Observed Changes in the South Atlantic Subtropical Gyre and Links to Water Mass and Transport Variations at 34.5°S

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Background

The South Atlantic subtropical gyre is forced by the large-scale mid-latitude wind stress curl patterns that form between the easterly Trade Winds and the subtropical westerlies, and is typically situated between 15°S and 40°S (Fig. 1). Sea surface height (SSH) and upper ocean heat storage in the gyre have recently been observed to increase in response to a southward shift/intensification of the subtropical westerlies. Superimposed upon these secular changes are interannual-to-decadal SSH, temperature and salinity variations associated with the spin-up and spin-down of the gyre circulation. It is crucial to document SSH, heat storage, and water mass variations within the gyre and understand the mechanisms controlling these changes, as they can exert an influence on the strength of the currents delineating the gyre boundaries and the intensity of the Meridional Overturning Circulation (MOC) in the South Atlantic (e.g., Garzoli et al., 2013; Dong et al., 2014; Lopez et al., 2016; Meinen et al., 2018).

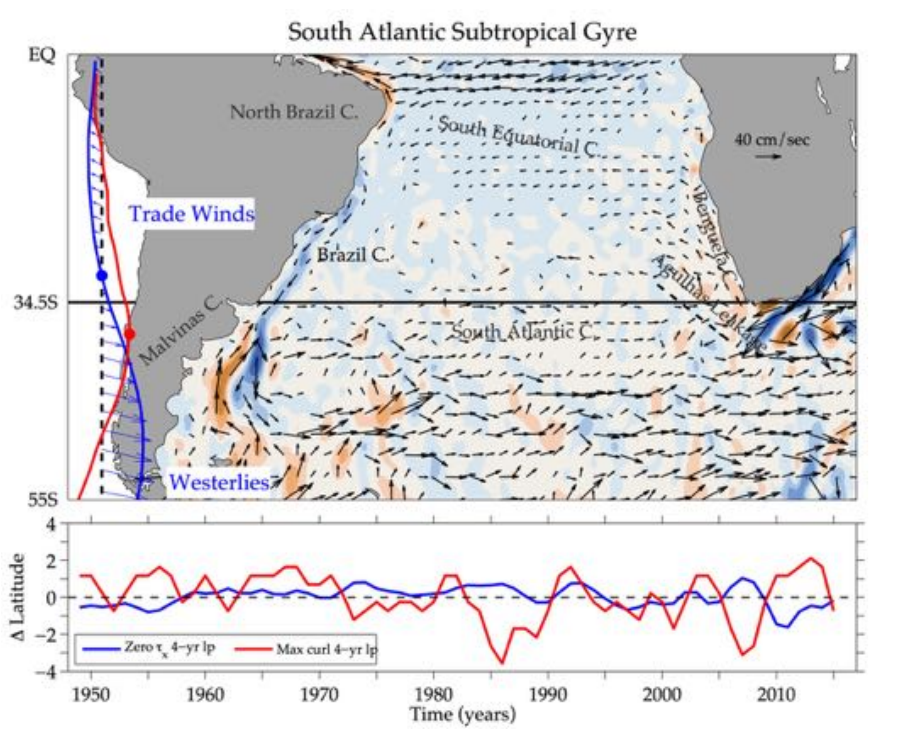


Fig. 1: (upper panel) Map of mean near-surface currents from Lumpkin and Johnson (2013) drifter climatology. Color shading: Mean meridional velocity. Blue vectors: Mean NCEP reanalysis wind stress averaged across basin, blue curve: mean zonal wind stress, red curve: mean wind stress curl.

(lower panel) Interannual evolution of the anomalous latitude of zero wind stress (blue) and maximum wind stress curl (red) from 1948 to 2017. A four-year low-pass has been applied to the annual means.

Objective: Satellite and in situ observations are used to examine interannual to decadal variations of SSH (AVISO, 1993-2016), upper ocean heat content (World Ocean Database, WOD, 1955-2016), and water mass properties (Argo, 2004-2016; SAMOC/SAMBA, 2008-2017) in the South Atlantic subtropical gyre (between 35°S to 15°S) and just south of the gyre (between 55°S and 35°S).

How are SSH and heat content changing across the gyre?

Upper ocean heat content in the South Atlantic subtropical gyre has increased at a rate of 0.17 x 10^{22} Joules per decade since 1955 (Fig. 2). The rate of increase, 0.12 x 10^{22} Joules per decade, is slower south of the gyre between 55°S and 35°S. These trends increase by a factor of 2 during the shorter AVISO period (1993-2016). Given their small area, these two regions in the South Atlantic are not the dominant contributors to global heat content trends. However, the heat increase in the gyre is dramatic relative to global values when you consider that the average heat content increase in a 1 x 1 degree box is 1.4 x 10^{18} Joules per decade in the gyre, and the average global value in a 1 x 1 degree box is half that value. When the linear trend has been removed, there is significant interannual to decadal variability in the South Atlantic.

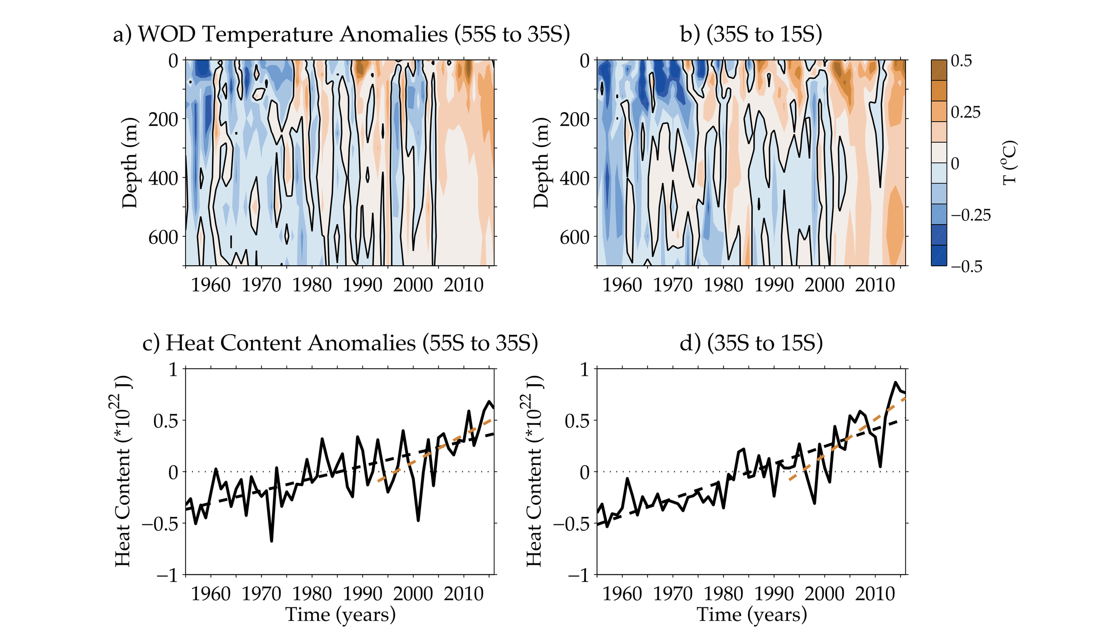
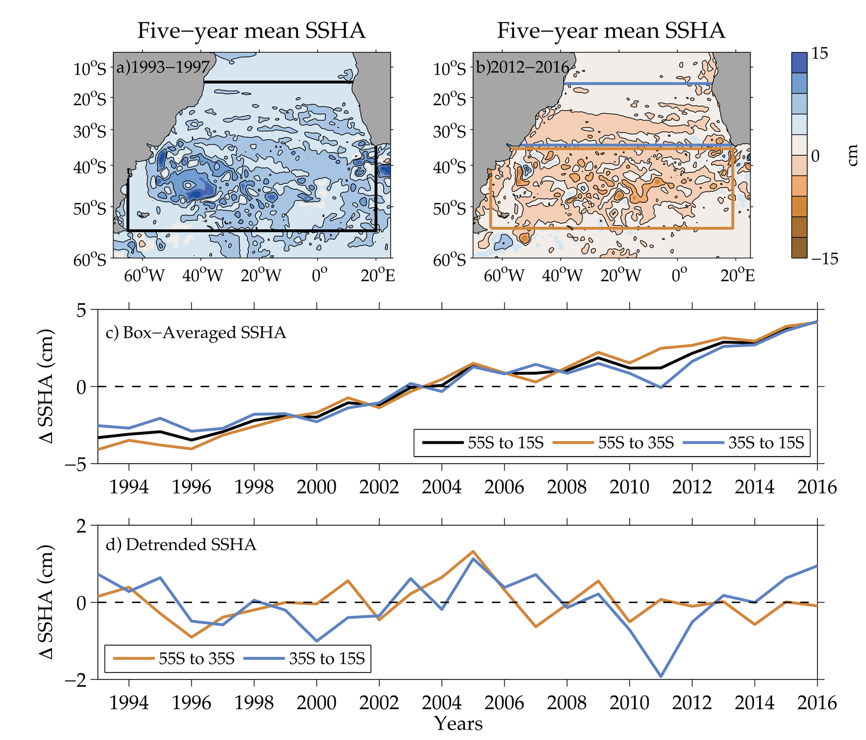


Fig. 2: Evolution of WOD annual ocean temperature in the upper 700 m averaged between 65°W and 20°E a) south of the gyre and b) within the gyre. Lower panels show the integrated heat content anomalies between the surface to 700 m. Trend lines are overlaid for entire record (black dashed line) and AVISO period (brown dashed line).

Fig. 3: AVISO SSHA in the South Atlantic. Five-year means during a) 1995-1999 and b) 2012-2016.

Panel c) shows the annual mean SSHA across whole South Atlantic (black line), south of the gyre (orange line) and within the gyre (blue line).

Panel d) shows detrended SSHA.



AVISO SSH anomalies (labelled as SSHA in figure captions) show positive sea level trends across the whole basin, with largest values clearly found south of the gyre (Figs. 3,4). In contrast, analysis of the WOD thermosteric SSH (from temperature contributions in the upper 700 m) finds that the largest SSH trends are within the gyre (Fig. 4). The thermosteric SSH trends are stronger during the AVISO period than during the full record, but are still far weaker than the AVISO period SSHA trends.

Question: What else is controlling the SSH increase?

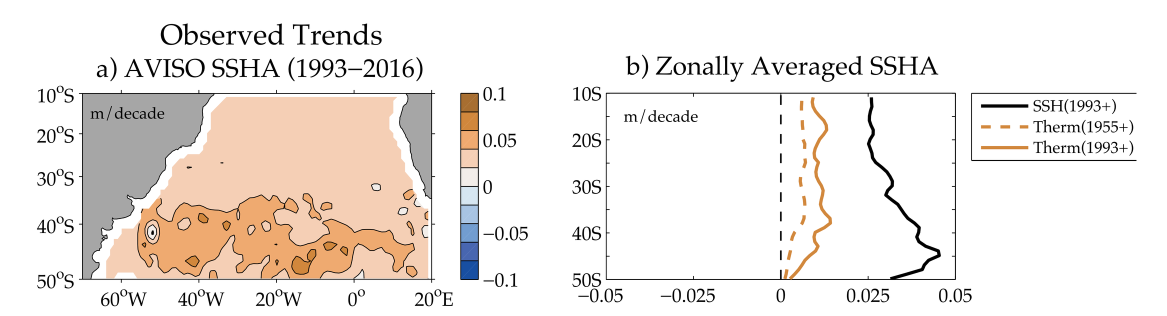


Fig. 4: Spatial pattern of linear trend computed from annual AVISO SSHA during the years 1993 to 2016 (panel a). Panel b) compares the zonally averaged AVISO SSHA (black solid line) and WOD thermosteric SSHA trends (using data in upper 700m) during 1955-2016 (brown dashed line) and 1993-2016 (brown solid line).

Water mass changes in and south of the gyre

Salinity, temperature, and density changes across the South Atlantic are not spatially uniform. During the Argo (2004-2016) time period, warming and salinification are observed in the gyre in the upper 700 m of the water column (Fig. 5a,c). South of the gyre, the warming in upper 700 m is paired with freshening (Fig. 5a,c). Between 700 and 2000 m, there is weak warming paired with freshening within and south of the gyre (Figure 5b,c). When averaged over the entire subtropical gyre, upper ocean temperature and salinity changes compensate for one another in terms of their thermosteric and halosteric SSH contributions, respectively, and largely cancel out. At intermediate levels and south of the subtropical gyre, however, temperature and salinity anomalies are not compensatory and lead to increasing SSH and decreasing density trends (Fig. 5f).

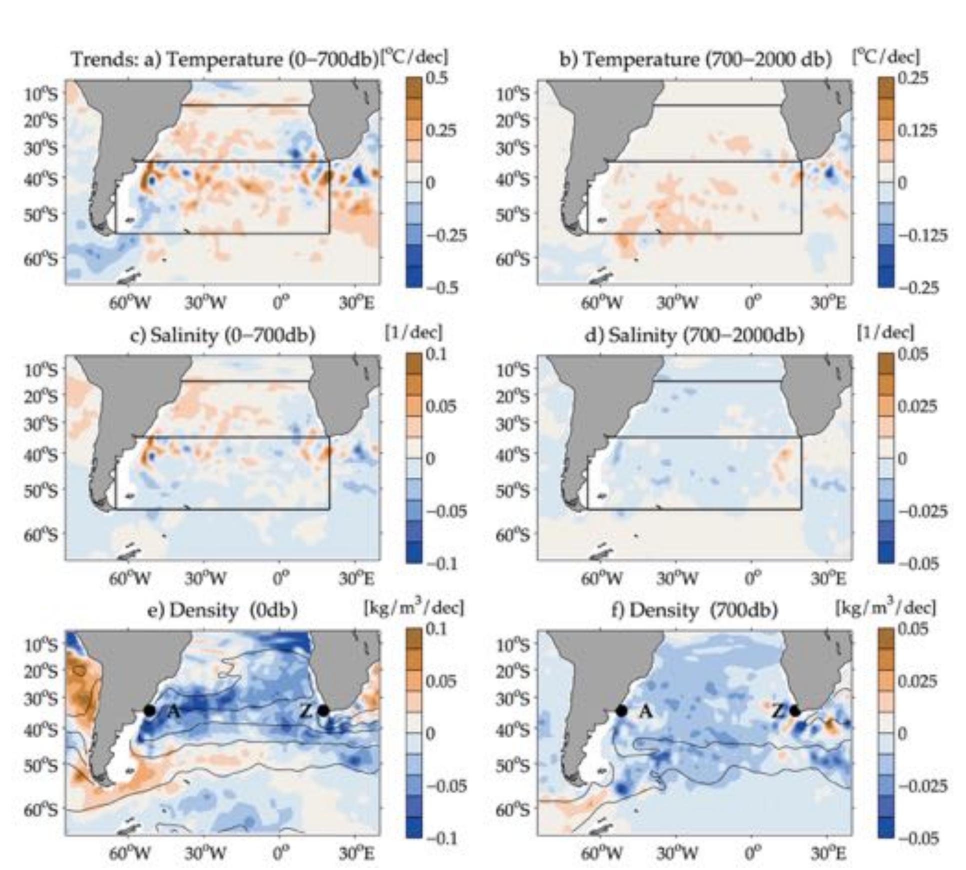
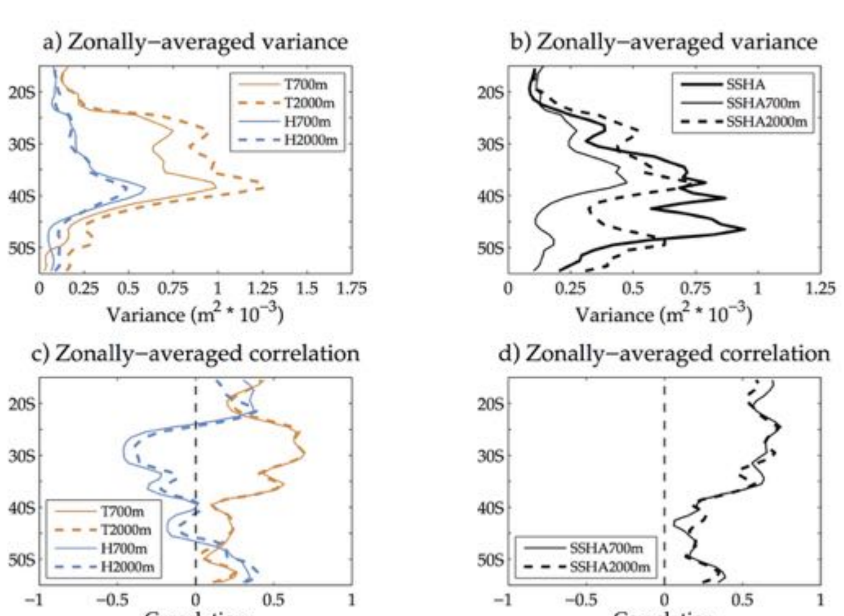


Fig. 5: Linear trends computed from annual Argo (2004-2016) temperature and salinity anomalies averaged between 0 and 700 db, and 700 and 2000 db, Panels e-f) show density trends at surface and 700 db, respectively.

Once trends are removed, thermosteric SSH variations in the upper 700 m control total SSH variations in the gyre (Fig. 6). However, inclusion of temperature variations between 700 and 2000 m and salinity variations in the upper 2000 m is necessary to reproduce the dominant mode of SSH variability (Fig. 7). This points to the importance of halosteric SSH changes and intermediate water mass changes in the South Atlantic.

Fig. 6: (right) Zonally averaged variance of a) detrended WOD thermosteric (brown lines) and halosteric (blue lines) SSHA in the upper 700 m (thin solid lines) and 2000 m (thick dashed lines) from 2004 to 2016. Panel b) compares the variance of total steric SSHA in the upper 700 m (thin solid line) and 2000 m (thick dashed line) with the AVISO SSHA variance (thick solid line). Lower panels: Same but correlations of SSHA with c) thermosteric and halosteric and d) total steric SSHA in the upper 700 and 2000 m.



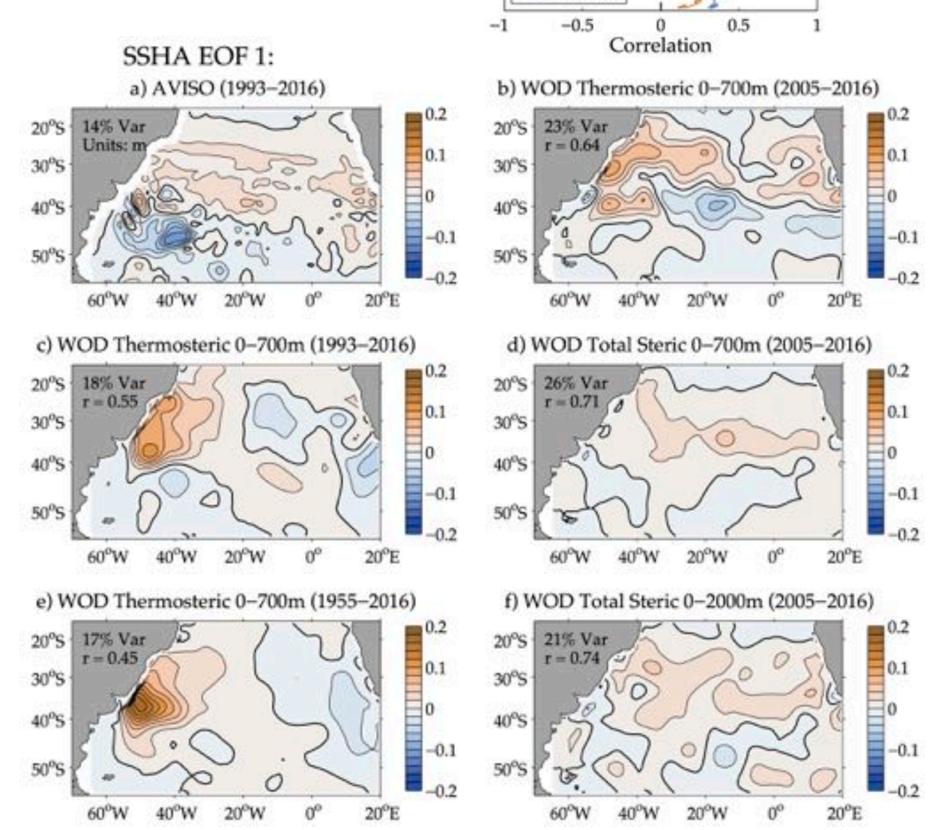


Fig. 7: (left) First EOF mode computed from annual mean detrended AVISO SSHA. Panels b,c,e) same for WOD thermosteric SSHA in upper 700 m for different time periods. Panel d,f) same for total steric SSHA in upper 700 m and 2000 m.

Key Findings

1. SSH and heat content in the South Atlantic have been increasing over the past decades, but at disparate rates within the gyre (larger heat content trends) and south of the gyre (larger SSH trends).
2. Salinity driven (halosteric) SSH changes compensate for temperature driven (thermosteric) SSHA changes in the gyre in the upper 700 m of the water column - over the past decade the surface waters in the gyre have become warmer and saltier on average. This halosteric - thermosteric compensation is less prevalent south of the gyre because upper ocean warming is paired with freshening. Water mass changes between 700 and 2000 m also influence SSH variations, where weak warming is combined with weak freshening in intermediate water layers.
3. Once the trend is removed, the dominant mode of SSH variability shows interannual to decadal gyre spin-up and spin-down with pattern shown in Fig. 7a. Although this mode captures only 14% of the total variance, it is strongly correlated with SSHA variability within the gyre, as well as with the 2nd mode of zonal wind and wind stress curl variability (not shown).
4. Similar EOF modal structures are reproduced from total steric SSH observations in the upper 700 m and 2000 m of the water column (Fig. 7d,f), pointing to the importance of salinity driven SSHA changes and intermediate water mass changes in the South Atlantic.

Implications

Interannual density changes (Fig. 8) at inshore sites of the SAMOC Basin-wide Array (SAMBA) along 34.5°S can drive changes in the MOC strength. To illustrate this, we examine density variations during strong (e.g., 2009) and weak (e.g., 2013, 2014) MOC years when baroclinic variations dominated MOC interannual variability (Meinen et al., 2018).

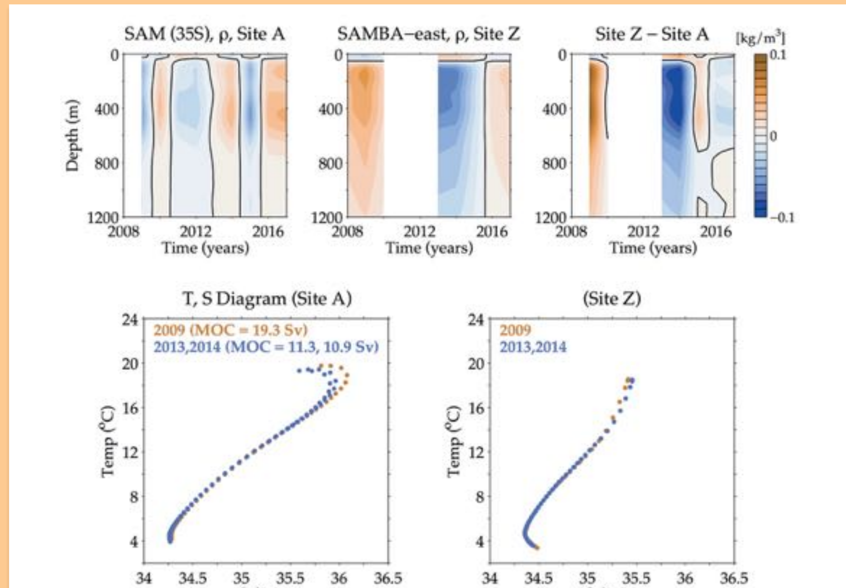


Fig. 8: (top) Annual mean changes in density at inshore sites of the SAMBA array and their difference (Site A from SAM array, Site Z from SAMBA-East array are shown in **Fig. 6e,f**).

(bottom) T-S diagrams show warmer, saltier waters at Site A in 2009 (strong MOC year) and fresher waters at Size Z relative to their values during 2013 and 2014 (weak MOC years).

Meinen et al., 2018 found that baroclinic variations, in particular density variations at Site Z, dominated MOC variations in 2009, 2013, and 2014. These water mass variations can induce +/- 4 Sv changes in the MOC strength.

2018 International AMOC Science Meeting

Funding: NOAA #NA13OAR4310131, NASA #NNX14AH60G