Long-term sea-level change revisited: the role of salinity

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Abstract
Of the many processes contributing to long-term sea-level change, little attention has been paid to the large-scale contributions of salinity-driven halosteric changes. We evaluate observed and simulated estimates of long-term (1950-present) halosteric patterns and compare these to corresponding thermosteric changes. Spatially coherent halosteric patterns are visible in the historical record, and are consistent with estimates of long-term water cycle amplification. Our results suggest that long-term basin-scale halosteric changes in the Pacific and Atlantic are substantially larger than previously assumed, with observed estimates and coupled climate models suggesting magnitudes of ~25% of the corresponding thermosteric changes. In both observations and simulations, Pacific basin-scale freshening leads to a density reduction that augments coincident thermosteric expansion, whereas in the Atlantic halosteric changes partially compensate strong thermosteric expansion via a basin-scale enhanced salinity density increase. Although regional differences are apparent, at basin-scales consistency is found between the observed and simulated partitioning of halosteric and thermosteric changes, and suggests that models are simulating the processes driving observed long-term basin-scale steric changes. Further analysis demonstrates that the observed halosteric changes and their basin partitioning are consistent with CMIP5 simulations that include anthropogenic CO2 forcings (Historical), but are found to be inconsistent with simulations that exclude anthropogenic forcings (HistoricalNat).

Keywords: oceanography, sea level, salinity, climate model, CMIP5, global change, water cycle

1. Introduction

Changes to global mean sea-level (GMSL) are a well-documented response to a changing climate (Church et al 2013a), and many processes associated with sea-level (SL) changes are active areas of research (e.g. Alley et al 2005, Velicogna 2009, Stammer 2010, Rignot et al 2011, Bouttes et al 2012, 2013, Griffies and Greatbatch 2012, Lorbacher et al 2012, Brunnabend et al 2012, Shepherd et al 2012, Wada et al 2012, Bouttes and Gregory 2014, Griffies et al 2014). These changes can be summarized into two primary mechanisms: mass addition from land-based glaciers and ice-sheets which act to increase the liquid mass content of the global oceans; and, in situ density changes either thermosteric, primarily driven by thermal expansion (contraction) as ocean waters warm (cool), or halosteric, driven by regional salinity changes, where a salinity reduction leads to expansion and enhanced salinity to a contraction. While thermosteric changes have received considerable attention, salinity-driven halosteric patterns of long-term SL change have not been thoroughly investigated. Regional halosteric anomalies are considered to be important drivers of steric SL variability on short timescales (Pattullo et al 1955, Tabata et al 1986, Maes 1998, Sato et al 2000, Wunsch et al 2007, Suzuki and Ishii 2011). However, these changes have been largely
ignored in long-term (>30 yr) observed estimates of SL change because halosteric fluctuations (excluding comparatively small mass contributions associated with land–ice changes e.g. Antonov et al 2002, Munk 2003, Ishii et al 2006) sum to near zero in the global mean (e.g. Gregory and Lowe 2000), and additionally due to the paucity of historical salinity measurements (e.g. Boyer et al 2013, Durack et al 2013). Consequently previous GMSL change estimates have primarily considered thermosteric effects along with mass contributions (Church et al 2013a).

Estimates of halosteric and thermosteric changes are respectively derived from in situ observations of salinity and temperature. Previous studies have reported long-term change estimates for ocean salinity (Antonov et al 2002, Boyer et al 2005, Ishii et al 2006, Hosoda et al 2009, Durack and Wijffels 2010, Helm et al 2010, Durack et al 2012, 2013, Skliris et al 2014) and temperature (Levitus et al 2000, 2005a, Antonov et al 2005, Ishii et al 2006, Smith and Murphy 2007, Domingues et al 2008, Ishii and Kimoto 2009, Gleckler et al 2012, Levitus et al 2012, Durack et al 2014). There is a general agreement in the broad-scale patterns and magnitudes of salinity and temperature changes among these independent studies. Formal climate change detection and attribution studies (Barnett et al 2005, Pierce et al 2006, 2012, Pardaens et al 2008, Gleckler et al 2012) have attributed ocean temperature changes to anthropogenic CO2 forcing. Two recent studies have investigated observed ocean salinity changes, and have successfully attributed anthropogenic influence as the cause of these salinity changes globally (60°S–60°N; Pierce et al 2012) and for the tropical Pacific and Atlantic Oceans (Terray et al 2012).

Fewer studies have focused on derived steric changes than on the underlying changes to the salinity and temperature fields. Several observational (e.g. Pattullo et al 1955, Tabata et al 1986, Maes 1998, Sato et al 2000, Antonov et al 2002, Levitus et al 2005b, Ishii et al 2006, Suzuki and Ishii 2011) and ocean reanalysis (e.g. Carton et al 2005, Wunsch et al 2007, Köhl and Stammer 2008, Köhl 2014) studies have highlighted the importance of salinity to regionally observed SL. Others have considered the global patterns of projected 21st century SL changes from climate models (Landerer et al 2007, Yin et al 2010, Pardaens et al 2011, Yin 2012, Bouttes and Gregory 2014).

In the present study we extend upon these previous analyses to contrast the relative importance of basin-scale halosteric and thermosteric changes in two independent observational datasets over the period 1950–2008, and use these estimates to evaluate the historically forced simulations available from CMIP5 (Taylor et al 2012). We show that halosteric patterns can be very important at basin-scales even though they do not contribute to GMSL change.

The paper is organized as follows: in section 2 we describe the observations, model simulations and methods used in this study, in section 3 we compare multi-decadal observed and simulated halosteric and thermosteric trends at basin- to regional-scales. In section 4 we conclude by discussing the implications of this work, touch on the limitations of the present study and outline further work required to better understand large-scale observed and simulated SL changes.

2. Data and methods

To evaluate the long-term halosteric and thermosteric SL changes from CMIP5 Historical simulations (Taylor et al 2012), we consider data from two independent observational analyses (Ishii and Kimoto 2009, Durack and Wijffels 2010—hereafter Ish09 and DW10 respectively).

The Ish09 analysis exploits the full salinity and thermal archive and employs a bias correction scheme in order to utilize problematic expendable BathyThermograph (XBT) and Mechanical BathyThermograph (MBT) profiles, that contain well-documented depth and thermosteric biases (Gourietski and Koltermann 2007, Wijffels et al 2008, Abraham et al 2013, Cowley et al 2013). This analysis uses an objective mapping technique to generate monthly mean globally gridded salinity and temperature maps for the period 1945–2012. We note that long-term temperature trends (and the corresponding thermosteric patterns) from the Ish09 analysis compare well with other objectively analysed products (e.g. Levitus et al 2012, Good et al 2014).

The DW10 analysis is based on the full salinity archive that is comprised of high-quality Niskin and Nansen (bottle) casts and CTD (conductivity–temperature–depth) profiles of salinity and temperature. As a consequence, while exploiting considerably less data than corresponding temperature-only analyses (CTD/bottle profiles comprise ~30% of the global ocean temperature archive), the results are free from XBT and MBT biases. We note however, that this analysis compares well to other globally integrated estimates of ocean heat content (OHC) change that use the full temperature archive (Durack et al 2014). The analysis uses a spatial and temporal parametric model, optimized to recover the broad-scale ocean mean structure, the annual and semi-annual cycle (and their spatial gradients) and the multidecadal linear trends from the sparse hydrographic (salinity and temperature) database over 1950–2008. Importantly, this analysis uses the Argo data and exploits the unprecedented spatial and seasonal coverage to best reduce seasonal and spatial sampling bias. In the sparsely observed Southern Hemisphere oceans, the analysis relies on Argo’s ability to highly resolve the mean, seasonal and El-Nino Southern Oscillation responses in salinity and temperature, and thus reduces aliasing due to these dominating modes of variability.

The CMIP5 models assessed in this study are a subset of the full suite, as drift correction in the deeper ocean was necessary. Consequently, 26 independent models (rather than 42 in a previous study: Durack et al 2014) were assessed and specific details on the model simulations used in this analysis are contained in table 1.

In order to directly compare the observational trends with those of the CMIP5 models it was necessary to account for model drift (Covey et al 2006, Sen Gupta et al 2012, 2013). To account for drift, a linear least-squares fit to a contemporaneous 150 yr portion of the piControl simulation
(1900–2049) was obtained at each grid point in three dimensions, and this drift estimate was then subtracted grid point by grid point from the corresponding forced simulation trend estimate before calculation of steric anomalies was undertaken.

From each observational dataset, 59 yr mean climatologies (1950–2008) were constructed along with least-squares linear trends. For models, 55 yr mean climatologies (1950–2004) were constructed along with least-squares linear trends. These fields were calculated on the original grid of the available observational products and models, from annual means derived from monthly mean data for Ishi09 and models that contributed to CMIP5. We note the temporal discrepancy between observed and simulated analyses which is a result of the limitation of CMIP5 Historical simulations which end in 2005 and the DW10 study which is dependent on the modern Argo period (2004–2008) to estimate the mean climatology and seasonal cycle. We investigated this temporal discrepancy using the Ishi09 data, and found that the 1950–2008 and 1950–2004 trend maps are very similar. Consequently the observation-model temporal discrepancy does not have much influence on the key conclusions of the study.

Estimates of total steric, thermosteric and halosteric specific volume anomalies (svan) were then calculated from all data using the UNESCO equation of state (Millero et al 1980, Millero and Poisson 1981):

\[
    \text{svan}_{\text{total}} = \alpha (S_{\text{exp}}, T_{\text{exp}}, P) - \alpha (\bar{S}, \bar{T}, \bar{P}),
\]

\[
    \text{svan}_{\text{thermosteric}} = \alpha (\bar{S}, T_{\text{exp}}, P) - \alpha (\bar{S}, \bar{T}, \bar{P}),
\]

\[
    \text{svan}_{\text{halosteric}} = \text{svan}_{\text{total}} - \text{svan}_{\text{thermosteric}},
\]

where \( \alpha \) denotes specific volume, \( S \) denotes Practical Salinity, \( T \) denotes in situ temperature and \( P \) pressure (dbar). In (1) and (2) overbars represent the climatological mean and subscript \( \text{exp} \) indicates the climatological values plus trend anomalies obtained from the observations and models. For comparison between observed and modelled estimates, we present all changes in units of mm yr\(^{-1}\). A key advantage of this method is that the nonlinearities in the equation of state are explicitly resolved, rather than calculating halosteric and thermosteric changes independently by using the coincident climatological values and perturbing salinity or temperature individually. However, we note that this methodology provides very similar results to halosteric quantities calculated using a perturbed salinity equivalent to (2), and our conclusions are insensitive to the method of analysis.

To enable observation and model intercomparison, and the calculation of a multi-model mean (MMM), all fields were regridded to a 2° longitude by 1° latitude grid extending from 70°S to 70°N which excludes marginal seas (Mediterranean

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Table 1. Observational and CMIP5 model datasets (model numbers denote realization \( X \) and model physics version \( Y \): rXi1pY).

| Model/Observation | 1950–2004 Historical (obs. version) | 1950–2004 HistoricalNat | Hist. drift correction |
|-------------------|------------------------------------|-------------------------|------------------------|
| Ishii and Kimoto (2009)—1950–2008 | 6.13 | — | — |
| Durack and Wijffels (2010)—1950–2008 | 1.0 | — | — |
| ACCESS1-0 | 1 | — | 1 |
| ACCESS1-3 | 1-2 | — | 1 |
| CCSM4 | 1-4,6 | 1-2,4,6 | 1 |
| CESM1-BGC | 1 | — | 1 |
| CMCC-CESSM | 1 | — | 1 |
| CMCC-CMS | 1 | — | 1 |
| CNRM-CM5 | 1-10 | 1-5,8 | 1 |
| CSIRO-Mk3.6.0 | 1-10 | 1-5 | 1 |
| CanESM2 | 1-5 | 1-5 | 1 |
| EC-EARTH | 2-3,5-7,9-10,12,14 | — | 1 |
| FGOALS-s2 | 1-3 | — | 1 |
| GFDL-CM3 | 1-5 | — | 1 |
| GISS-E2-H | 1-5 (\( p = 1-3 \)) | 1-5 (\( p = 1,3 \)) | 1 (\( p = 1-3 \)) |
| GISS-E2-H-CC | 1 | — | 1 |
| GISS-E2-R | 1-6 (\( p = 1,3 \)) | 1-5 (\( p = 1,3 \)) | 1 |
| GISS-E2-R-CC | 1 | — | 1 |
| HadGEM2-CC | 1-3 | — | 1 |
| HadGEM2-ES | 1-4 | 1-4 | 1 |
| IPSL-CM5A-LR | 1-6 | 1-3 | 1 |
| IPSL-CM5A-MR | 1-3 | 1-3 | 1 |
| IPSL-CM5B-LR | 1 | — | 1 |
| MPI-ESM-LR | 1-3 | — | 1 |
| MPI-ESM-P | 1 | — | 1 |
| NorESM1-M | 1-3 | 1 | 1 |
| NorESM1-ME | 1 | — | 1 |
| bcc-csm1-1 | 2 | — | 1 |
Sea, Baltic Sea, Red Sea, Persian Gulf, China Seas, Sea of Japan, Java Sea, Banda Sea and Arafura Sea) and vertically interpolated to 18 standard pressure levels (5, 10, 20, 30, 40, 50, 75, 100, 125, 150, 200, 300, 500, 700, 1000, 1500, 2000 dbar). To fairly compare both observations and models that have differing land/sea masks, after horizontal interpolation an iterative nearest neighbour filling algorithm was employed to infill regions so that the land/sea masks of all analyses were identical.

3. Results

3.1. Steric changes: global perspective

Warming-driven thermosteric expansion (figure 1 (A2) versus (B2)) is fairly homogenous throughout and between individual basins in the global ocean. There is agreement in the sign of observed estimates nearly everywhere, particularly in the well-sampled Northern Hemisphere, where a relatively larger thermosteric expansion is apparent in the Atlantic and in the Western subtropical North Pacific. In the Southern Hemisphere we find agreement along the axis of the Antarctic Circumpolar current. These features are also captured in the CMIP5 MMM (figure 1 (C2)), however as expected the MMM result is smoother, with magnitudes smaller than the observations as a result of averaging across simulations with uncorrelated variability. The thermosteric contraction (cooling) in the Western subpolar North Pacific and around Australia, though present in the two observational estimates, is largely absent in the MMM. There is less agreement between observations in the Southern Hemisphere with larger magnitude changes apparent in DW10 and the MMM (figure 1 (B2) and (C2)) compared to a muted result in Ish09 (figure 1 (A2)). We note that discrepancies between the observations in the Southern Hemisphere are likely due to poor spatio-temporal observational coverage and conservative infilling methods which yield conservative change estimates in Ish09 (e.g. Gille 2002, 2008, Gregory et al 2004, Goertzki and Koltermann 2007, Durack et al 2014). Discrepancies between the observed and simulated estimates, particularly in the North Pacific, may be in part associated with the unresolved long-term mode of natural variability in observations (e.g. Pacific Decadal Oscillation; Mantua et al 1997) as agreement exists in the observations however is absent in the MMM.

In both observational estimates large-scale halosteric contraction (increased salinity) is evident across most of the Atlantic and Western Indian Oceans, in contrast to expansion (decreased salinity) in the Pacific (figure 1 (A3) versus (B3)). This basin contrast between halosteric contraction and expansion is also apparent in the MMM (figure 1 (C3)), but inter-model agreement greater than 50% is only found in the equatorial and South Pacific regions due to uncorrelated variability found across models and independent model simulations (no stippling, figure 1 (C3)). In the Atlantic, observations express a sign reversal to halosteric expansion for latitudes greater than 50°N. This may be linked to coincident enhancements to precipitation and riverine discharges into the Arctic Ocean, as well as cryospheric contributions (Peterson et al 2006, Kwok and Cunningham 2010, Krishfield et al 2012, Straneo and Heimbach 2013) or may also be
explained by ocean dynamical responses to changing surface buoyancy fluxes (e.g. Bouttes et al. 2013), however we do not further investigate potential sources here.

We note that the largest magnitude halosteric and thermosteric changes are often opposite in sign, and therefore lead to a more homogeneous pattern in the resolved total steric changes, a feature particularly prominent in the North Atlantic (figures 1 (A1)–(C1)). This density compensation is not well understood, however mechanisms driving the compensation have been discussed by Mauritzen et al. (2012), Bouttes et al. (2013) and Köhl (2014).

3.2. Regional importance of salinity

As noted earlier, GMSL change estimates have mostly neglected halosteric effects, however a number of more recent thermosteric (OHC) change estimates have utilized coincident sea surface height (SSH; total steric) in order to better estimate the regional distribution of ocean heat uptake and thermosteric SL changes (Domingues et al. 2008) or provide OHC change uncertainty estimates (Lyman and Johnson 2008, 2014). However, as shown (figures 1 (A3)–(C3)) we note that halosteric change magnitudes are large enough in many regions that they play an important role in column-integrated total steric volumes and salinity-driven changes should not be neglected in future SL studies.

To further evaluate the importance of salinity, we present maps that show the contribution of the absolute halosteric change to the sum of absolute thermosteric and absolute halosteric changes. To highlight changes on larger spatial scales and reduce noise associated with the observational estimates, all fields were smoothed before plotting using a 3-point boxcar filter, which is applied to the 2° longitude by 1° latitude grid. These maps show where the halosteric magnitude is less than 30% (orange) or greater than 30% (blue) of the absolute total, with the 30% threshold obtained by comparing basin mean MMM halosteric to their coincident thermosteric values (see observed and simulated basin-scale comparisons in a subsequent section, figure 4). We note that this is an extremely difficult test, as both change sign and magnitude in three dimensions are combined to provide the grid point value. The spatial disagreement between observations (stippling) due to observational sparsity and differing analysis techniques is apparent, however large-scale similarities exist (figure 2). Blue regions are shown in the high latitude North Pacific and Atlantic along with the Western equatorial Pacific and Southern subtropical Pacific and Indian Ocean, and suggest halosteric changes may in some regions be the leading contributor to total steric change (greater than 50% of the absolute total; dark blue). However, we note that even though correspondence exists between the observed estimates, the differences require further investigation to better understand the influence of data sparsity convolved with unresolved modes of variability.

3.3. Regional steric compensation

Previous studies have identified several regional features where counteracting halosteric contraction (increased salinity) and thermosteric expansion (warming) changes occur (e.g. Antonov et al. 2002, Levitus et al. 2005b, Ishii et al. 2006, Lowe and Gregory 2006, Pardaens et al. 2011, Mauritzen et al. 2012, Bouttes et al. 2013, Griffies et al. 2014). As a result the total steric change is more spatially uniform between and across basins (figures 1 (A1)–(C1)). In observations, examples include the thermosteric expansion (warming) that is partially offset by halosteric contraction (enhanced salinity) in the North Atlantic, and thermosteric contraction (cooling) that is largely offset by halosteric expansion (decreased salinity) in...
the equatorial and Southwestern Pacific. A similar compensation occurs in the Eastern Indian Ocean, while in the Northwestern Indian Ocean strong halosteric contraction (enhanced salinity) compensates for a strong thermosteric expansion (warming). Another key region where strong compensation occurs is in the subpolar North Atlantic, which shows a halosteric expansion (decreased salinity) and corresponding thermosteric contraction (cooling) in observations (figure 1). The models exhibit a large spread in the polar and subpolar regions, and the sign of changes in the subpolar North Atlantic is highly variable even between multiple realizations of the same model (not shown). Some of the regions where observed halosteric and thermosteric changes compensate are also present in the MMM, but are much weaker than in the observations and are likely due to averaging across modelled results.

To further investigate the basin-scale consistency in the patterns of thermosteric and halosteric changes, basin zonal means for each observational estimate and the MMM are shown (figure 3). The sign consistency between the observed and modelled estimates is encouraging, with particularly good broad-scale agreement in the Pacific and Atlantic basins. In the Pacific (figure 3(B)), all estimates suggest a freshening-driven halosteric and warming-driven thermosteric expansion is occurring—steric changes that augment. Observations and simulations are also consistent in the Atlantic, however with the opposite signed changes—density compensation through halosteric contraction and thermosteric expansion. For the Southern Hemisphere Pacific and Indian Oceans, both the DW10 and MMM suggest larger halosteric change amplitudes than Ish09, and their corresponding thermosteric changes are approximately equal in both hemispheres. The larger Southern Hemisphere result is not reproduced in Ish09 possibly due to the conservative nature of resolved changes in regions of poor spatial coverage (e.g. Gille 2002, 2008, Gregory et al 2004, Gouretski and Koltermann 2007, Durack et al 2014). In the Atlantic (figure 3(C)), a strong warming-driven thermosteric expansion and a near basin-wide halosteric contraction approximately half the thermosteric magnitude is present in observations, a feature that is matched by the MMM in the North Atlantic. In the subpolar Atlantic, strong halosteric and thermosteric agreement is present between observations, however the MMM shows an equally large halosteric change of the opposite sign. For the Indian (figure 3(D)), the observations and MMM mostly agree in sign of the thermosteric change, with warming across the entire basin. However, due to the presence of marginal seas with strong regional trends (Arabian Sea and Bay of Bengal), there is no agreement in halosteric sign between the observations and MMM North of the equator. In the globally integrated result, reasonably good agreement exists between the observations and MMM of the Northern high latitudes. However, these global zonal mean results mask the strong zonal salinity structure within basins as well as the compensation in the halosteric responses within and between basins (the full-depth, global mean halosteric response should be near zero).

3.4. Observed and simulated basin-scale comparisons

To further examine the ability of the CMIP5 suite to simulate the observed basins-scale steric responses, we contrast the Atlantic and Pacific long-term basin mean halosteric trends
for the observations, CMIP5 MMM and individual model results (figure 4(A)). By considering the large-scale basin means, we further reduce the influence of unforced and uncorrelated variability which is the primary reason for model disagreements in the maps (figures 1 and 2) and zonal mean results (figure 3). The Pacific and Atlantic basin halosteric sign consistency of the MMM with observations (figures 1 (A3), (B3) versus (C3)) is captured in 22 of 26 Historical simulations, with halosteric contraction (increased salinity) in the Atlantic and expansion (decreased salinity) in the Pacific (figure 4(A), grey symbols). In figure 4 we also include CMIP5 HistoricalNat simulations that exclude anthropogenic CO₂ and aerosol forcing (green symbols), and for halosteric changes these results span all four quadrants of the scatterplot. This contrast between the Historical and HistoricalNat results suggests anthropogenic forcing is required to produce the halosteric Pacific/Atlantic basin asymmetry in the Historical simulations, a result that is consistent with the recent positive detection and attribution of observed salinity changes by Pierce et al (2012) and Terray et al (2012).

We also find that there is substantial agreement between observed and simulated basin contrasts in thermosteric changes (figure 4(B)), here with a positive SL contribution in both basins. As with halosteric changes, thermosteric changes in the Historical simulations show better agreement with observations than the HistoricalNat simulations, and are again consistent with previous detection and attribution studies (Barnett et al 2005, Pierce et al 2006, 2012, Pardaens et al 2008, Gleckler et al 2012).

Interestingly, when comparing the magnitude of the halosteric basin-scale changes to their thermosteric counterparts, we find they are not negligible as previously assumed. In the Atlantic the mean halosteric compensation of the thermosteric anomaly for CMIP5 Historical simulations is 24% and may hide local steric expansion. In the Pacific, where the sign of halosteric and thermosteric agree, halosteric changes contribute 25% to the total steric anomaly (figure 4).

4. Discussion

Our examination of the observed long-term halosteric contributions to SL suggests that coherent changes throughout the observed ocean depth have occurred at basin-scales during 1950–2008. By contrasting halosteric and thermosteric changes, our findings highlight that salinity contributions to SL changes are important even at basin-scales.

Unlike temperature, observed and simulated basin-scale salinity changes exhibit a dipole response—a freshening Pacific and a saltier Atlantic (Boyer et al 2005, Hosoda et al 2009, Durack and Wijffels 2010; Helm et al 2010, Durack et al 2012, 2013, Terray et al 2012, Skliris et al 2014)—providing a more clearly defined basin-scale fingerprint of change when compared to the relatively homogenous observed upper-ocean warming pattern (Levitus et al 2012, Rhein et al 2013, Durack et al 2014). There is good agreement between the observed analyses, and halosteric changes show a greater basin-scale heterogeneity—changes of opposing sign in the Pacific and Atlantic basins—which is markedly different to their thermosteric counterparts (figures 1 (A3), (B3) versus (A2), (B2)). The inhomogeneous nature of basin-scale ocean salinity changes and the observed enhancement of spatial gradients and basin contrasts provides an opportunity to evaluate historically forced climate model simulations with ocean salinity observations that are largely independent of temperature.

Comparison of observations with CMIP5 simulations suggests anthropogenic forced changes are driving a coherent pattern of broad-scale halosteric (salinity-driven) changes in the world ocean in agreement with past studies (Pierce et al 2012).
et al 2012, Terray et al 2012). This basin contrast of depth-integrated halosteric changes are consistent with previous work that reported near-surface (and subsurface) ocean salinity pattern amplification and associated water cycle change (Boyer et al 2005, Hosoda et al 2009, Durack and Wijffels 2010, Helm et al 2010, Durack et al 2012, 2013, Pierce et al 2012, Terray et al 2012, Skliris et al 2014), however we note that attribution of the processes driving such changes is complex (e.g. Lowe and Gregory 2006, Bouttes et al 2012, 2013, Bouttes and Gregory 2014) and not yet well understood. Conversely, simulations that exclude anthropogenic forcing (CO2 and aerosols; HistoricalNat) over the period of analysis cannot reproduce the pattern of halosteric and thermosteric changes that are captured in observed estimates.

We note that natural variability associated with climate modes can drive measurable changes to regional patterns of ocean surface freshwater fluxes that can influence GMSL on short timescales (Pardaens et al 2008, Boening et al 2012, Fasullo et al 2013, Cazenave et al 2014). However, the influence of natural variability is likely reduced in long-term (50 yr or longer) observed and modelled change estimates, particularly as we consider the MMM (figures 1–4) which averages across the unforced, uncorrelated variability present in individual model simulations. In addition to changes in the surface freshwater fluxes (evaporation minus precipitation; $E − P$), depth-integrated changes are also influenced by ocean circulation changes that can also be responsible for salinity/freshwater redistribution, or water mass changes attributable to the coincident broad-scale warming (Lowe and Gregory 2006, Durack and Wijffels 2010, Bouttes et al 2012, 2013, Bouttes and Gregory 2014).

The current generation CMIP5 climate models do not interactively simulate land-ice changes, and glacier and ice-sheet changes are primarily calculated using offline models (Church et al 2013b). The inclusion of these processes is an anticipated improvement for future coupled modelling systems that will be contributing to CMIP6 (Meethi et al 2014). Consequently, consideration for such differences must be accounted for during observation-model intercomparison studies and particularly when considering future model projections, as land–ice contributions become a more dominant contributor to GMSL.

Further work is necessary to better understand and quantify the processes responsible for the observed and simulated regional SL changes, and for this idealized ocean-only simulations are a well suited compliment to results from fully-coupled models (Griffies et al 2009, Stammer 2010, Bouttes et al 2012, 2013, Durack et al 2012, Lorbacher et al 2012, Bouttes and Gregory 2014, Danabasoglu et al 2014, Griffies et al 2014). Additional work is also needed to better understand the complex space–time observational coverage and its impact on estimates of spatially complete steric changes (e.g. Gille 2006, Cheng and Zhu 2014a, 2014b, Lyman and Johnson 2014). This is particularly relevant as recent works have highlighted that Southern Hemispheric long-term global OHC and thermosteric change estimates are likely biased low due to the poor spatial coverage of historical observations and current analysis techniques (Gille 2002, 2008, Gregory et al 2004, Gourretski and Koltermann 2007, Durack et al 2014).

Our study confirms that halosteric contributions to steric SL changes are non-negligible on regional to basin-scales. This result has not been acknowledged in previous works as most long-term SL change assessments have been largely focused on GMSL change, thereby explicitly excluding the consideration of halosteric effects. The magnitude of halosteric changes suggests that some care is required when using SSH altimetry to infer regional thermosteric or heat content change (Domingues et al 2008) or their uncertainties (Lyman and Johnson 2008, 2014), because neglecting halosteric effects may mask (or enhance) regional warming signals (figure 2).

Our new results also demonstrate that contrasting basin-scale halosteric and thermosteric changes reveals robust signatures in observations, and that the current CMIP5 generation of historically forced climate models capture the integrated basin-scale characteristics of the observed halosteric changes, even in the presence of substantial regional discrepancies.

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References

Abraham J P et al 2013 A review of global ocean temperature observations: implications for ocean heat content estimates and climate change Geophys. Res. Lett. 39 L23602

Antonov J I, Levitus S and Boyer T P 2002 Steric sea level variations during 1957–1994: importance of salinity J. Geophys. Res. 107 8013

Antonov J I, Levitus S and Boyer T P 2005 Thermosteric sea level rise, 1955–2003 Geophys. Res. Lett. 32 L15312

Adams M D, Landerer F W and Godfrey C 2012 The rate of sea-level rise Ocean Circulation and Climate, A 21st Century Perspective 2nd edn ed S Bindoff, L Leetmaa, J C Beers, M W Wolansky, S Visbeck (Cambridge: Cambridge University Press) pp 225–267

Antonov J I, Levitus S and Boyer T P 2005 Penetration of human-induced warming into the world’s oceans Science 309 284–7

Boening C, Willis J K, Landerer F W, Nerem R S and Fasullo J 2012 Long-term salinity changes and implications for the global water cycle Ocean Circulation and Climate, A 21st Century Perspective 2nd edn ed G Siedler, S M Griffies, J Gould and J A Church (Oxford: International Geophysics, Academic, Elsevier) vol 103 pp 72–87 chapter 28

Bouttes N, Wijffels S E and Matear R J 2012 Ocean salinities reveal strong global water cycle intensification during 1950–2000 Science 336 455–8

Covey C, Gleckler P J, Phillips T J and Bader D C 2006 Secular trends and climate drift in coupled ocean-atmosphere general circulation models J. Geophys. Res. 111 D03107

Cowley R, Wijffels S, Cheng L, Boyer T and Kizu S 2013 Biases in expendable bathythermograph data: a new view based in historical side-by-side comparisons J. Atmos. Ocean. Technol. 30 1195–225

Danabasoglu G et al 2014 North Atlantic simulations in coordinated ocean-ice reference experiments phase II (CORE-II): Part I: mean states Ocean Modelling 73 76–107

Domingues C M, Church J A, White N J, Gleckler P J, Wijffels S E, Barker P M and Dunion J R 2008 Improved estimates of upper-ocean warming and multi-decadal sea-level rise Nature 453 1090–3

Durack P J, Gleckler P J, Landerer F W and Taylor K E 2014 Quantifying underestimates of long-term upper-ocean warming Nat. Clim. Change 4 999–1005

Environ. Res. Lett. (2014) 114017 P J Durack et al

Fernandes F 2014 python-seawater v3.3.2. doi:10.5281/zenodo.11395 Available online: (http://doi.org/10.5281/zenodo.11395)

Gille S T 2002 Warming of the Southern Ocean Since the 1950s Science 295 1275–7

Gille S T 2006 How nonlinearities in the equation of state of seawater can confound estimates of steric sea level change J. Geophys. Res. 109 C03005

Gille S T 2008 Decadal-scale temperature trends in the Southern Hemisphere Ocean J. Clim. 21 4749–65

Griffies S M et al 2012 Human-induced global ocean warming on multidecadal timescales Nat. Climate Change 2 524–9

Hemming M 2014 Ocean heat content 1955–2013 A review of global ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates J. Geophys. Res. 118 6704–16

Houghton R J et al 1990 The effect of global climate changes on the volume of ocean water in 2010 in a suite of interannual CORE-II ensembles J. Geophys. Res. 105 C12 26349–52

Hosoda S, Suga T, Shikama N and Mizuno K 2009 Global surface layer salinity change detected by argo and its implication for hydrological cycle intensification J. Oceanogr. 65 579–96

Ishii M and Kimoto M 2009 Re-evaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections J. Oceanogr. 65 287–99
Williams D N et al 2014 UV-CDAT v2.0. doi:10.5281/zenodo.12251 Available online (http://doi.org/10.5281/zenodo.12251)

Wunsch C, Ponte R M and Heimbach P 2007 Decadal trends in sea level patterns: 1993–2004 J. Clim. 20 5889–911

Yin J 2012 Century to multi-century sea level rise projections from CMIP5 models Geophys. Res. Lett. 39 L17709

Yin J, Griffies S M and Stouffer R J 2010 Spatial variability of sea level rise in 21st century projections J. Clim. 23 4585–607