Importance of the assimilation of Argo float measurements on the Meridional Overturning Circulation in the South Atlantic

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[1] The meridional overturning circulation (MOC) and meridional heat transport (MHT) obtained from two GFDL coupled models, with and without data assimilation, are examined and compared with observations collected at nominally 34°S in the South Atlantic. The results demonstrate that the performance of the Geophysical Fluid Dynamic Laboratory (GFDL) coupled data assimilation (CDA) model is quite different between the two periods, 1979-2002 and 2003–2007, due to the assimilation of Argo data in later period. The MOC components from the GFDL CDA during 1979-2002 are similar to those from GFDL CM2.1 IPCC simulation, both give weak boundary currents and strong interior overturning transport compared to observations. However, after assimilating temperature and salinity profiles from the Argo floats, the performance of the GFDL CDA is greatly improved in terms of representing the observed MOC and MHT structure: the transports of boundary currents are twice as strong as those during pre-Argo period, and the overturning flow in the interior region is reduced. Possible causes for the changes in model performance are discussed. Citation: Dong, S., M. Baringer, G. Goni, and S. Garzoli (2011), Importance of the assimilation of Argo float measurements on the Meridional Overturning Circulation in the South Atlantic, Geophys. Res. Lett., 38, L18603, doi:10.1029/2011GL048982.

1. Introduction

[2] The meridional overturning circulation (MOC) has attracted increasing interest due to its link to abrupt climate change [e.g., Broecker, 1997; Clark et al., 2002; Manabe and Stouffer, 1988; Vellinga and Wood, 2002]. Current in situ and satellite observations to monitor changes in the MOC are inadequate for long-term variability studies. Our current understanding of the MOC and its governing mechanisms depends heavily on the use of numerical models [e.g., Manabe and Stouffer, 1994; Thorpe et al., 2001; Stouffer et al., 2006; Smith and Gregory, 2009], which have provided important insights into MOC behavior. However, in order to investigate the climate impacts of the MOC and predict future climate variability, it is important to accurately simulate MOC processes, including changes in the MOC in response to forcing and the sensitivity of the meridional heat transport (MHT) to the MOC variability. Observational data are needed to assess the performance of models in simulating MOC processes.

[3] A zonal high-density XBT transect (AX18) has been in operation in the South Atlantic at nominally 34°S between South Africa and South America since 2002. One of the main objectives of this transect is to monitor the upper limb of the MOC as it enters the Atlantic. Data from AX18 have been used to investigate the time-mean and seasonal variations in the MOC and MHT [*Baringer and Garzoli*, 2007; *Garzoli and Baringer*, 2007; *Dong et al.*, 2009]. In this study we assess how well the MOC and MHT processes at 34°S in the South Atlantic are represented in models with and without data assimilation, with an emphasis on the effect of the Argo float profiles on the performance of data-assimilating model. Results of the MOC and MHT estimates from AX18 [*Dong et al.*, 2009] are considered as "truth" for comparison.

2. Models

[4] In this paper, the products from two different models, the GFDL CM2.1 IPCC AR4 20th century run (hereafter GFDL_{CM2.1}) and the GFDL coupled data assimilation (hereafter GFDL_{CDA}) are analyzed. The GFDL_{CDA} applied a two-step data assimilation procedure for an Ensemble Kalman Filter under a local least-square framework to GFDL_{CM2.1}. Satellite sea surface temperature, hydrographic data from World Ocean Database, and Argo float profiles were assimilated in the GFDL_{CDA}, which was run from 1979 to 2007. The space/time coverage of observations during Argo period (2003 and afterward) is much better, particularly for the Southern Hemisphere [Zhang et al., 2009]. The ocean component of both models is the fourth version of the Modular Ocean Model (MOM4) configured with 50 vertical layers and 1° by 1° horizontal resolution with the meridional resolution equatorward of 30° telescoping from 1° to 1/3° near the equator. Only last 22 years (1979–2000) of the GFDL_{CM2.1} model outputs are analyzed to compare with GFDL_{CDA} model and observations. No significant differences in the MOC and MHT were found when the entire time series (1861–2000) of GFDL_{CM2.1} were used. Publically available monthly model outputs are analyzed in this study. For further details on the models, readers are referred to Delworth et al. [2006] for details of the GFDL_{CM2.1} and Zhang et al. [2007] for GFDL_{CDA}.

3. Analysis and Discussion

3.1. Meridional Overturning Circulation Across 34°S

[5] The correspondence between the strength of the MOC (hereafter referred to as MOC) and MHT, and the contributions from various processes from the two models, are examined and compared with the results obtained from data collected along the AX18 XBT transect [*Dong et al.*, 2009]. Note that the MOC and MHT are calculated from the models outputs of temperature, salinity, and velocity fields, and the meridional Ekman transport is calculated from zonal

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			GFDL CDA		
	Contribution	GFDL CM2.1 1979-2000	1979–2002	2003-2007	AX18 2002–2008
		MOC (Sv)			
Geostrophic and Ekman	Ekman	$\textbf{2.5}\pm\textbf{3.1}$	0.4 ± 2.3	0.5 ± 2.7	$\textbf{2.2} \pm \textbf{2.0}$
	Geostrophic	16.7 ± 1.1	18.5 ± 2.2	12.8 ± 3.4	$\textbf{15.7} \pm \textbf{2.6}$
Regional contributions	West	-12.0 ± 2.8	-15.2 ± 6.9	-29.8 ± 6.7	-27.7 ± 5.3
	Interior	19.3 ± 2.9	20.2 ± 8.8	17.1 ± 6.2	16.5 ± 6.3
	East	11.9 ± 1.8	13.8 ± 5.3	$\textbf{26.0} \pm \textbf{6.3}$	$\textbf{29.2} \pm \textbf{5.2}$
Total		19.2 ± 3.2	$\textbf{18.9} \pm \textbf{3.6}$	13.3 ± 4.2	17.9 ± 2.2
		MHT (PW)			
Geostrophic and Ekman	Ekman	$\textbf{0.17} \pm \textbf{0.21}$	0.02 ± 0.17	0.03 ± 0.20	0.15 ± 0.13
	Geostrophic	0.33 ± 0.05	$\textbf{0.44} \pm \textbf{0.10}$	0.28 ± 0.17	$\textbf{0.40} \pm \textbf{0.17}$
Regional contributions	West	-0.75 ± 0.16	-0.87 ± 0.34	-1.55 ± 0.30	-1.59 ± 0.33
	Interior	0.68 ± 0.18	0.65 ± 0.34	$\textbf{0.74} \pm \textbf{0.33}$	$\textbf{0.80} \pm \textbf{0.35}$
	East	0.57 ± 0.08	0.69 ± 0.20	1.12 ± 0.29	$\textbf{1.33} \pm \textbf{0.27}$
Overturning and horizontal	Overturning	$\textbf{0.63} \pm \textbf{0.19}$	0.58 ± 0.19	0.52 ± 0.24	$\textbf{0.75} \pm \textbf{0.12}$
	Horizontal	-0.12 ± 0.03	-0.12 ± 0.05	-0.21 ± 0.06	-0.20 ± 0.10
Total		$\textbf{0.50} \pm \textbf{0.21}$	0.46 ± 0.21	0.31 ± 0.25	$\textbf{0.55} \pm \textbf{0.14}$

Table 1. Summary of Time-Mean MOC and MHT and Contributions From Various Processes at 34°S in the South Atlantic From GFDL CM2.1 and GFDL CDA Models and AX18 Measurements^a

^aThe ground 'truth' and the closest values to the ground 'truth' are given in bold.

wind stress. The MOC is defined as the maximum cumulative transport from the sea surface to the ocean bottom. Table 1 summarizes the mean values and standard deviations of MOC and MHT and contributions from different components from the two models and the corresponding values from AX18 for comparison.

[6] Results of the MOC at 34°S in the GFDL_{CM2.1} model exhibits a mean value of 19.2 Sv (1 Sv = 10^6 m³/s) and fluctuates with a standard deviation of 3.2 Sv (Figure 1a), slightly higher than the mean MOC of 17.9 ± 2.2 Sv estimated from AX18 observations [*Dong et al.*, 2009]. GFDL_{CDA} gives a similar MOC strength during the period 1979–2002, 18.9 ± 3.6 Sv. However, the MOC in GFDL_{CDA} decreases after 2002 when Argo float profiles started being assimilated

(Figure 1a). The mean MOC during 2003–2007 from GFDL_{CDA} is about 13.3 ± 4.2 Sv, lower than the value from AX18. Therefore, to illustrate the effect of Argo float measurements in GFDL_{CDA}, the MOC and MHT and contributions from different components are separated into two periods in the following analysis: 1979–2002 (pre-Argo) and 2003–2007 (Argo period).

[7] Dong et al. [2009] found a linear response of the MHT to the MOC changes at 34°S from AX18, where one Sv increase in the MOC would give 0.055 ± 0.003 PW (1 PW = 10^{15} Watts) increase in MHT. Analysis of the MOC and MHT from the GFDL_{CM2.1} suggests an increase of 0.060 ± 0.002 PW in MHT with one Sv increase in the MOC. The GFDL_{CDA} gives similar results, 0.059 ± 0.002 PW and



Figure 1. Time series of the (a) MOC at 34°S in the South Atlantic from GFDL CM2.1 (black) and GFDL CDA (red), and contributions of western boundary (red), eastern boundary (green), and interior region (blue) to the MOC from (b) GFDL CM2. 1 model and (c) GFDL CDA model. (d, e, and f) Similar to Figures 1a, 1b, and 1c, respectively, but for the MHT. Units are Sv for MOC, and PW for MHT.



Figure 2. Meridional velocity from GFDL CDA averaged (a) during 1979–2002 and (b) during 2003–2007 and (c) differences in averaged meridional velocity for the two periods, 2003–2007 and 1979–2002. Unit is m s⁻¹.

 0.056 ± 0.003 PW increase in MHT for the two periods (1979–2002 and 2003–2007), respectively. Although the responses of MHT to MOC in both models are not statistically different from AX18 estimates, the assimilation of Argo data in later period indeed gave a value of MHT change in response to MOC change closer to that obtained from AX18. Also consistent with Dong et al. [2009], the geostrophic component from both models is the major contributor to the time-mean MOC (Table 1). However, unlike the results from AX18 where the variability of the geostrophic transport is slightly stronger than that of the Ekman transport, the variability of geostrophic transport in GFDL_{CM2.1} is much weaker than the Ekman transport. The Ekman transport is weak in GFDL_{CDA}, which can be attributed to two factors: the weak wind stress and the slightly southward shift of the wind pattern which further weakens the westerly wind at 34°S.

3.2. Regional Contributions to the MOC

[8] Similar to Dong et al. [2009], the MOC is separated into three regions: a) the western boundary, west of where current changes from southward to northward, normally around 48°W, b) the eastern boundary, east of Walvis ridge (\sim 3°E), and c) the interior between 48°W and 3°E. The transport in each region is integrated from surface to the depth of the maximum cumulative transport. The regional contributions to MOC from GFDL_{CM2.1} (Figure 1b) vary slightly around their time-mean contributions. The interior region contributes the most to the MOC with a mean contribution of 19.3 ± 2.9 Sv, stronger than the value of 16.5 ± 6.3 Sv from AX18 transect (Table 1). The contributions from both eastern and western boundary currents are weaker, less than half of those estimates from AX18 transect, with southward transport of -12.0 ± 2.8 Sv in the western boundary and northward transport of 11.9 ± 1.8 Sv in the eastern boundary. The variability of the regional contributions is also weaker than the observed values (Table 1).

[9] The regional contributions to the MOC from GFDL_{CDA} during 1979–2002 are similar to those from $\text{GFDL}_{\text{CM2.1}}$, although the contributions are slightly higher in all three regions for GFDL_{CDA} (Figure 1c). However, the variability of regional contributions to MOC from GFDL_{CDA} is much larger than those from $\text{GFDL}_{\text{CM2.1}}$, and comparable to the observed values (Table 1). This strong variability in regional transport is likely related to the strong variability in the temperature and salinity fields in GFDL_{CDA} (not shown). For the GFDL_{CDA} model itself, the contributions from boundary currents after 2002 were twice as much as those during 1979–2002, whereas the interior contribution decreased to 17.1 Sv, slightly larger than the value of 16.5 Sv from AX18. Thus, despite the weak MOC, the regional contributions estimated from AX18 transect are much better reproduced in GFDL_{CDA} during 2003–2007 (Table 1). The weaker MOC in GFDL_{CDA} during 2003–2007 is likely due to the relatively weaker northward transport in the eastern boundary and stronger southward transport in the western boundary, which may be related to the lack of Argo data near the boundaries, particularly in the western boundary.

[10] The changes in both models show statistically significant correlation with the western boundary contribution, in particular during Argo period in GFDL_{CDA} with a high correlation of 0.84. The eastern boundary contribution during Argo period is also significantly correlated (0.4) with the MOC, but not during pre-Argo period in GFDL_{CDA} as well as in GFDL_{CM2.1}. No significant correlations were found between the interior contribution and the MOC in GFDL_{CDA} for both periods, inconsistent with the results from AX18 transect [Dong et al., 2009]. However, the interior transport in GFDL_{CM2.1} does show significant correlation (0.40) with the MOC. Consistent with the results from AX18, the regional contributions to MOC are negatively correlated with each other in both models, except between the eastern boundary and interior region during Argo period in GFDL_{CDA}.

3.3. Meridional Heat Transport Across 34°S

[11] The comparison of MHT (Figures 1d, 1e, and 1f) between $GFDL_{CM2.1}$ and $GFDL_{CDA}$, and that between $GFDL_{CDA}$ before and after 2003 are similar to that of MOC. In general, the performance of the $GFDL_{CDA}$ before 2003 and $GFDL_{CM2.1}$ are similar, with both the southward heat transport in the western boundary and northward heat transport in the eastern boundary weaker than estimates from AX18 transect (Table 1). Although the interior contribution to the MOC is stronger than that from AX18, the



Figure 3. Temperature differences between (a) $GFDL_{CDA}$ 2003–2007 and $GFDL_{CDA}$ 1979–2002, (b) $GFDL_{CDA}$ 1979–2002 and WOA09, and (c) $GFDL_{CDA}$ 2003–2007 and WOA09. (d, e, and f) Similar to Figures 3a, 3b, and 3c, respectively, but for salinity differences. (g, h, and i) The corresponding density differences. Units are degree Celsius for temperature differences, psu for salinity differences, and kg m⁻³ for density differences.

heat transport in the interior region is lower than estimate from AX18 (Table 1). This feature will be discussed in the next section. Similar to the MOC, the heat transports from boundary currents during 2003–2007 in GFDL_{CDA} were about twice as much as those before 2003, and the values are comparable with observations (Table 1). The statistical relationships between the total MHT and regional contributions and among the regional contributions are similar to those from MOC, thus no further discussion is given here.

[12] Separating the MHT into overturning and horizontal gyre contributions following *Bryden and Imawaki* [2001], we found that the contribution from gyre circulation is about 0.12 PW from both the GFDL_{CM2.1} and GFDL_{CDA} before 2003, about half the value estimated from AX18 (Table 1). During 2003–2007, the GFDL_{CDA} gives heat transport from gyre circulation of 0.21 PW, comparable with the value of 0.20 PW from AX18. Those comparisons suggest that assimilating Argo float profiles has greatly improved model performance in capturing the observed MOC and MHT processes at 34°S in the South Atlantic, though the mean MOC and, consequently the MHT, are lower than the values estimated from AX18 measurements owing to the lack of Argo data near the boundaries.

3.4. Possible Causes for Differences in MOC and MHT

[13] To examine what causes the differences in the MOC and MHT before and after Argo float data are assimilated, the velocity, temperature and salinity fields are compared. The averaged fields of velocity, temperature and salinity from GFDL_{CM2.1} are similar to those from GFDL_{CDA} before 2003, thus only averages from GFDL_{CDA} during 1979-2002 and 2003-2007 are shown here. The averaged meridional velocities from both periods show top-to-bottom southward flow at the western boundary, and northward flow in the upper ocean and southward flow in the deep ocean at the eastern boundary (Figures 2a and 2b). However, the velocities at the boundaries during 2003-2007 are much stronger (Figures 2b and 2c). At the eastern boundary the strong northward flow is confined to upper 800 m before 2003, whereas after 2003 the strong northward flow reaches 1500 m depth and is more constrained to the boundary (Figure 2b). On average, the interior region shows anomalous southward flow in upper 1500 m and anomalous northward flow below during 2003-2007, which explains the reduced interior overturn transport.

[14] Differences in temperature and salinity fields along 34°S during 1979-2002 and during 2003-2007 (Figures 3a and 3d) are examined to investigate the possible causes for the changes in meridional velocity. The temperature difference between the two periods ($T_{2003-2007}$ - $T_{1979-2002}$, Figure 3a) shows that the temperature during 2003-2007 has an increasing warm anomaly towards the western boundary, which would give an anomalous northward flow. In contrast, the increasing salty anomaly towards the western boundary during 2003-2007 (Figure 3d) would cause an anomalous southward flow. Thus, the stronger southward flow in the western boundary during 2003-2007 can be attributed to the changes in salinity field, which is also clearly shown in the density differences (Figure 3g). At the eastern boundary, the temperature anomaly (Figure 3a) tends to be less warm (above 1000 m) or more cold (below 1000 m) towards the boundary, suggesting a northward flow anomaly. Whereas the salinity anomaly during 2003-2007 (less salty above 600 m and more fresh below) suggests a southward flow anomaly. Thus, unlike at the western boundary, the stronger northward flow during 2003–2007 in the eastern boundary is likely due to the changes in the temperature fields. Temperature and salinity differences between model and observations are also examined to understand the potential causes for differences in MOC processes between model and data. Comparisons of model fields with temperature/salinity maps from Argo float profiles (0-2000 m) are very similar to the differences between model and World Ocean Atlas 2009 (WOA09) [Antonov et al., 2010; Locarnini et al., 2010]. Therefore only the differences between model and WOA09 are shown to demonstrate distribution over the entire water column (Figure 3). The temperature averaged during 1979-2002 from GFDL_{CDA} at 34°S is colder than WOA09 in upper 1000 m water column and warmer than WOA09 below (Figure 3b). This distribution of temperature differences explains the lower MHT despite the higher MOC compared to observations in both the GFDL_{CM2.1} and GFDL_{CDA} during 1979-2002 (Table 1). The temperature during 2003-2007 from GFDL_{CDA} is warmer than WOA09 throughout the water column (Figure 3c), except in the upper 1000 m water column near the western boundary and in the upper 2000 m east of 5°E. The lower MHT is likely a consequence of lower MOC during this period. The cold bias in upper 1000 m at the western boundary contributes to the stronger southward flow compared with observations. The cold bias centered at 10°E in upper 1000 m decreases towards the eastern boundary, and the warm bias below that increases from 10°E to the eastern boundary, both suggest southward flow anomaly, which explains the slightly weaker northward flow at the eastern boundary in GFDL_{CDA} during 2003–2007.

[15] Similar to temperature differences, the salinity averaged during 1979–2002 from GFDL_{CDA} in upper 700 m is fresher than WOA09 and saltier below that (Figure 3e). Most interestingly, unlike the more east–west evenly distributed temperature differences, the salinity differences show an upward slope from west to east, suggesting that the salinity in GFDL_{CDA} tends to have more positive bias towards the east. This upward slope in salinity differences induces similar distribution in density field (Figure 3h), i.e., density bias tends to increase towards more positive (or less negative) values to the east, which would cause a northward flow anomaly. Thus, the salinity differences can explain the

stronger interior overturning flow in GFDL_{CDA} before 2003, as well as in GFDL_{CM2.1}. The salinity averaged during 2003–2007 shows relatively smaller differences from WOA09 (Figure 3f), with relatively fresher water in upper 500 m and saltier water elsewhere. The saltier bias below 700 m at the western boundary also contributes to the stronger southward flow. In fact, the salinity biases play a dominant role in the density biases (Figures 3h and 3i).

4. Summary

[16] Examination of the MOC and MHT from GFDL_{CM2.1} and GFDL_{CDA} models at 34°S in the South Atlantic shows that both the GFDL_{CM2.1} and GFDL_{CDA} before assimilating Argo data give similar time-mean values of MOC and MHT to those estimated from XBT measurements. However, the boundary currents are too weak and interior overturning flow is relatively strong. After 2002 when Argo data started being assimilated, the performance of GFDL_{CDA} in simulating the MOC processes was greatly improved, though the mean values of the MOC and MHT are lower compared to the estimates from AX18 transect. The boundary currents were twice as much as those prior to 2003, and the interior overturning flow is reduced by 20% due to a better representation of salinity field. The improvement of the boundary currents, despite the lack of Argo data at the boundaries, in particular the western boundary, is probably due to better temperature/salinity representation at the interior side of the boundaries. The weak MOC and MHT since 2003 in GFDL_{CDA} is likely due to the slightly stronger southward transport in the western boundary and slightly weaker northward transport in the eastern boundary in GFDL_{CDA} than those estimated from XBT measurements. Those comparisons suggest the importance of the Argo float measurements in improving data-assimilating model performance in representing the MOC processes. The lack of Argo data at the boundaries may be responsible for the weak MOC, suggesting that measurements from other platforms are needed at the boundaries to further improve MOC processes in data-assimilating models.

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