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.
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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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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]

	Contribution	GFDL CM2.1 1979–2000	GFDL CDA 1979–2002	GFDL CDA 2003–2007	AX18 2002–2008
		MOC (Sv)			
Geostrophic and Ekman	Ekman	**2.5** ± **3.1**	0.4 ± 2.3	0.5 ± 2.7	**2.2** ± **2.0**
	Geostrophic	**16.7** ± **1.1**	18.5 ± 2.2	12.8 ± 3.4	**15.7** ± **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	**26.0** ± **6.3**	**29.2** ± **5.2**
Total		19.2 ± 3.2	**18.9** ± **3.6**	13.3 ± 4.2	**17.9** ± **2.2**
		MHT (PW)			
Geostrophic and Ekman	Ekman	**0.17** ± **0.21**	0.02 ± 0.17	0.03 ± 0.20	**0.15** ± **0.13**
	Geostrophic	0.33 ± 0.05	**0.44** ± **0.10**	0.28 ± 0.17	**0.40** ± **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	**0.74** ± **0.33**	**0.80** ± **0.35**
	East	0.57 ± 0.08	0.69 ± 0.20	**1.12** ± **0.29**	**1.33** ± **0.27**
Overturning and horizontal	Overturning	**0.63** ± **0.19**	0.58 ± 0.19	0.52 ± 0.24	**0.75** ± **0.12**
	Horizontal	−0.12 ± 0.03	−0.12 ± 0.05	**−0.21** ± **0.06**	**−0.20** ± **0.10**
Total		**0.50** ± **0.21**	0.46 ± 0.21	0.31 ± 0.25	**0.55** ± **0.14**

[a]The 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 m^3/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

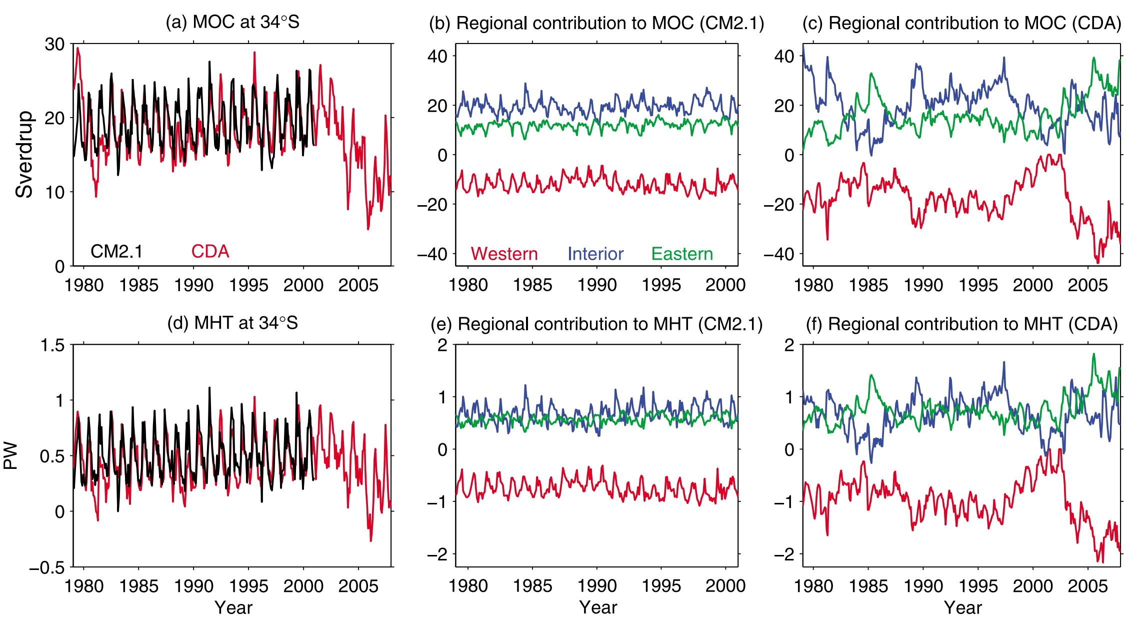

Figure 1. Time series of the (a) MOC at 34°S in the South Atlantic from GFDL CM2.1 (black) and GFDL CDA (red), and contributions of western boundary (red), eastern boundary (green), and interior region (blue) to the MOC from (b) GFDL CM2. 1 model and (c) GFDL CDA model. (d, e, and f) Similar to Figures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