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Effects of Different Wind Stress Climatologies on the North Atlantic Circulation: Model results

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Can we use ocean circulation models to test wind stress fields? Even in the case of a perfect model, several issues need to be considered if we want to learn something from comparing simulated volume transports with observations. Obviously, we have to identify circulation regimes where the oceanic transports are (predominantly) driven by the wind stress, so that changes in the winds have significant effects on the resulting circulation. In addition, we have to focus on those areas in the ocean where the transport is well-known from observations. In this report, I shall discuss these issues for the case of the North Atlantic. The model being used is that developed by Bryan and Holland (1989) as a “Community Modeling Effort” (CME) under the World Ocean Circulation Experiment (WOCE). The model spans the Atlantic Ocean between 15°S and 65°N. In recent years, a suite of model experiments has been conducted by the CME groups at NCAR and at IfM Kiel, differing in a number of model factors, including horizontal resolution, frictional parameterization, wind and thermohaline forcing. For model descriptions, list of experiments, and detailed accounts of the mean circulation in different parts of the basin, the reader is referred to Bryan et al. (1994) and Böning et al. (1994). Model results discussed in this report are all from a model version with a grid resolution of 1/3 deg. in latitude, 2/5 deg. in longitude, and 30 levels in the vertical.

Large-scale ocean circulation is forced by the momentum, heat and freshwater fluxes at the surface. The thermohaline forcing in the Atlantic Ocean is associated with deep water renewal in subarctic regions, driving an overturning motion with a northward flow of warm water in the upper 1000 or 1200 m, and southward flow of cold, North Atlantic Deep Water between 1000 m and 4000–4500 m. The deep flow has a strong impact on the vorticity balance of the horizontal circulation in the subpolar North Atlantic. Both the CME-results (Bryan et al. 1994) and diagnostic modeling by Greatbatch et al. (1991) suggest that the structure and strength of the subpolar gyre is governed by the thermohaline-driven flow and its interaction with bottom topography, and to a much lesser degree by the wind stress. (This does not hold, however, for the seasonal variability which, in good approximation, can be understood in terms of a linear response to the variation in the wind stress curl. Lack of data would presently not allow to use this behavior for a test of different wind stress fields in the subpolar North Atlantic.) A model evaluation in terms of a wind-driven transport has to be restricted to the upper-layer circulation in the tropics and subtropics, south of the Gulf Stream recirculation regime.

The second requirement noted above, knowledge of volume transports from observations in the ocean, readily lead to further restrictions. As recently discussed in the review of Schmitz and McCartney (1993), there is very little quantitative information on oceanic transports; the singular exception for the North Atlantic is the transport through the Straits of Florida which had been studied over many years with different methods. The mean northward transport is 30 - 31 Sv, with little interannual variability, and a well defined seasonal cycle. Both the mean and the seasonal variation of the Florida Straits transport had been studied with the CME model, using two different wind stress climatologies (i.e., HR and IH, respectively; see below) (Böning et al. 1991a). As it turns out, however, focusing on the Florida Straits transport alone is of limited value for a test of the wind driven circulation in the subpolar gyre. The seasonal variation of the Florida Current is largely due to the variation of the meridional wind stress along the coast (Böning et al. 1991a). The mean transport, on the other hand, only partly represents the northward return flow of the wind-driven, southward flow over the interior of the basins; about 40% is considered to be part of the meridional overturning (Schmitz and Richardson 1991). Some fraction of the wind-driven gyre flow does not enter the Caribbean Sea to feed the Florida Current, but flows northward in a western boundary current to the east of the Bahamas (in what is sometimes called the Antilles Current, though it does not represent a continuous flow along the Antillean Archipelago). In the context of model validation, this leads to at least two problems. First, even after several years of current meter measurements, there is considerable uncertainty about the mean transport due to a strong variability on monthly time scales, associated with a meandering of the current axis (Lee et al. 1990); recent estimates seem to converge at 5–10 Sv (at 26.5°N). Second, in model simulations the fraction of the flow entering the Caribbean through the narrow island passages must be sensitive to details of the topography, friction, etc. The situation for the 1/3-degree CME model is illustrated in Fig. 1, showing the mean flow in the western subtropical North Atlantic at 232 m and 2125 m, and Fig. 2, showing a zonal section of the mean meridional velocity at 26°N.

According to the situation described above a quantitative model-data comparison concerning the wind-driven transport in the subpolar gyre cannot focus on the Florida Current; it has to be based on the total northward transport in the western boundary currents (WBQ to the west and east of the Bahamas. Present estimates for this are 35–40 Sv (and one can expect the uncertainties to decrease over the next several years due to ongoing measurement programs east of the Bahamas). In addition we need information about the fraction of the total WBC transport associated with the thermohaline overturning. (Model results indicate that at this latitude, because of the confinement of the deep flow to the western boundary, the total northward transport may in good approximation be considered as a linear superposition of a thermohaline and a wind-driven part.) From zonal, transatlantic hydrographic sections along 25°N the overturning is estimated to be about 15 Sv, leaving 20–25 Sv for the net contribution of the wind-driven gyre to the northward, upper-layer flow at the western boundary. The transport budget at this latitude is schematically illustrated in Fig. 3.

CME experiments have been carried out with four different, monthly mean wind stress climatologies: the stresses based on historical marine observations given by:

(i) Hellerman and Rosenstein (1983); in the following denoted HR;
(ii) Isemer and Hasse (1987), denoted IH;
(iii) the model stresses given by Trenberth et al. (1990) based on their analysis of the 1000 mb winds of the ECMWF for the period 1980 - 1986, denoted ECMWF;
and
(iv) monthly mean stresses from a 10 yr. control integration of NCAR's Climate Community Model 2; denoted CCM2.

A more detailed discussion of the mean circulation in these experiments may be found in Bryan et al. (1994). The wind stress climatologies in (i) and (ii) are compared in Böning et al. (1991b). The interesting question in the present context is to which extent these climatologies lead to differences in the transport of the subpolar gyre in the North Atlantic. As outlined above, this may be boiled down to a single number: the southward transport in the upper layer (top 1000 m) at 25°N, between the coast of Africa and the eastern edge of the WBC east of the Bahamas. The results are

24 Sv for HR
31 Sv for IH
25 Sv for ECMWF
19 Sv for CCM2.

These numbers represent averages over several years of integration. (For a discussion of the interannual variability see Bryan et al., 1994.) Comparison with the observed wind-driven transport indicates IH to be too strong, HR and ECMWF about right, and CCM2 somewhat too weak at this latitude.

In summary, it is important to stress the singularity of the situation at 25°N: it represents the only latitude in the North Atlantic where we both have fairly good information on the total volume transport and can, to a good approximation separate the relative contributions from the thermohaline and wind-driven flows. It is important to stress also, that for a model-data comparison a circulation model with sufficiently fine grid spacing to resolve the WBC system is required; and that a comparison can not be based on the well-measured Florida Current alone, but has to take into account the significant, but less-known transport to the east of the Bahamas.

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Figure 1a: CME model estimate of mean flow in the western subtropical North Atlantic, at 2125 m depth.

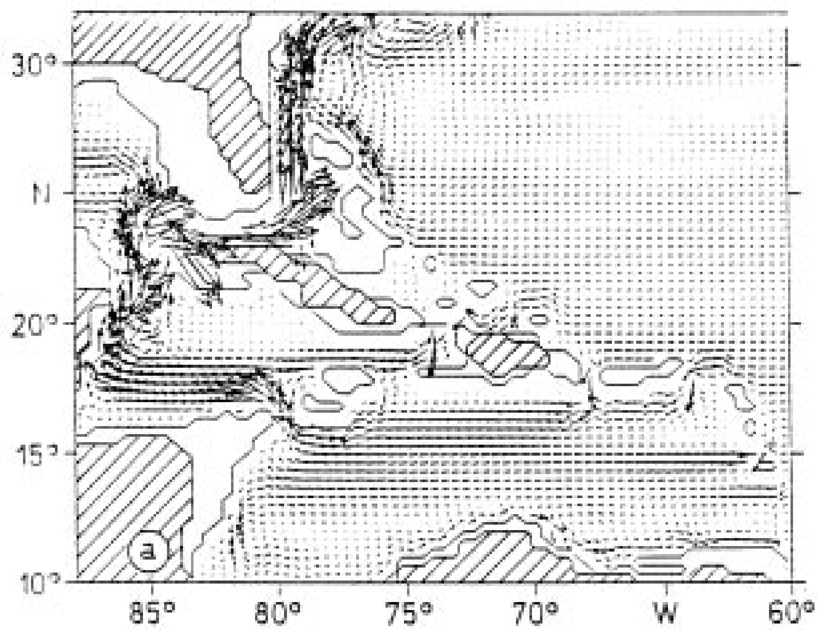

Figure 1b: CME model estimate of mean flow in the western subtropical North Atlantic, at 2125 m depth.

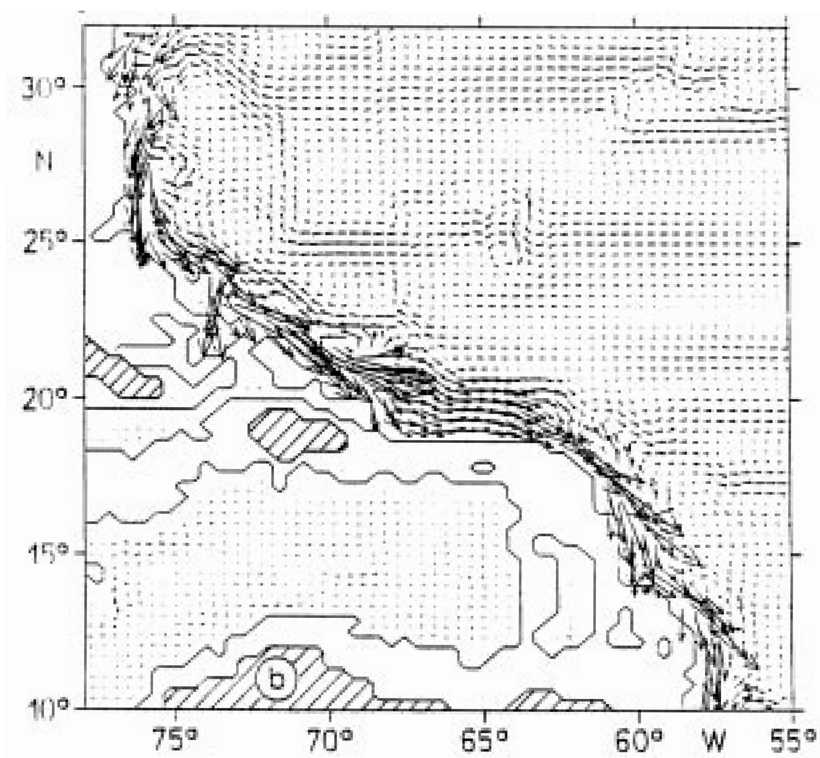

Figure 2: Zonal cross-section of mean meridional velocity near 26°N.

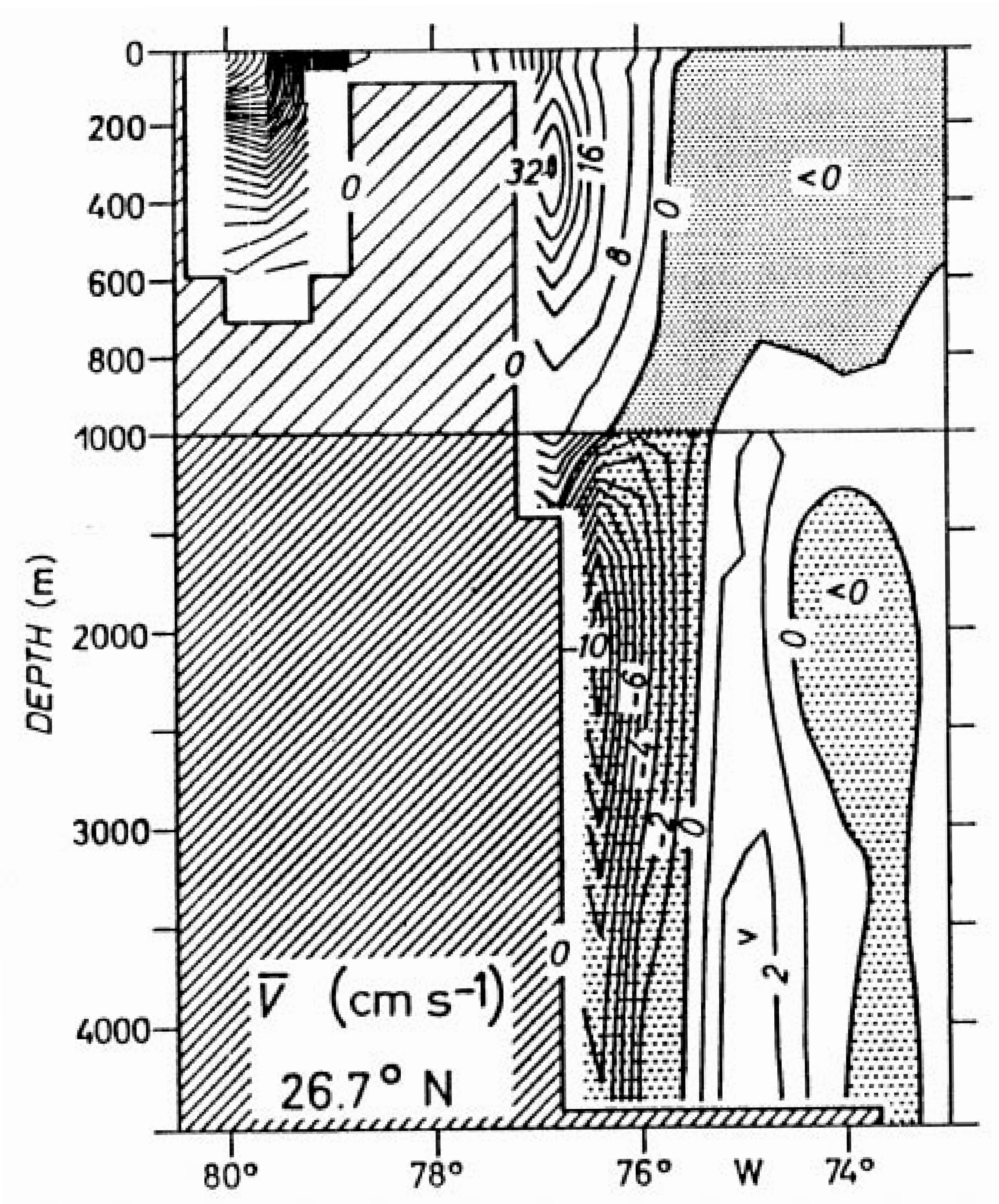

Figure 3: Ocean transport budget at 26°N. Values is Sv.