The ocean heat transport and meridional overturning near 25°N in the Atlantic in the CMIP models

Yanli Jia
Southampton Oceanography Centre, Southampton, UK
Yanli.Jia@soc.soton.ac.uk

1. Introduction

The models considered in this article are participants of the Coupled Model Intercomparison Project (CMIP). CMIP examined climate variability and predictability as simulated by the models, and compared the model output with observations where available (Covey and Meehl, 1997). In the first phase (CMIP1), the performance of the models in producing the mean climate was examined using model output from "control experiments", in which the external forcing terms such as atmospheric CO_2 concentration and solar luminosity are held constant. For the second phase of the project (CMIP2), model responses to an idealised scenario of anthropogenic climate forcing (a 1% per year increase in atmospheric carbon dioxide) are examined. Parallel "control experiments" are also available. Analysis of the model output is done partly in the form of diagnostic subprojects. This article reports some of the results from one such subproject that concerns the ocean components of the coupled models. The focus is on the ocean heat transport.

Recent advances in both atmospheric and ocean general circulation models have resulted in much improved coupled models that are capable of producing stable SST without the need for flux corrections (e.g. Boville and Gent 1998; Gordon et al. 2000). This success is believed to be a result of the compatibility in the poleward heat transports by the atmosphere and the ocean components. However, more often the ocean heat transport computed from an ocean model or the ocean component of a coupled model is lower than that derived from observed atmospheric fluxes or implied by atmospheric models. In a coupled ocean-atmosphere general circulation model, such a discrepancy will lead to a climate drift that introduces great uncertainties to the understanding of anthropogenic climate change.

Based on direct oceanographic measurements, Bryden (1993) pointed out the different mechanisms of ocean heat transport in the North Atlantic and the North Pacific oceans, and emphasised the ultimate dependence of ocean heat transport on ocean circulation. In the North Atlantic, the meridional heat transport is achieved through the meridional overturning circulation driven by thermohaline circulation, while in the North Pacific the meridional heat transport is accomplished by the horizontal circulation driven by wind forcing. In this article, the ocean heat transport across 25°N in the Atlantic from the "control experiments" of CMIP1 and CMIP2 is compared with estimates from oceanographic measurements, and its correlation to the oceanic structure and ocean circulation is investigated.

2. Model results

Hall and Bryden (1982) estimated the total ocean heat transport across 25°N in the Atlantic to be 1.22 PW (PW=10^{15}W) northward from direct oceanographic measurements (1957 IGY section). This estimate is supported by several other calculations (inverse or direct) based on measurements made in 1981 (Roemmich and Wunsch 1985) and 1992 (Lavín et al. 1998). The northward heat transport is due entirely to a deep vertical-meridional circulation cell, with northward flowing warm surface waters in the form of a western boundary current (the Gulf Stream) and southward flowing cold deep waters (the North Atlantic Deep Water). The contribution from the horizontal circulation is negligible (0.06 PW southward (Bryden 1993)). The strength of the meridional overturning circulation at 25°N is estimated to be 19.33 Sv (Sv≡$10^6 m^3 s^{-1}$) from Table 5 of Hall and Bryden (1982).

The total heat transport and the strength of the meridional overturning circulation near 25°N are extracted from fourteen CMIP1 models and eleven CMIP2 models (some of the CMIP2 models are participants of CMIP1 as well) and are displayed in Fig. 1 together with the estimates from Hall and Bryden (1982). We see that all but one of the models underestimate the total heat transport at this latitude.

Böning et al. (1996) derived a near linear relation between the overturning rate and the total heat transport at 25°N from a set of experiments (also displayed in Fig. 1) using the ocean model developed under the Community Modeling Effort (CME). It is suggested that for every 2 Sv gain in the overturning rate, the heat transport across 25°N increases by approximately 0.1 PW. Such a correlation is also found in several other ocean only models (e.g. the three DYNAMO models, see DYNAMO Group (1997)).

As shown in Fig. 1, a large number of the CMIP coupled models, however, do not follow the linear trend, with the heat transport much lower than the correlation would suggest. This result is not unexpected. Assuming that the contribution from the horizontal gyre circulation is negligible, the heat transport depends not only on the strength of the overturning rate but also the temperature difference between the upper and lower branches of the overturning cell. In the case of the ocean only models, a near linear correlation indicates that the temperature difference is very similar among the models. This is perhaps because the integrations are usually for a small number of centuries and the model oceans do not drift very far from their initial conditions. To demonstrate this, diagnostic calculations are performed with model outputs from one of the DYNAMO ocean models, the MICOM model (a layer model at

1/3° resolution). The total integration length is for 20 years and the final 5 years are used for the diagnostic calculation. At 25°N, the overturning rate is 19.07 Sv, the total heat transport is 1.16 PW (the gyre contribution is 0.001 PW southward). The average temperatures (the zonal mean temperature weighted by the zonal mean volume transport) of the upper and lower branches of the meridional cell are 17.70°C and 2.86°C respectively, yielding a temperature difference of 14.84°C.

The same model was integrated for 30 years at a lower resolution (4/3°). At 25°N, it produced an overturning rate of 15.93 Sv, a total heat transport of 0.95 PW (the gyre contribution is 0.03 southward). The average temperatures of the upper and lower overturning branches are 18.47°C and 3.42°C respectively, yielding a temperature difference of 15.05°C.

The lower heat transport obtained from the coarse resolution experiment, therefore, is mostly due to the lower overturning rate (resulting from weaker production of NADW in the high latitudes) as the temperature difference is very similar to that in the higher resolution experiment.

The observational estimates of the average temperatures of the upper and lower branches are obtained by making use of the information in Table 5 of Hall and Bryden (1982). The results are 17.76°C for the upper branch, 3.08°C for the lower branch, and a temperature difference of 14.68°C.

At a temperature difference of 15°C (as suggested by the observational estimate and model results from the DYNAMO MICOM experiments), the heat transport would increase at a rate of 0.12 PW for every 2 Sv increase in the overturning strength. This rate is consistent with the linear trend derived by Böning et al. (1996). At a smaller temperature difference of 10°C, it reduces to 0.08 PW per 2 Sv.

The average temperatures are also computed for the CMIP models and are displayed in Fig. 2. We see that a large number of the models have the temperature difference below 15°C, most fall between 15°C (the solid line) and 10°C (the dashed line), with a few outside this range. The coupling of a small temperature difference and a weak overturning strength is the primary cause of a low heat transport for most of the coupled models. Yet for some other models, the overturning strength is far higher than the observational estimate but the heat transport is still low. Further investigations reveal that the contribution from the horizontal gyre circulation in some of the models is not negligible but significantly southward (greater than 0.3 PW) thus further reducing the magnitude of the total northward heat transport.

Fig. 2 also shows that all the models have a too warm deep ocean, some are only slightly but others are far warmer than the observational estimate. This is an indication that certain high latitude processes (e.g. deep convection, overflows and diapycnic mixing) are not properly represented by these models, a problem that is already recognised by ocean modellers (see WOCE (1999)). We also see from Figs. 1 and 2 that the strength of the overturning circulation and the average temperature of the upper branch vary over wide ranges among the models, a reflection that there is much uncertainty in the physical processes that determine these two elements.

To conclude, there are considerable challenges in achieving the correct ocean heat transport in climate models. They involve improved understanding of many physical processes that determine various aspects of ocean circulation and oceanic structure. The synthesis of the hydrographic measurements made during WOCE should help in this endeavour.

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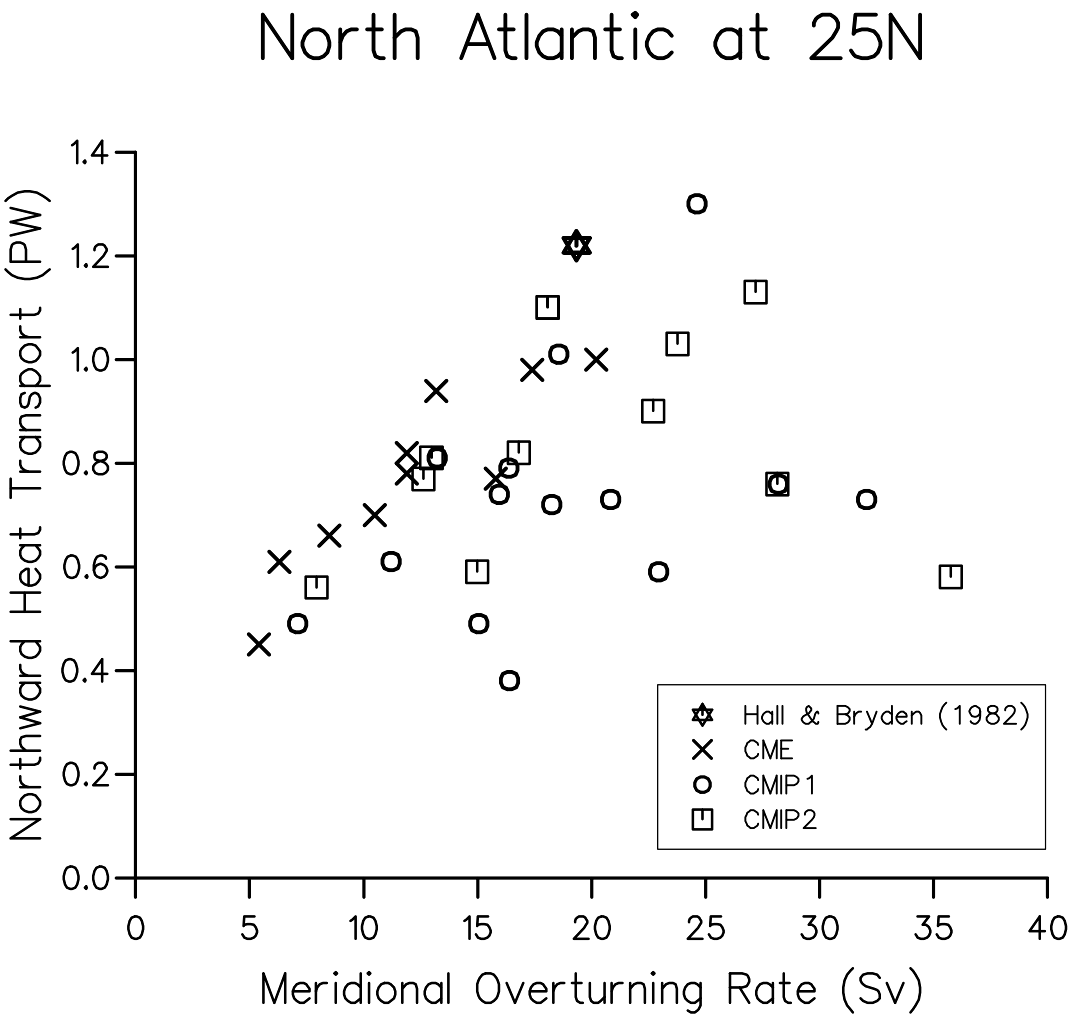
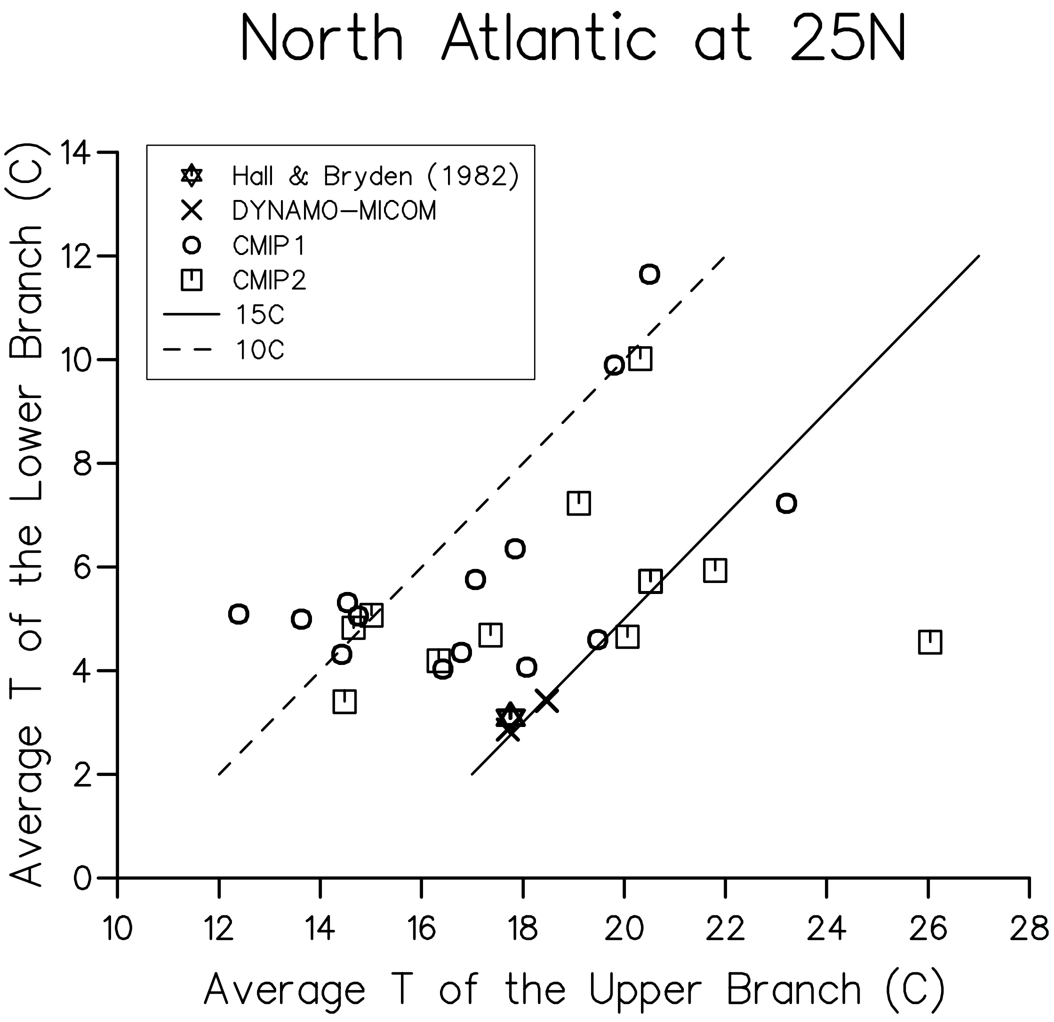
FIGURES

Fig. 1. The total northward ocean heat transport is displayed as a function of the strength of the overturning circulation near 25°N in the Atlantic. The star is for the observational estimate based on Hall and Bryden (1982), the crosses are for the CME experiments from Böning et al. (1996), the circles are for the CMIP1 models, and the boxes are for the CMIP2 models.

Fig. 2. The average temperatures (weighted by the volume transport) of the upper and lower branches of the overturning cell near 25°N in the Atlantic. The symbols are the same as for in Fig. 1 except that the crosses are for the DYNAMO experiments. The solid line indicates a temperature difference of 15°C between the upper and lower branches, and the dashed line is for 10°C.


North Atlantic at 25N


North Atlantic at 25N
Hall & Bryden (1982)
DYNAMO–MICOM
CMIP1
CMIP2
15C
10C
Average T of the Lower Branch (C)
0
2
4
6
8
10
12
14
Average T of the Upper Branch (C)
10
12
14
16
18
20
22
24
26
28