accurate observations of global sea level patterns and trends. An example is provided in the top panel of Fig. 5 showing an estimate of the trend in SSH estimated for the period 1992 through 2001. Moreover, because altimetric height is highly correlated with heat content and steric height (White and Tai, 1995; Stammer, 1997; Gilson et al., 1998; Willis et al., 2003, 2004), this fact can be exploited, both to assess the sampling error of the sparse in situ networks and to correct it (Willis et al., 2003). A comparison of GECCO results from this period with otherwise available information about sea level changes will therefore be a test of the GECCO results.

Fig. 5b shows the model adjustment in sea surface height as it results from the 50-year run, but estimated now only over the last 10 years, 1992 - 2001. Amplitude and pattern of the estimated trend closely match the changes observed by TOPEX/POSEIDON data during the same period (top panel). The largest changes are of the order of more than ± 2 cm per year which can be found in the Pacific, the Labrador Sea, the Malvinas, and over the Pacific sector of the ACC. Positive SSH changes are in the western and negative changes in the eastern Pacific. For the Indian Ocean, the opposite can be seen. In comparison to the previous 11-year ECCO optimization (bottom panel) described by Köhl et al. (2007), the estimate resulting from the 50-year run clearly is superior in simulating the observed SSH trend during the last decade. As an example, the southern Pacific in the GECCO run shows roughly the observed increase that is mostly absent from the shorter run. Likewise the Southern Ocean and the subpolar North Atlantic show much more realism in the SSH trend in the GECCO run, which is less obvious from the shorter ECCO run. Both examples demonstrate of the significant impact of the model initial adjustments on estimates of decadal changes that negatively impact the shorter ECCO runs, underpinning the need for long estimation runs. On the same note, Wunsch et al. (2007) provide estimates of SSH changes based on their 13-year long ECCO-GODAE results. Mostly similar in set-up to the ECCO run from Köhl et al. (2007), the
ECCO-GODAE result also shows similar patterns of SSH change.

A comparison of Fig. 1a and 5b reveals that the SSH trend during the 4 decades 1962-2002 is in general only about one third of the trend of the decade 1992-2002 and that for most regions both estimates reverse sign. As before, the steric component explains most of the SSH trend. But in contrast to the first estimate, the contribution of the thermosteric component is now significantly larger than the halosteric component, which results in a total steric component that is dominated by the thermosteric part (Fig. 6). Only a few exceptions can be seen in the subpolar North Atlantic and in the Agulhas Retroflection, as well as in the Malvinas Retroflection. This suggest a slightly different mechanism for SSH changes to take place during the 1990s. The global pattern of thermosteric sea level change, 1992-2001, from GECCO can be compared with similar results in terms of heat content available from Willis et al. (2004)[their Fig. 4].

Time series of thermosteric SSH changes during the last 10 years of the GECCO run, shown in Fig. 7 for the same latitude bands as shown for the 50-year time series (Fig. 2), can be compared with similar results provided by Willis et al. (2004) and Lyman et al. (2006). Estimates of global thermosteric height were obtained by Willis et al. (2004) using in situ data alone and in combination with altimetric height. For the former, temperature was objectively mapped as anomalies from the 1993-2003 mean. For the latter, the altimetric height correlation with subsurface temperature was used to form a first guess of the thermosteric height variability, and then anomalies from this first guess were objectively mapped using the subsurface data. Using the same technique, Lyman et al. (2006) later extended the time-series through 2005. In the total domain (60°S-60°N), the larger increase of the total sea level observed by altimeter can be attributed to the eustatic component whereas in the subdomains, also indicated in Fig. 6, a halosteric trends may become relevant.

The thermosteric component from GECCO shows generally good agreement with the estimate of Willis et al. (2004) and Lyman et al. (2006), although in the equatorial region it shows a considerably larger trend during 1993-1995. Our estimate of the trend of the thermosteric part of 1.84 mm/yr over the last decade is (as it was true for the trend of the heat content) slightly larger than their estimates. During the time period 1993-2003, Willis et al. (2004) and Lyman et al. (2006) found that thermosteric (0-750 m) sea level
increased by $1.6 \pm 0.3$ mm/yr while Wenzel and Schröter (2007) found from their coarse resolution state estimation a larger value of 2.5 mm/yr steric change. The thermosteric rise was much larger than in the previous 40 years, though a comparable rate was observed in the 1970s (Antonov et al., 2005).

6 Causes for Regional SSH Trends

Generally, several processes can cause changes in regional SSH, including responses to local wind stress and buoyancy forcing as well as remote forcing communicated via Rossby wave signals. Focusing on the South Pacific, Roemmich et al. (2007) suggested that an increase in the circulation of the South Pacific subtropical gyre led to a sea surface height increase of up to 12 cm between 1993 and 2004 due to increased wind stress curl associated with an increase in the atmosphere’s Southern Hemisphere annular mode (SAM). The pattern of change in atmospheric sea level pressure is co-located with the change in dynamic height and anomalous Ekman downwelling associated with SAM causes a gyre spin up (Hall and Visbeck, 2002). On the other hand a 5-year lag between SAM and the response in SSH was explained by a baroclinic response of the circulation that propagates as described by Qiu and Chen (2005) in the form of baroclinic waves created further east of the main SSH increase. From altimeter data, the authors hypothesize that a similar mechanism is responsible for SSH changes in most or all ocean basins, i.e., that mid-latitude gyres in all of the oceans have been affected by variability in the atmospheric annular modes on decadal time scales. In the following we will test this hypothesis based on GECCO results.

The oceanic response to wind stress forcing is in the form of Rossby waves and a time-dependent Sverdrup circulation is established within the time it takes for long Rossby waves to propagate across the basin. For large horizontal scales, a quasi-stationary solution of the linear barotropic vorticity equation to time-varying wind stress curl is established within a few weeks (Willebrand et al., 1980). However, baroclinic waves, forced by the anomalous Ekman pumping, and their associated SSH signal may take many years to cross the basin (Chelton et al., 1998). These transient phenomena are important to establish the vertical structure of the circulation. For a barotropic circulation, the relation
\[ \psi = i(gH/f)\zeta, \] with \( H \) the water depth, describes the relation between sea level and the streamfunction. The vertical structure of the circulation increases the SSH response to 1-2 cm SSH change for 1 Sv circulation change.

For long-term SSH trends, at least in lower latitudes \((40^\circ S-40^\circ N)\), the signal carried by baroclinic waves is expected to cross the basin in less than a decade and the trend of the barotropic streamfunction as shown in Fig. 8 from the GECCO result should explain most of the SSH trend. A comparison of Fig. 8 with Fig. 1 and 5 reveals a clear correspondence of the resulting streamfunction trend pattern with those found in SSH, notably during the period 1962-2001 (note the sign change for the streamfunction when crossing the equator).

Consistent with the slow propagation speed of baroclinic waves, only about 43% of the SSH variability can be explained by the barotropic streamfunction on interannual time scales. However, the explained variance increases to 72% on interdecadal time scales, when the assumption, that the trend of the SSH response is already equilibrated by baroclinic waves, is more appropriate.

To confirm that the changes in the barotropic streamfunction are driven by changes in the wind field according to the barotropic vorticity equation, we show in the lower part of Fig. 8 the trend in the pure Sverdrup circulation as it results from the GECCO wind stress fields over the same periods. For that purpose the Sverdrup transport streamfunction was evaluated from monthly mean GECCO wind stress fields according to

\[
\Psi_{Sw}(x, y, t) = \frac{1}{\beta \rho_0} \int_x^{x_{east}} \nabla \times \tau(x, y, t) \tag{2}
\]

with \( \beta = \partial f / \partial y \), \( \rho_0 \) a reference density, and \( \tau \) the wind stress. Trends in the Sverdrup transport streamfunction were calculated subsequently from the monthly mean fields. Patterns of the trends of the Sverdrup transports correspond reasonably well with the trend of the streamfunction, especially in the eastern parts of mid-latitudes gyres, in agreement with the analysis of ECCO fields in the eastern North Pacific by Douglass et al. (2006). Note that the Sverdrup theory becomes invalid near the western boundary currents and in the tropics. The large positive trend in the Labrador Sea is also not captured by the Sverdrup transports. In general the trends of the Sverdrup transports overestimate the streamfunction trend since bottom topography and stratification is not considered.
To further quantify the amount in SSH changes that are due to wind stress changes as opposed to other mechanism (e.g., local surface heat fluxes), we performed two additional experiments. In the first experiment the buoyancy (heat and freshwater) fluxes were replaced by climatological fluxes calculated from the monthly mean GECCO fields. Ideally this experiment would already identify the impact of the changing wind stress. However, longterm changes due to adjustments to the initial conditions as well as the necessary inclusion of a weak relaxation to surface temperature and salinity still effect the SSH changes. The influence of the latter two processes was therefore estimated by a second experiment in which all fluxes including in the wind stress were climatological. The difference between these two experiments is then finally used as an estimate of effect of the changing wind stress on sea level trend. For this decomposition, linearity of the associated processes is assumed. The remaining residuals from a comparison of the sum of the trends with the total trend indicate some nonlinearity of the system which also might lead to the imperfect removal of the trend associated with the model drift.

The zonal average of the associated trend in sea level is shown in Fig. 9 together with the zonal average of the total sea level trend. Shown are results for the two periods 1962 - 2001 and 1992 - 2001, respectively. As can be expected from the previous results, the wind stress explains most of the SSH trend over the period 1962 - 2001. A larger discrepancy exists only south of 50°S in the ACC due to longterm model adjustments there. Considering the period 1992 - 2001, the same mechanism holds for the southern hemisphere. However, a larger fraction of the SSH trends in the northern hemisphere can not be explained by wind stress changes alone.

A complementary experiment, driven now by climatological wind stress but time-dependent buoyancy forcing was performed. Ideally the SSH trend calculated from this experiment represents the part of the trend that is buoyancy driven and explains the difference between the wind driven and the total trend. Unfortunately, the trend of this experiment contains an unknown component due to model drift. A separation from the unforced model drift by calculating the difference to a run with only climatological forcing is not possible, since any bias in the climatological buoyancy forcing will also explain a part of the buoyancy driven trend and the climatological run still contains a certain amount of time-dependent buoyancy forcing due to the relaxation term. However, the buoyancy
and wind driven components add reasonably well to explain the total SSH drift, although differences remain.

Over the period 1962-2001, the SSH trend in the Southern Ocean is mainly explained by buoyancy forces but reduced by wind driven trends. This wind driven trend intensifies over time and is able to compensate most of the buoyancy forced component during the last decade. However, during this last decade, buoyancy forces become generally more important and, especially in the subtropical regions of the northern hemisphere, explain a large fraction of the trend. We conclude, that over the period 1962-2001 most of the estimated SSH changes are caused by changes in the wind stress and the associated barotropic streamfunction. However, this does not hold for the last decade, where surface heat and freshwater fluxes contribute significantly to sea level trends, especially in the northern hemisphere and the ACC region.

7 Concluding Remarks

Because global and regional increase in sea level are quantities of specific societal relevance and of large interest (Cabanes et al., 2001; Munk, 2002; Miller and Douglas, 2004), there is the expectation that ocean syntheses will contribute to this discussion in a quantitative manner. In this context one has to recall, however, that essentially all ocean models to date are Boussinesq models and therefore conserve volume globally rather than mass. Greatbatch (1994) suggested that one can correct the change in mass given that the total freshwater flux into the ocean is known. Unfortunately the estimation of the global mean freshwater flux from sparse salinity data is not well conditioned in our approach and an unrealistically large bias of -1.0 cm/yr is estimated over the last 40 years. Therefore only thermosteric contribution to the global sea level rise could be determined, which amounts to 0.92 mm/yr between 1962 and 2001 and 1.84 mm/yr for the period 1992 and 2001. The optimized averaged heat flux into the model is close to zero until 1980 and increased to $1.5\pm0.7$ W/m$^2$ for the period after 1992. Unfortunately not much is known over the global water cycle to date and a challenge for ocean synthesis efforts over the next years will lie in an attempt to improve our understanding of sea level in the presence of insufficient salinity sampling over the last 40 years and simultaneous serious uncertainties in river runoff and ice melt rates. Explanations of SSH changes from the ocean synthesis therefore primarily
focus on thermal expansion and regional changes before improved estimates of the global water cycle and mass changes can be taken into account.

GECCO results have shown that estimates of large scale integral quantities are sensitive to initial model adjustments and that, accordingly, results obtained from the 50-year estimate are improved over those obtained from the 11-year estimation run. In terms of SSH changes, the results of the long run are found to be in better agreement with the data than the previous 11-year run but differences are not large. This indicates to some extent the need for dynamically consistent ocean synthesis efforts covering several decades in duration in support of climate research, including estimates of sea level change.

Heating trends are observable in the southern hemisphere from the beginning of the estimation in the mid 1950s but are visible in the northern hemisphere only since the beginning of the 1980s. The tropics show a cooling until mid the 1970s and a warming thereafter. Only after 1980 is a dominance of linear trends observable.

Analysis of regional patterns of heat and salt contribution to SSH change revealed that, in general, halosteric and thermosteric changes oppose each other. Advective processes are therefore suggested to explain the observed regional trends. In agreement with Roemmich et al. (2007), increased wind stress curl is found to be responsible for the increase in gyre circulation that explains the rising sea level observed in almost all subtropical gyres. For the last decade, especially in the northern hemisphere, local surface heat flux becomes more important and may explain up to 50% of the trend.

As an example, Lombard et al. (2005), based on an EOF analysis, suggest that much of the observed interannual-to-decadal variability in sea level is caused by changes in heat content which can be attributed to climate phenomena such as El Nino/Southern Oscillation, the Pacific Decadal Oscillation, or the North Atlantic Oscillation. We confirm here that for regional changes during the 1990s most of the estimated changes in SSH are related to changes in heat content. However, this does not seem to hold during the last 40 years. Since most of the regional sea level trends are related to wind driven changes of the circulation, salt effects need to be considered as well: GECCO results suggest that during the last 40 years the salt effect on regional sea level changes might be almost equally large as that resulting from heat content changes. We note here that the problem of estimating the eustatic component (the global freshwater imbalance) from salinity does
not significantly affect the estimation of regional sea level changes since only the halosteric contribution of the freshwater flux, which is a factor of 35 smaller, may cause regional changes. The volume effect is equilibrated by barotropic waves on time scales of a few days.

The great advantage of our approach to bring an ocean circulation model into consistency with most of the observations, collected since the beginning of the 1950s, is that no ad hoc method is needed to treat data-void regions since the information is carried by the dynamics of the model. On the other hand, since the method is not designed to correct for deficiencies of this model, the GECCO estimate is limited by the realism of this numerical model which is, due to the cost of the method, of much coarser resolution than current simulation efforts. We also note that no estimation is provided. This error would most likely be dominated by an unknown model bias which in fact could be estimated by a multi model approach but only if the set of models would not all share the same problems. Altogether, our estimate is not intended to provide a final answer to the problem of sea level change but a complementary view to data based studies.

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