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Seasonal cycle of meridional heat transport in the subtropical North Atlantic: a model intercomparison in relation to observations near 25°N

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Abstract

Three different, eddy-permitting numerical models are used to examine the seasonal variation of meridional mass and heat flux in the North Atlantic, with a focus on the transport mechanisms in the subtropics relating to observational studies near 25°N. The models, developed in the DYNAMO project, cover the same horizontal domain, with a locally isotropic grid of 1/3° resolution in longitude, and are subject to the same monthly-mean atmospheric forcing based on a three-year ECMWF climatology. The models differ in the vertical-coordinate scheme (geopotential, isopycnic, and sigma), implying differences in lateral and diapycnic mixing concepts, and implementation of bottom topography. As shown in the companion paper of Willebrand et al. (2001), the model solutions exhibit significant discrepancies in the annual-mean patterns of meridional mass and heat transport, as well as in the structure of the western boundary current system.

Despite these differences in the mean properties, the seasonal anomalies of the meridional fluxes are in remarkable agreement, demonstrating a robust model behavior that is primarily dependent on the external forcing, and independent of choices of numerics and parameterization. The annual range is smaller than in previous model studies in which wind stress climatologies based on marine observations were used, both in the equatorial Atlantic (1.4 PW) and in the subtropics (0.4–0.5 PW). This is a consequence of a weaker seasonal variation in the zonal wind stresses based on the ECMWF analysis than those derived from climatologies of marine observations.

The similarities in the amplitude and patterns of the meridional transport anomalies betwen the different model realizations provide support for previous model conclusions concerning the mechanism of seasonal and intraseasonal heat flux variations: they can be rationalized in terms of a time-varying Ekman transport and their predominantly barotropic compensation at depth. Analysis for 25°N indicates that the net meridional flow variation at depth is concentrated near the western boundary, but cannot be inferred from transport measurements in the western boundary current system, because of significant and complex recirculations

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over the western half of the basin. The model results instead suggest that the main requirement for estimating the annual cycle of heat flux through a transoceanic section, and the major source of error in model simulations, is an accurate knowledge of the wind stress variation.

Contents

1. Introduction

The northward transport of heat in the Atlantic Ocean represents an essential factor both in the planetary energy budget and for the regional climate in northwestern Europe. While considerable progress has been made in quantitatively determining the pattern of ocean heat transport on the basis of available transoceanic hydrographic sections and advancing methodologies (MacDonald & Wunsch, 1996), there are still considerable uncertainties because of fundamental limitations in the oceanic data base. One issue is the representativeness of a single hydrographic section for estimating long-term 'mean' fluxes of an ocean circulation governed by a wide spectrum of low-frequency fluctuations. Of particular concern has been the potential effect of the large annual signal, first noted in the indirect estimates of global ocean transports by Oort and Vonder Haar (1976), Carrissimo, Oort and Vonder Haar (1985) and Hsiung, Newell and Houghtby (1989), Carrissimo et al. (1985) and Hsiung et al. (1989). All these calculations indicated a huge annual variation for the tropical ocean, with northward transport anomalies in boreal winter. However, Hsiung et al. (1989) differed from the earlier studies in noting a different phase for the subtropics, which was more in line with the patterns of heat flux variation suggested by earlier model studies (Bryan, 1982; Sarmiento, 1986).

For the North Atlantic at 25°N, Hsiung et al. (1989) obtained a winter (January) minimum in the northward heat transport, which had an annual range of about 1 PW. This is in rough agreement with more recent attempts to estimate monthly heat transports quasi-directly, by utilizing the seasonal climatological hydrographic data base (Levitus, 1982), in conjunction with the moored measurements of the seasonal velocity and temperature variations of the western boundary currents at 26.5°N. The first attempt by Molinari, Johns and Festa (1990) used current meter data only for the Straits of Florida, and found a mean heat transport of 1.21±0.34 PW, ranging from a low of 0.81 PW in February to a high of 1.63 PW in August. Fillenbaum, Lee, Johns and Zantopp (1997), by including the annual cycle of the boundary current system (Antilles Current and Deep Western Boundary Current) east of the Bahamas determined by Lee, Johns, Zantopp and Fillenbaum (1996), arrived at a somewhat larger annual mean (1.44±0.33 PW), and a variation between 0.96 PW (February) and 1.86 PW (August).

Model studies have generally found an annual cycle of heat transport with a similar phase, but smaller amplitude than in these observational estimates. Inspection of various North Atlantic models, including a suite of sensitivity experiments carried out under the WOCE 'Community Modelling Experiment' (CME) indicated the wind forcing is the most decisive factor in determining the annual range in the subtropics (Böning & Herrmann, 1994, henceforth BH): eddy-permitting CME cases produced a range of about 0.4 PW with the wind stress climatology of Hellerman and Rosenstein (1983), but nearly 0.8 PW in the case of forcing with the climatology of Isemer and Hasse (1987). Similarly low values (0.3–0.4 PW) for models with HR forcing have also been reported by Sarmiento (1986), Philander and Pacanowski (1986), and Fillenbaum et al. (1997), the latter from another CME-case with HR-forcing.

A puzzling feature of these studies is the contribution resulting from the interior baroclinic flow. In the observational estimates based on the Levitus (1982) climatology this component accounts for about 0.3 PW of the total annual range (Molinari et al., 1990; Fillenbaum et al., 1997). Support for the existence of an annual signal in baroclinic heat flux of that magnitude is provided by a recent analysis of another climatology and four synoptic sections between 24° and 26°N (Baringer & Molinari, 1999). This observational evidence appears in striking contrast to model solutions for which the basic characteristics of the annual cycle have generally been found consistent with a mechanism identified by Bryan (1982). It can be understood in terms of wind-driven mass transport variations in the meridional-vertical plane: transport anomalies induced in the surface (Ekman) layer by the seasonal cycle of the zonal wind stress are compensated by nearly depth-independent return flows, i.e., without any significant baroclinic adjustment except for a narrow equatorial belt. The significance of seasonal, top-to-bottom anomalies in meridional overturning has been confirmed in a variety of models: in CME results for the North Atlantic (BH) as well as in a number of Indian Ocean simulations (Wacongne & Pacanowski, 1996; Garternicht & Schott, 1997). A comprehensive analysis of the mechanisms has been provided by Lee and Marotzke (1998) based on a GCM inversion of Indian Ocean hydrography with seasonal data and forcings: a dynamical decomposition of both the meridional overturning and the heat transport into contributions equivalent to the 'barotropic', 'Ekman' and 'baroclinic' components defined by Hall and Bryden (1982) showed that the time-varying Ekman flow plus its barotropic compensation can explain a large part of the seasonal variation in the net meridional transports.

Understanding the mechanism of heat transport variations, in particular, the role of an interior baroclinic signal is obviously of great relevance for assessing the representativeness of transport estimates from one-time hydrographic sections. Theoretical considerations (Gill & Niiler, 1973) and model studies suggest that the seasonal variation in meridional transport of heat in extratropical latitudes has little impact on changes in heat storage. An oceanic response to seasonal and intraseasonal atmospheric forcing according to these results would imply that the geostrophic shear observed in one-time hydrographic sections should still reflect the longer-term mean conditions (BH), in apparent conflict with the observational analyses of Molinari et al. (1990), Fillenbaum et al. (1997) and Baringer and Molinari (1999). Obviously, numerical model deficiencies are a plausible cause behind this discrepancy: the possibility of systematic model errors represents a main motivation for the present study.

Concern about some hidden, systematic model errors is raised especially by the fact that virtually all previous studies of seasonal heat transport variations have been based on a single class of numerical model, i.e., adaptations of the GFDL model (Cox, 1984; Pacanowski, Dixon & Rosati, 1991). Model intercomparisons with both coarse resolution (Marsh, Roberts, Wood & New, 1996; Chassignet, Smith & Bleck, 1996) and with eddy-permitting resolution, as in the DYNAMO project (Willebrand et al., 2001), demonstrate there are significant differences between different numerical models both in the patterns of the annual-mean and zonally-integrated fluxes of mass and heat, and in the structure of the western boundary currents where the meridional transports are concentrated. If, on the other hand, the seasonal variability can be understood in terms of a linear, wind-driven mechanism, differences in the structure of the mean, thermohaline-driven circulation should have no effect. Indeed, the comparison by Chassignet et al. (1996) of various realizations of a geopotential and an isopycnic model at 1°-resolution showed little differences in the seasonal variations, despite strong discrepancies in the mean overturning and heat transport.

In this study we revisit the question of the annual cycle of heat transport in the subtropical North Atlantic on the basis of the three numerical models that have been developed in the DYNAMO project (DYNAMO Group, 1997). There are two main goals. Firstly, we want to test the robustness of previous model conclusions about the mechanism of the seasonal variability by comparing models that differ in a number of potentially important factors: vertical coordinate scheme (geopotential, isopycnic and sigma coordinates) and, associated with that, the implementation of bottom topography, parameterization of surface mixed layer processes and parameterization of lateral mixing. Secondly, we want to complement the earlier studies by examining the relationship between variations in the net, zonally-integrated transports (which cannot be observed directly) and the transports in the flow regime near the western boundary. The seasonal and intraseasonal variations of the mass transport in the western boundary regime appear fairly well understood, based on a host of model studies (Anderson & Corry, 1985a,b; Greatbatch & Goulding, 1989; Smith, Boudra & Bleck, 1990; Böning, Döscher & Budich, 1991) and recent multi-year current meter measurements across the Bahamas Escarpment at 26.5°N (Lee et al., 1996), their role in variations of the net, zonally-integrated transport of heat is still under debate.

2. Model experiments

The study uses three primitive equation models of the Atlantic Ocean between 20°S and 70°N based on different concepts for the discretization of the vertical coordinate: a geopotential level (z-coordinate) model, originally based on the GFDL-MOM code (Pacanowski et al., 1991), an isopycnal model, based on the MICOM code (Bleck & Chassignet, 1994), and a depth-following sigma-coordinate model, based on the SPEM code (Haidvogel, Wilkin & Young, 1991). The models will henceforth be referred to as LEVEL, ISOPYCNIC and SIGMA, respectively. Their configurations are described in more detail in the companion paper by Willebrand et al. (2001); here we will note only the main aspects of particular relevance to the present study.

The models span the same horizontal domain, with a grid of $\delta\lambda$=1/3° in longitude λ and $\delta\varphi$=1/3° cos φ in latitude φ. The resolution of the locally isotropic grid thus varies from 37 km at the equator to 13 km at 70°N. While the models use the same boundary condition in the north, they differ in their southern boundary conditions. ISOPYCNIC and SIGMA are closed there and temperatures and salinities are restored to climatological values, similar to previous North Atlantic models; whereas LEVEL uses an open boundary condition in which temperature and salinity are prescribed only at inflow points. The effect of the southern boundary condition on the structure of the seasonal cycle will be assessed by a comparison of the LEVEL-solution with previous CME-studies that have used a geopotential model with a grid structure as in LEVEL, but with a similar boundary condition to that of in ISOPYCNIC and SIGMA.

Atmospheric forcing fields are derived from global 6-hourly ECMWF analyses (Barnier, Siefridt & Marchesiello, 1995; Siefridt, 1994). The basic model cases are driven by monthly-mean fields from averages over the years 1986–1988. The analysis is based on a five-year span following a 15-year spin-up period. In addition, two sensitivity experiments were performed with LEVEL that help to elucidate the role of wind stress variations: DAILY is forced by daily wind stresses for the period of 1987–1993, NO-WIND is a short 'spin-down' case where wind forcing was shut-off for a 3-year period. (The latter case also used a different specification of the vertically-integrated mass transport along the southern boundary than the reference experiment whose effect, however, was largely confined to the southern hemisphere.)

Wind-induced turbulence in the mixed layer is not explicitly accounted for in LEVEL and SIGMA, except in one sensitivity experiment. The minimum depth of the well-mixed layer is the uppermost grid cell (35 m) in LEVEL, and 50 m in SIGMA. Deeper mixed layers can be obtained following convective adjustment, as a result of cooling and/or evaporation but not through wind-induced mixing. The formulation in ISOPYCNIC is different, using a Kraus–Turner type mixed layer model, which also accounts for wind-induced deepening of the mixed layer. An implication of the mixed layer formulation in ISOPYCNIC is that the velocity within the mixed layer is always uniform with depth whereas in LEVEL and SIGMA a current shear may persist through the mixed layer.

The significance of wind forced convection for the seasonal heat budget was examined in a CME-sensitivity study by BH. Despite substantial effects on the annual cycle of mixed layer depth and some modification of the annual range of heat content changes, the impact on heat transport variation was of relatively minor importance, e.g., negligible compared to the differences obtained by using alternative wind stress products. A similar result has been obtained in the present experiments: the impact of wind-induced mixing was explicitly considered in a sensitivity run with the geopotential model (referred to as LEVEL-KT; see Willebrand et al., 2001) which included the mechanical part of a Kraus–Turner bulk parameterisation scheme. Because the impact on the large-scale velocity fields was rather small, the experiment does not add to the conclusions of this study and will not be reported here.

3. Seasonal heat transport and overturning

Fig. 1 displays the differences in northward heat transport between the winter (defined as the 5-year mean over the period January–March) and summer seasons (July–September) for the three

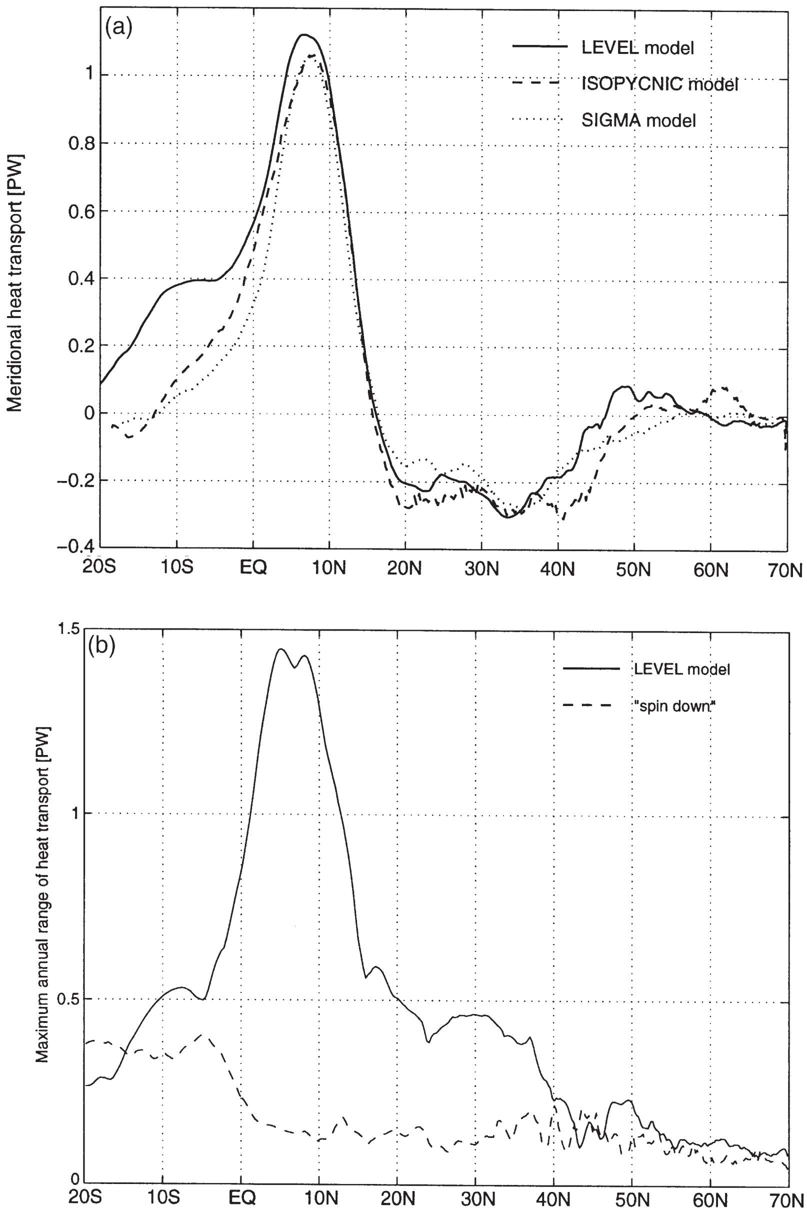


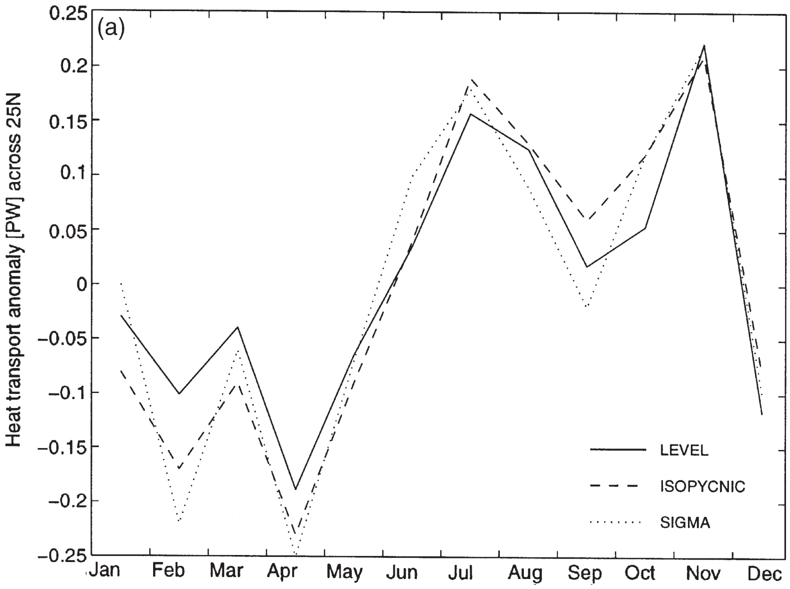
Fig. 1. (a) Difference in 5-year mean northward heat transport between winter (January–February–March) and summer (July–August–September), for three DYNAMO cases with monthly mean forcing based on ECMWF analyses for 1986–1988. (b) Annual range of heat transport, defined as the difference between maximum and minimum monthly mean heat transports for each latitude: the LEVEL case as in (a), and the third year of the spin-down experiment NO-WIND.

basic DYNAMO experiments. In striking contrast to the situation for the annual mean transports in which the models deviate quite substantially (Willebrand et al., 2001), the patterns of seasonal variation are very similar. The latitudinal dependence of the transport anomalies agrees with previous model studies: the equatorial Atlantic is characterized by seasonal heat transport anomalies directed from the summer to the winter hemisphere, while in the subtropics the maximum northward heat transport occurs in summer. The maximum amplitude is found at 6–8°N, corresponding to the changes in heat content to the north and south of the seasonally-varying North Equatorial Counter Current (NECC) (Philander & Pacanowski, 1986; Sarimento, 1986). A comparison of CME sensitivity experiments with previous model solutions indicated that the simulated amplitude in this regime is strongly affected by two factors: the wind forcing and the latitudinal grid spacing (BH). The annual range in the NECC regime (Fig. 1b) in the DYNAMO cases based on the ECMWF forcing is less than 1.5 PW, significantly smaller than derived in models using a comparable horizontal resolution, but with forcing based on the marine wind stress climatologies of HR or IH, that have resulted in typical ranges of 2 or 2.5 PW, respectively. The similarity between the DYNAMO solutions implies that model choices such as vertical coordinate schemes, parameterizations for vertical and lateral mixing, and the surface mixed layer scheme, have a negligible influence on the seasonal cycle.

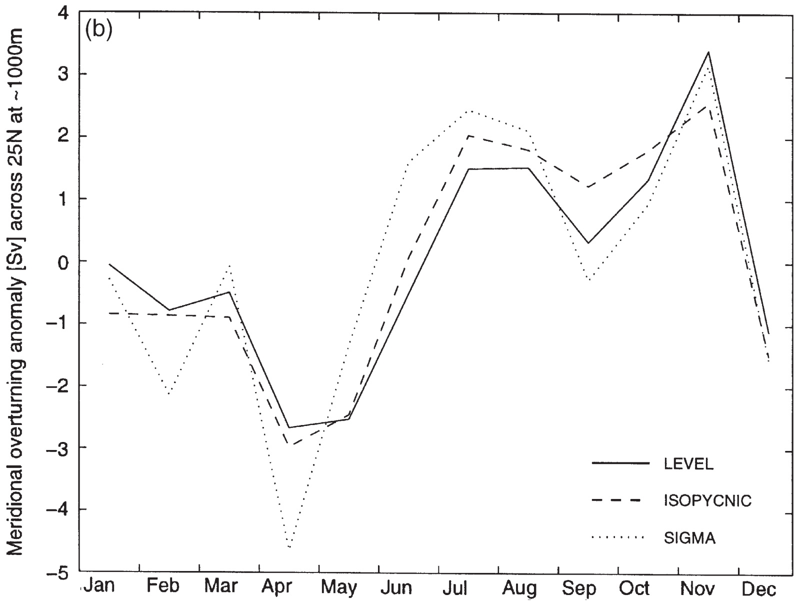
In the subtropics and at higher latitudes the amplitude of the seasonal variation is smaller and the phase differs from the tropical regime, with an enhancement in northward heat transport during summer. The only region where the model solutions show some divergence is in the southern hemisphere where LEVEL yields a much stronger northward transport anomaly than the other two models. As discussed below, this deviation is associated with a different seasonal cycle of the deep meridional currents and can be attributed to the different formulation of the southern boundary condition. The annual range reaches a maximum of about 0.5 PW near 30°N (0.4 PW at 25°N), which is not very different from previous model cases with HR forcing (Sarmiento, 1986; Fillenbaum et al., 1997), but smaller than those cases with IH forcing (0.7–0.8 PW between 25° and 30°N, as reported in BH).

The role of the wind stress as the prime factor causing the seasonal variation is emphasized by the corresponding result of NO-WIND (Fig. 1b). In the last (third) year of this experiment the amplitude had dropped to about 0.1 PW in the tropical and subtropical North Atlantic. (The behavior south of the equator should not be interpreted in this context because of different formulation for the southern boundary condition in NO-WIND.)

The similarity between the DYNAMO models is not restricted to the seasonal mean patterns, but is also manifested in the time series of heat transport. A comparison for 25°N is given in Fig. 2a, showing monthly mean heat transport anomalies for the three basic model cases. The seasonal cycle is less smooth than in previous model solutions, probably an effect of the rather short (3-years) analysis period used for the calculation of the monthly mean wind stresses. It is interesting to note, however, the close correspondence between the variations in the zonally-integrated transports of heat and mass: as a measure of the seasonal cycle of the overturning circulation at this latitude, Fig. 2b depicts the monthly mean, 1000 m-values of the zonally-integrated transport streamfunctions for the three model cases. (In all three models, the separation of the northward, upper-layer flow and the southward, lower-layer flow occurs near 1000 m, see Fig. 1 in Willebrand et al., 2001) The correlations between the heat transport anomalies are 0.92 for LEVEL, 0.94 for ISOPYCNIC, and 0.96 for SIGMA, respectively.



25°N Heat transport anomalies



25°N/1000 m Overturning anomalies

Fig. 2. Annual cycle at 25°N of 5-year monthly mean anomalies in zonally-integrated meridional transports, (a) of heat, (b) of mass above 1000 m.

In order to examine the mechanisms of the heat transport variation, the net advective transport H across a given latitude, which is given by the covariance of meridional velocity v and potential temperature T across the zonal extent of the basin, may be decomposed in two different ways. One is to split the variables into their zonal means and deviations, thus yielding the contributions to H by the overturning circulation in the meridional–vertical plane (H_{OT}), and the correlations of the v and T anomalies in the horizontal plane (H_{GY}). The alternative, which is the basis of the 'direct' method for calculating heat transports in the ocean as developed by Bryan (1962), is to split the variables into their depth-averaged parts and deviations, partitioning the heat transport into its 'barotropic' (H_{BT}) and 'baroclinic' components. For practical purposes (i.e., estimation based on hydrographic section data) the latter is defined as consisting of the contributions from geostrophic flows in the ocean interior (H_{BC}), together with a wind-driven component (H_{EK}), provided by the Ekman transport at the surface and a compensatory flow at depth that has to be postulated to assure zero net mass flux for each of the components.

It should be noted that the definition of H_{EK} involves inherent ambiguities as a result of the necessary specification of the vertical profile of the flow related to the Ekman volume transport. Firstly, there is some quantitative uncertainty in estimating Ekman temperature fluxes because of the possibility that part of the ageostrophic, wind-driven flow at the surface may penetrate below the mixed layer, which would imply a transport-weighted temperature less than the surface temperature (Chereskin & Roemmich, 1991). Further fundamental uncertainty arises through the necessity of specifying a temperature for the deep return flow. While this is of no consequence for the net heat transport, i.e., the sum of H_{BC} and H_{EK}, it clearly affects the distribution of heat transport between the two. Accordingly, the individual components of this partition are useful in the calculation of heat transport from (observed) section data, but have little physical meaning per se. In particular, H_{EK} cannot, a priori, be considered as quantitatively representing the effect of the Ekman transport on meridional heat transport. As suggested by the previous model analyses, in the annual mean case, prescription of the depth-averaged temperature for the return flow leads to a gross over-estimation of the Ekman-transport contribution by H_{EK}, since the wind-driven cells tend to be closed near the surface, by baroclinic flows in the upper 200–400 m (e.g., Böning & Bryan, 1996). This may be different for wind-driven variability at seasonal or shorter time scales, i.e., as long as there is little baroclinic compensation and the deep compensatory flows are weakly depth-dependent: in that case a formal calculation of H_{EK}, with the assumption that the transport-weighted temperature is given by the vertically averaged temperature, may indeed approximate to the effect of the seasonal wind-driven overturning cells.

The alternative decompositions of H are presented (for LEVEL only) in Figs 3a and b. The results are in agreement with previous model studies. The variation in the net transport H can be understood primarily in terms of a variation in the overturning component (H_{OT}). The contribution by H_{GY} is negligible, and has an amplitude of about 0.05PW, and a phase that is quite different from H_{OT}. In turn, the variation of H_{OT} or, equivalently, H appears to resemble rather closely the H_{EK}-term in the alternative partition. (In the calculation of H_{EK}, the surface (mixed layer) temperature and the depth-average temperature were taken.) The other two terms in Fig. 3b are quite variable, with a tendency for extrema of opposite sign. The outcome, rather than providing an interpretation of the physical mechanism, should probably be regarded more as a manifestation of the artificial nature of the decomposition.

Because of the dominant role of H_{OT}, it is instructive to turn to a closer inspection of the

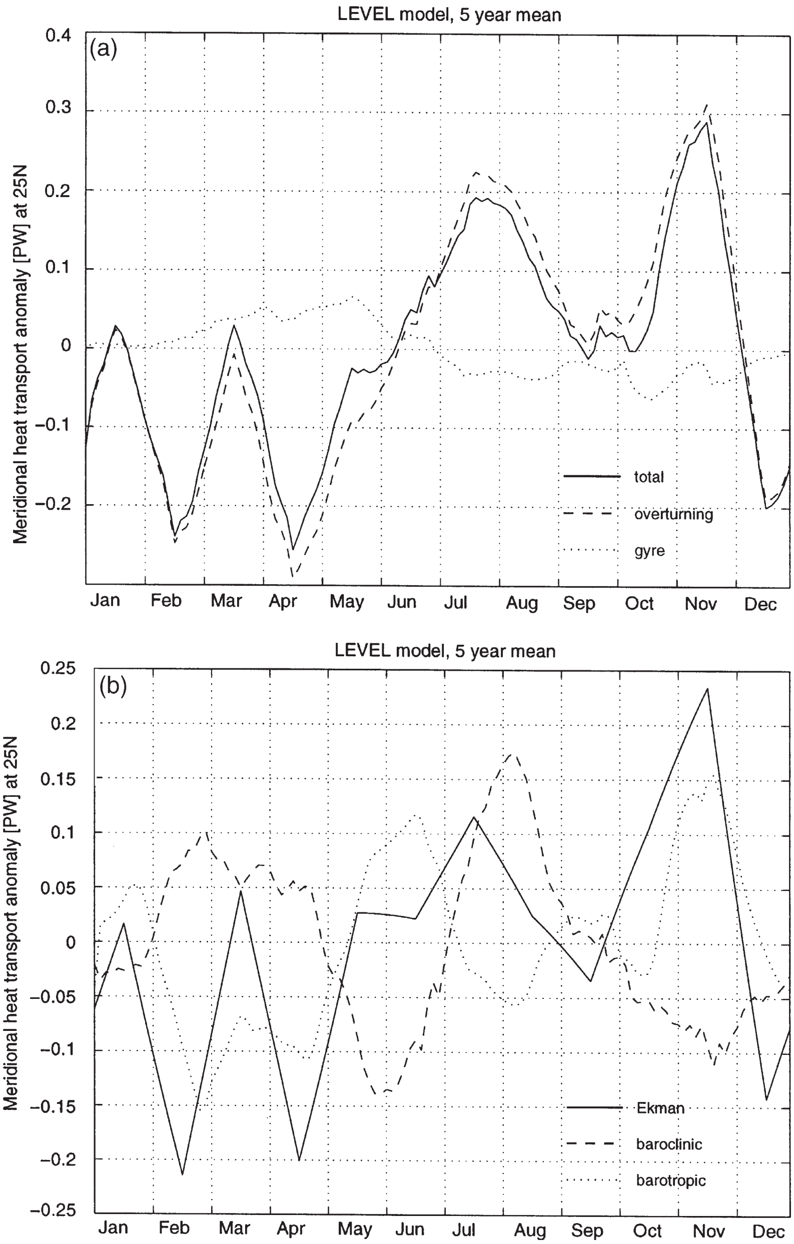


Fig. 3. Annual cycle of 5-year daily mean heat transport anomalies for LEVEL. (a) Total transport H and its partition in H_{OT} and H_{GY}, (b) partition in H_{BT}, H_{BC} and H_{EK}.

patterns in the seasonal variation of meridional overturning (Fig. 4) and its relation to the wind forcing (Fig. 5). Except for the deep ocean south of the equator and, again, in striking difference to the annual mean distributions discussed by Willebrand et al. (2001), there is a similar structure in all models, with deep-reaching seasonal overturning cells in the tropics and, with opposite

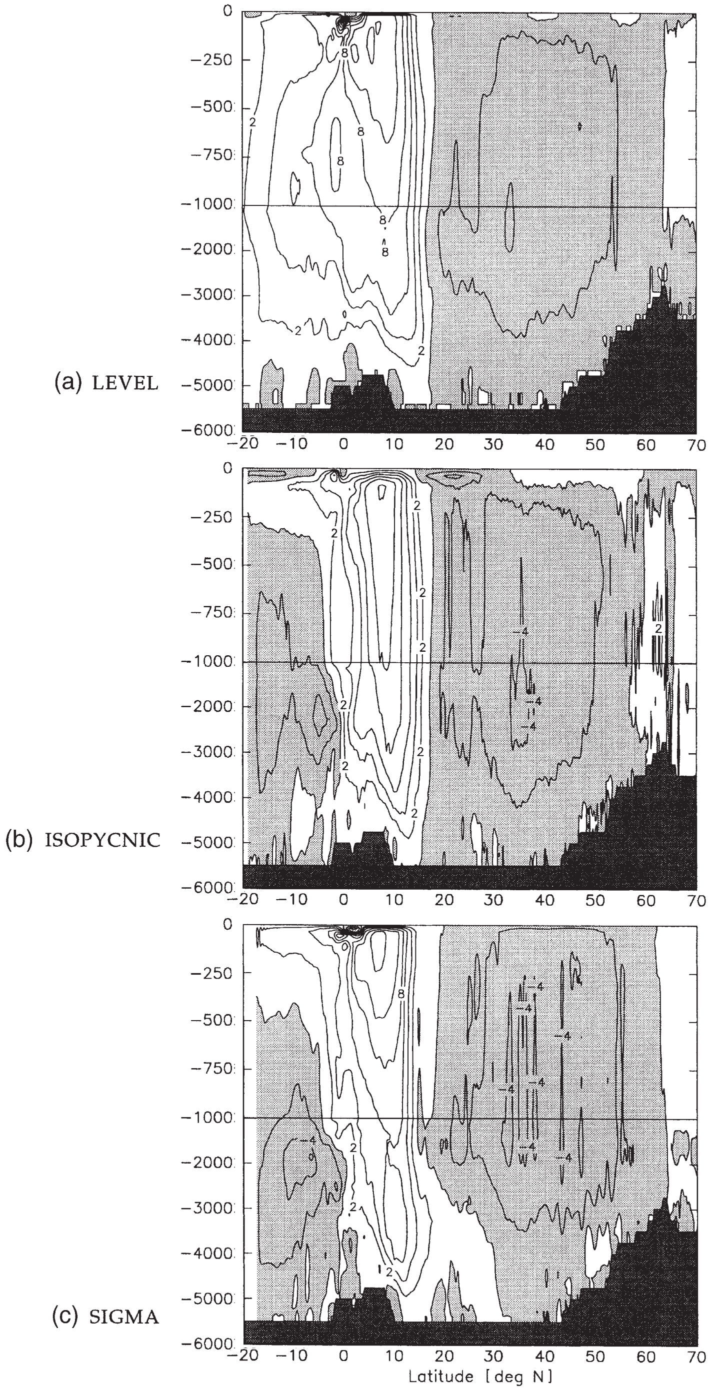


Fig. 4. Difference between winter and summer (5-year means) in the streamfunction of zonally-integrated volume transport, for (a) LEVEL, (b) ISOPYCNIC, (c) SIGMA. Contour interval is 2 Sv.

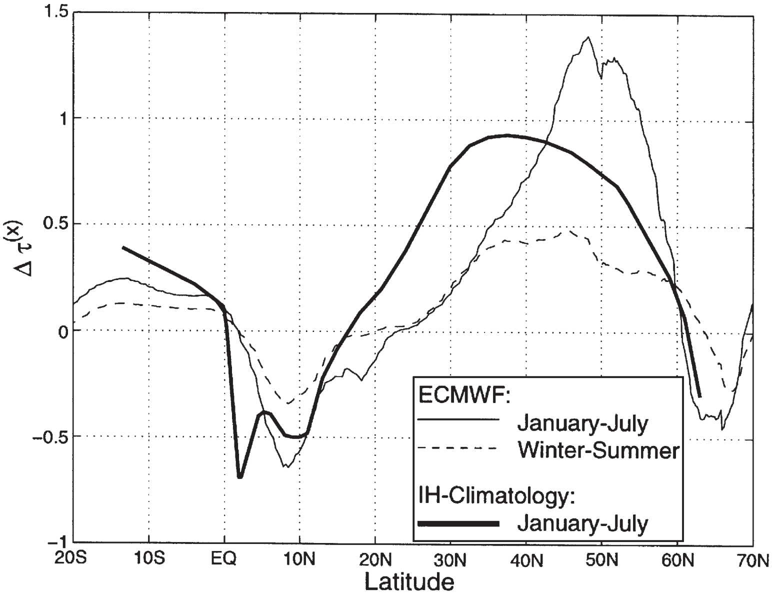


Fig. 5. Seasonal variation in zonal wind stress, averaged over the width of the Atlantic Ocean. Displayed are: the winter–summer and January–July differences for the 3-year mean ECMWF stresses used in this study, in comparison to the January–July difference of the marine wind climatology of Isemer and Hasse (1987) used in the CME-study of BH.

phase, in the midlatitudes. The latitudinal distribution of the meridional transport anomalies near the surface is clearly related to the seasonal changes in zonal wind stress which forces southward (northward) Ekman flow anomalies north (south) of about 15°N. While the basic latitudinal pattern of the seasonal wind stresses appears similar to the marine climatologies discussed in BH, the amplitude of the annual cycle in the ECMWF-based stresses is significantly smaller over the subtropical North Atlantic (Fig. 5).

A prominent aspect of the streamfunction patterns (Fig. 4) is the extension of the seasonal flow anomalies over the whole water column that is consistent with the previous model studies. While the different DYNAMO models appear similar in the amplitude of the seasonal cycle in the midlatitudes, there are some differences in the deep vertical structure of the transport anomalies in the tropics which, however, have minor effects for the transport of heat. A more comprehensive examination of the model behavior in the equatorial regime needs to include a discussion of the role of baroclinic modes and their interactions with the western boundary regime. However, this is outside the scope of the present paper and will be subject of a separate study.

While LEVEL reveals a coherent cell over the whole tropical Atlantic, both SIGMA and ISOPYCNIC differ radically south of the equator. A comparison with the CME-analysis of BH suggests that this difference in behaviors is probably unrelated to the different numerical models, but is mainly a consequence of the closed southern boundary in SIGMA and ISOPYCNIC. With the same numerical model and similar grid resolution as used in LEVEL, but with a closed wall (at 15°N) and relaxation to the seasonal Levitus climatology as in SIGMA and ISOPYCNIC, the CME cases exhibited a similar, counter-rotating cell south of the equator. Since these deep cells are not connected to the surface, they must be regarded as an effect of the imposition of seasonal hydrographic data near the southern boundary. The model response suggests that restoring to a climatology may induce spurious seasonal variation in the deep density field, corresponding to a geostrophic, meridional flow signal sufficiently strong to overcome the effect of the local wind forcing. In contrast to the boundary dominated cases, the pattern of the wind-induced overturning anomalies in the case of LEVEL appears to be consistent with the observed deep boundary current transport at 18°S, which includes an apparent seasonal signal with a maximum southward transport around February and a minimum around September (Weatherly & Kim, 1998).

If the emergence of weakly depth-dependent meridional overturning anomalies can be attributed to the fact that the slow phase speeds of extra-tropical baroclinic Rossby waves, effectively prevent a baroclinic compensation to wind-driven flow variations at the surface, a similar response pattern must be expected on even shorter, intraseasonal time scales. Figures 6a and 6b display time-series of heat transport and overturning at 25°N for a 3-year period of DAILY. Both integral quantities show a pronounced response to the synoptic variability in the atmospheric forcing. Oscillations on timescales of a few days to weeks are dominant, effectively masking any annual or longer-period signal. The covariance spectrum (Fig. 6c) reveals a high coherence between the overturning and heat transport anomalies throughout the frequency range resolved by the 3-d sampling, i.e., coherence exceeds 0.9 for periods larger than 8 days, and is 0.7 for the Nyquist frequency (6 days).

4. Variability of western boundary currents

While the zonally integrated patterns of the wind-driven transport anomalies appear to have a rather simple spatial structure, they actually represent the net effect of a complicated set of meridional current anomalies. Conceptually, the variations in the meridional mass transport of a mid-latitude ocean basin in response to seasonal and intraseasonal wind forcing may be understood in two, complementary ways. The one followed so far has been based on the momentum balance and has involved consideration of meridional Ekman transport and its compensation at depth. It is useful to rationalize the principle mechanism of seasonal heat transport variations in ocean models, but it cannot provide an interpretation of the behaviors of individual current systems which, for example, is a basis necessary for comparing model results with observations.

Alternatively, the variation of the horizontal mass transport in response to anomalies in the wind stress curl may be considered. Theory suggests that at mid-latitudes the response should primarily be barotropic and rapidly transmitted to the western boundary by barotropic Rossby waves. As predicted by a host of model studies following the work of Anderson and Corry (1985a,b), recent observations (Lee et al., 1996) have indeed found a large annual signal in the transport of the boundary current system to the east of the Bahamas at 26.5°N. The amplitude and phase of the mean annual cycle were similar to that expected from the Sverdrup balance (using wind stresses from climatologies based on marine observations), with a maximum northward transport in winter and minimum in fall. The annual amplitude for the net, top-to-bottom transport found in both observations and model studies is about ±13 Sv, the bulk of which associated with the DWBC. In actual transport time series, both in model solutions (Böning et al., 1991) and observations (Lee, Johns, Schott & Zantopp, 1990; Lee et al., 1996), strong, stochastic fluctuations on timescales of 70–100 days are superimposed upon this signal. The transport in the Florida Straits is effectively shielded from the predominantly barotropic signal to the east of the

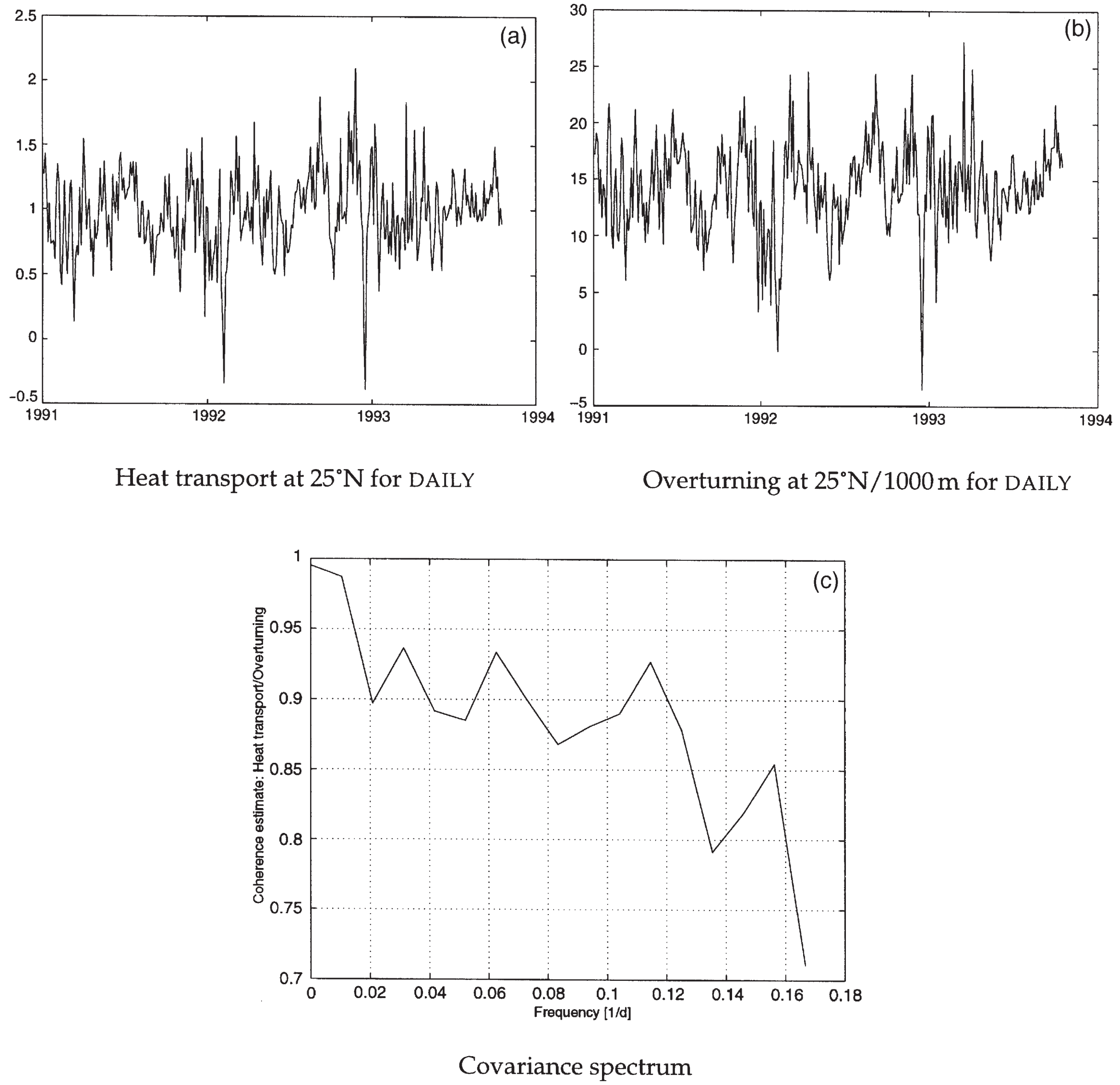


Fig. 6. Time series of 3-day values for the last three years of DAILY of northward heat transport (a) and 1000 m-overturning streamfunction (b) at 25°N; (c) spectrum of the covariance between the heat transport and overturning anomalies.

Bahamas, and it exhibits its own annual signal, with a maximum in July–August and minimum in October–November, responding to variations in the local, meridional wind stress (Anderson & Corry, 1985a; Schott, Lee & Zantopp, 1988; Böning et al., 1991). Its annual range is 4.7 Sv according to the 9-year time series of cable measurements analysed by Larsen (1992).

Of particular interest to the present model analysis is the question of how this annual signal in the boundary currents can be reconciled with the (much smaller) signal in the zonally-integrated transport. Is there a relation between the net, zonally-integrated seasonal transport anomalies which determines the heat transport variation across that latitude (but cannot be observed) and the transport of the western boundary current system, which is accessible to observations?

While the meridional flow anomalies in the surface (Ekman) layer are obviously distributed across the zonal extent of the ocean basin, the associated anomalies of the geostrophic flows below that layer may be concentrated near the western boundary, as a result of the fast adjustment process resulting from barotropic Rossby wave action. In Fig. 7 the zonal structure of the deep (below 1000m) transport anomalies is illuminated in two different ways, focussing initially on LEVEL only. The transport per unit longitude (Fig. 7a) exhibits peak values in the DWBC adjacent to the continental slope east of the Bahamas, near 78°W, with some oscillatory behavior to the east. In summer the southward transport density in the DWBC is enhanced. In Fig. 7b the cumulative transports (starting at the eastern boundary) are calculated for the two seasons. The transport by the DWBC between 78°W and 77° varies between about 17 Sv in winter and 25 Sv in summer. In both seasons, a significant fraction (about 7–8 Sv) of the DWBC recirculates west of 70°–71°W. During winter, an additional recirculation feature is found around 50°W, but it produces only a small change in the net, zonally-integrated transport between the two seasons, between −13.3 Sv in summer and −11.4 Sv in winter, i.e., the value appearing in the overturning anomaly shown in Fig. 4.

Apparently, knowledge of the DWBC variation alone is insufficient for inferring the seasonal change of the net, zonally-integrated transport at this latitude. This is illustrated in Fig. 7c, which shows the cumulated transport anomalies between winter and summer for all three models. Significant recirculating seasonal transports occur both in narrow cells close to the boundary and in wider cells extending across the western basin. There is general agreement between the three models in the seasonal changes of the DWBC and the net effect of the recirculation cells, resulting in the similarity in the variation of the net transports across the latitude circle. This does not extend, however, to there being a similarity in the zonal distribution of the meridional recirculation patterns. In the details of the flow structure we thus begin to see a manifestation of the differences in model concepts, implementation of bottom topography, and mixing parameterization.

Because of differences in the structuring of the seasonal current anomalies, it is somewhat difficult to define the areas in a zonal cross section representative for the Florida Current (FC), Antilles Current (AC), and DWBC regimes in all three models. (For the mean flow patterns near the western boundary see Fig. 6 in the companion paper of Willebrand et al., 2001). For a comparison of time series of meridional transport at about 26.5°N (Fig. 8) we have chosen to put the boundaries between the FC and AC regimes at 78°W, and between the AC and DWBC at 1000 m. In order to obtain meaningful measures of the net WBC transports, the eastward extension of the AC/DWBC-regime is put at 73°W, i.e., the integration is extended across most of the recirculation patterns in the models, thereby ameliorating the effects of the differences in the boundary current patterns.

Comparing the results for the three models (Fig. 8), we first note the significantly stronger month-to-month variability in SIGMA, both for the FC and for the regime to the east of the Bahamas. This behavior is reminiscent of the stochastic fluctuations discussed in the CME study of Böning et al. (1991) which arose because of instabilities in the boundary currents. Apparently, in SIGMA these fluctuations are of a much higher amplitude and are smoothed out to a lesser degree by a 5-year average than in the other two models; a behavior that appears to be consistent with the analysis of eddy dynamics in the western equatorial Atlantic presented in the companion

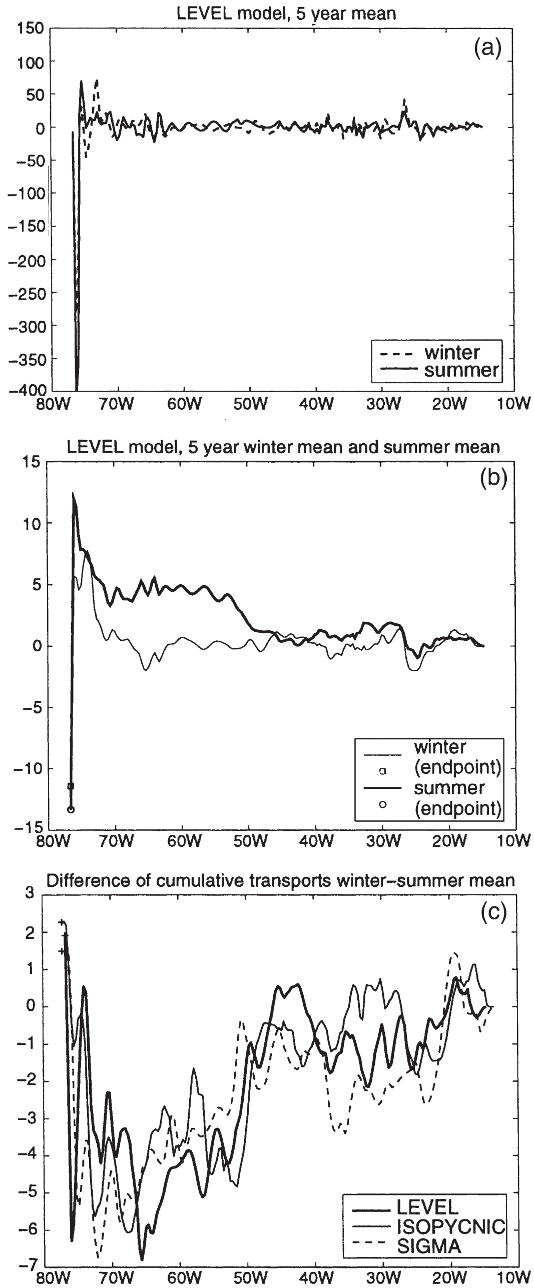


Fig. 7. Zonal distribution of 5-year seasonal mean meridional transports in the deep ocean (1000 m-bottom) near 26.5°N. (a) Transport per unit longitude, showing a concentration in the DWBC with a northward anomaly in winter (LEVEL). (b) Cumulative transports, starting at the eastern boundary, for winter and summer (LEVEL). (c) Cumulative transport difference (winter–summer), for all three models: The northward transport anomaly of about 8 Sv in the DWBC is to a large extent recirculated in a number of cells across the basin, leaving a net zonally-integrated transport difference of about 2 Sv (compare Fig. 4).

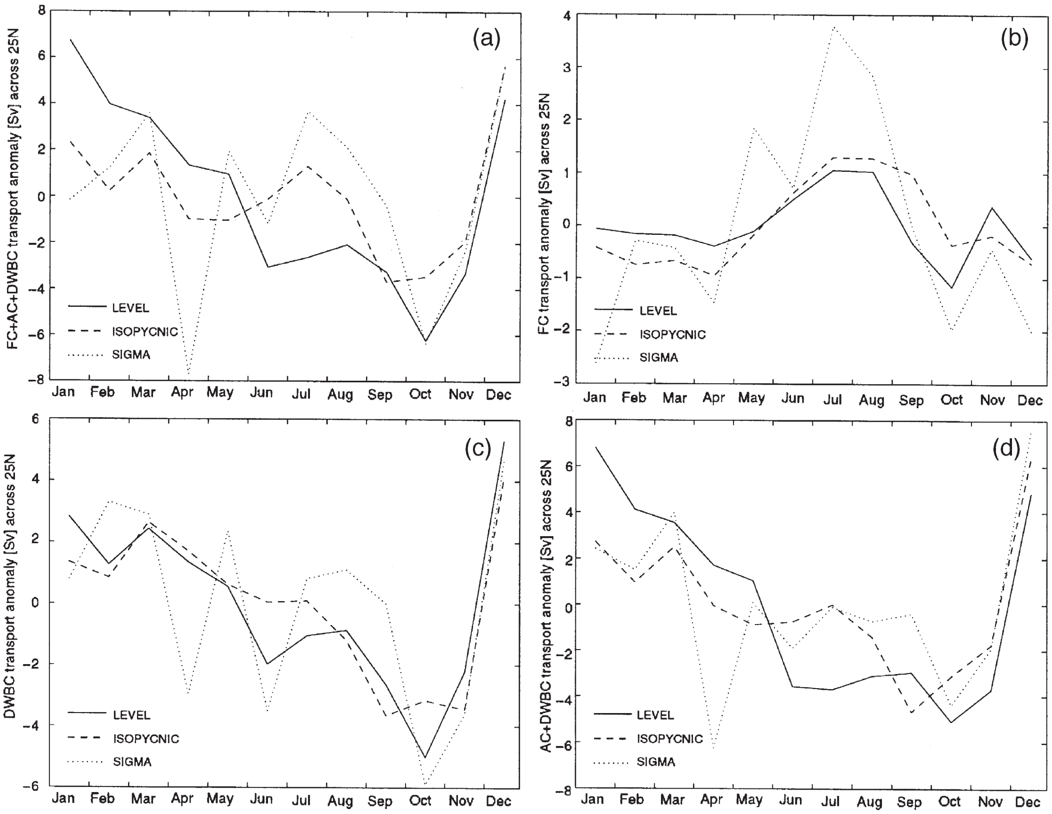


Fig. 8. 5-Year mean annual cycles of northward transport anomalies for (a) the whole western boundary regime comprised of the FC, AC, and DWBC; (b) the FC; (c) the boundary regime east of the Bahamas comprised of the AC and DWBC; (d) the DWBC.

paper by Barnier, Reynaud, Böning, Molines and Barnard (2001). Also contributing is the weaker effect of the Bahamian Archipelago as a barrier between the AC and FC systems as a result of the stronger topographic smoothing in SIGMA; meandering of the currents across our artificial computational boundary also leads to some spurious variability in the separate sections.

A comparison of the longer time scales, which may be attributed to the deterministic annual cycle, reveals much closer similarities between the three models, except for the amplitude in the FC (Fig. 8b). Compared to observations, the amplitudes for FC in both LEVEL and ISOPYCNIC are too small by at least a factor of two. However, interpretation of the quantitative model differences in this regime is difficult because of the relatively strong topographic smoothing of the Bahamian Archipelago in SIGMA. Whether the differences in model topographies, or, equally possible, the smaller frictional retardation characterizing this model (see, e.g., the discussion in Barnier et al., 2001) contributes to the increase in the annual variation, cannot yet be decided on the basis of this model realization.

The annual cycle to the east of the Bahamas is similar in all three models (Fig. 8c). The phase is much the same as in the observations (Lee et al., 1996) and previous model solutions, with a maximum northward transport anomaly in winter (December) and minimum in fall (October), which is consistent with what is expected if the annual cycle of the subtropical gyre transport is driven by the large-scale wind stress curl. The annual range of about 10 Sv, however, is smaller than in model solutions driven by either the HR or IH climatologies. Comparison with Fig. 8d shows that, as in the observations, a significant fraction of the total variation to the east of the Bahamas is contained in the DWBC. There is a general similarity between the models in this respect, suggesting that the differences in the detailed manifestation of the large-scale, wind-driven signal in the western boundary regime, resulting from interactions with topography, frictional boundary layers and eddies, are insignificant for changes in net meridional transport anomalies.

5. Summary and conclusions

The three different, eddy-permitting models of the Atlantic Ocean developed as part of the DYNAMO project, have been used to probe the robustness of previous conclusions concerning the mechanism of the seasonal cycle of meridional heat transport, and thus to shed light on a lingering controversy resulting from a fundamental discrepancy between model studies and recent observational analyses. The three models cover the same horizontal domain between 20°S and 70°N, with a locally isotropic grid of 1/3° resolution in longitude, and are subject to the same monthly-mean atmospheric forcing based on a three-year ECMWF climatology. The models are based on alternative concepts for the vertical discretization, using geopotential, isopycnic, and sigma coordinate schemes, respectively. This implies basic differences in the treatment of bottom topography, lateral boundary conditions, and lateral and diapycnic mixing schemes, including a different implementation of the surface mixed layer.

In striking contrast to the annual-mean behavior which exhibit significant differences in both large-scale transports and local flow patterns (Willebrand et al., 2001), the model results are in close agreement with respect to the major aspects of the seasonal variation in the meridional fluxes of mass and heat. All solutions with monthly-mean forcing are characterized by seasonal overturning cells in the tropical and subtropical Atlantic of the same structure and amplitude, except in the southern hemisphere as a result of different formulations of the southern boundary condition. Corresponding to that, the models exhibit a similar seasonal cycle of meridional heat transport in the tropical and subtropical North Atlantic, with a maximum annual range (about 1.4 PW) and winter maximum of northward transport in the NECC-regime around 6–8°N, and smaller annual range (about 0.4 PW), with different phase, for the subtropics around 25°N. The mean annual cycle of heat transport is highly correlated with the meridional overturning at this latitude; the amplitude of ±0.2 PW in heat flux corresponds to an amplitude of about ±3 Sv in meridional overturning at 25°N. Intraseasonal variability in the wind field, examined by forcing with daily ECMWF stresses in one of the models, induces much stronger changes, exceeding 25 Sv in overturning circulation and 2.5 PW in heat transport on time scales of a few weeks; there is a high coherence between these down to periods of 6–8 days. Both seasonal and intra-seasonal variability in meridional overturning and associated heat transport rapidly fades away in a spin-down experiment where wind forcing was shut-off; it is negligible in the third year of this experiment.

The similarity of model solutions with rather different mean flow patterns suggests an essentially linear mechanism governs the atmospherically-forced flow variability on seasonal time scales. Alternative choices of numerical algorithms and parameterization of subgrid physics have a negligible impact on the patterns and amplitude of the seasonal cycle simulated, demonstrating a robust model behavior with respect to the response to atmospheric forcing on these time scales. The solutions of the three different DYNAMO models therefore add to a remarkable consistency in model results concerning the mechanism of meridional flux variations on seasonal time scales.

In all models, the variation in total heat transport is largely given by variations in the overturning component, i.e., the correlation between the zonal mean potential temperature and the zonal mean meridional velocity. The seasonal cycle of heat transport can thus be understood in terms of wind-driven mass transport variations in the meridional–vertical plane, i.e., a mechanism proposed by Bryan (1982) and confirmed in both prognostic (BH) and inverse model calculations (Lee & Marotzke, 1998).

The mechanism of the seasonal cycle in heat transport has been under debate because of the discrepancy between CME model results and the observational analysis of Fillenbaum et al. (1997) for the subtropical North Atlantic near 25°N. In contrast to the models, the seasonal hydrographic climatology given by Levitus (1982) suggested that baroclinic flows in the interior make a significant contribution to the annual cycle. The role of this contribution is of course of great relevance to the question whether or not single hydrographic sections provide estimates of large scale interior density gradients that are representative of annual-mean conditions, i.e. the applicability of the classical ('direct') oceanographic method for calculating meridional heat transport.

One possible cause for the discrepancy noted by Fillenbaum et al. (1997) may result from limitations in the climatological database: a comparison of baroclinic heat flux estimates based on different climatologies by Wacongne and Crosnier (1997) suggested that in the low-latitude Atlantic uncertainty in the seasonal fluxes may be of the same magnitude as the inferred annual amplitude. Conversely, conclusions based on the Levitus-climatology appear to be consistent with the results from a recent analysis by Baringer and Molinari (1999) of four individual sections between 24° and 26°N. Another cause for the discrepancy may be possible deficits in the model simulations. Since we are concerned here with the response of the ocean to atmospheric variability, two potential model problems must be distinguished: deficiencies in the internal physics and/or numerics of the ocean model, and errors in the forcing fields. The first possibility is difficult to reconcile with the present demonstration that there is a close agreement in the patterns, amplitude and mechanism of the seasonal transport variations as obtained with three different numerical models subject to identical atmospheric forcing.

However, the robustness of model behaviors does not imply that the annual cycles obtained in these or any other model studies are realistic. The prime factor, and thus prime uncertainty governing any model simulation, is the imposed wind stress field. Could it be that the amplitude of heat flux variation in model simulations is too small just because of deficits in the wind forcing? The zonal wind stresses based on the ECMWF analysis used in this study have a weaker annual range than fields based on marine wind climatologies. Fig. 9 relates the annual cycle of meridional heat transport obtained in the DYNAMO experiments to previous CME cases with two different wind forcings (BH), as well as to the observational estimate of Fillenbaum et al. (1997). While the amplitude obtained with ECMWF forcing is similar as in the CME case based on the wind stresses of Hellerman and Rosenstein (HR), it is smaller by a factor of about 2 than in both the observational analysis and the CME case using the climatology of Isemer and Hasse (IH).

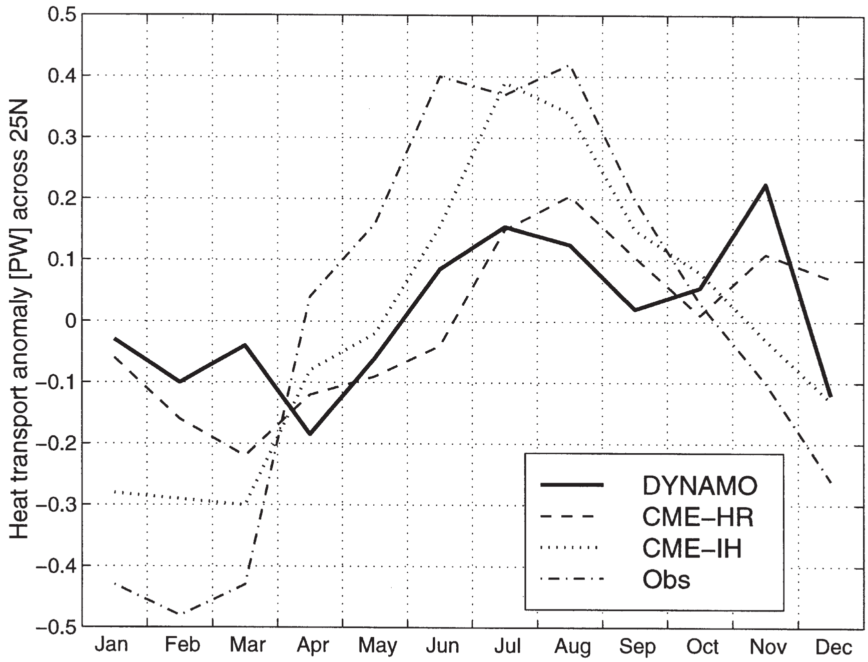


Fig. 9. Annual cycle of monthly mean heat transport anomalies at 25°N, for DYNAMO forced with wind stresses based on ECMWF analyses, compared with CME-cases of BH forced with the marine wind stress climatologies of HR and IH, and the observational estimates of Fillenbaum et al. (1997).

Probably the most powerful means of quantitatively testing the imposed seasonal wind stress fields is provided by a comparison of the model simulations with the meridional transport variability at the western boundary. Of particular relevance for a model-data comparison is the annual cycle obtained by the multi-year current meter measurements of Lee et al. (1996) at 26°N. A robust aspect of the model solutions is the zonal pattern of deep seasonal current variations. The correlation between time series of deep boundary current transports and net overturning is small, and seasonal flow anomalies are not confined to the western boundary current, but include complex recirculation features across the whole western basin. The models thus consistently indicate that it is not possible to make quantitative inferences about the net meridional flux variation on the basis of transport variations near the western boundary.

The present model simulations underestimate the annual range of the western boundary current transport by at least a factor of 2. This obviously implies a much too weak annual variation of the curl of the ECMWF-based wind stresses at this latitude, which may be taken as an indication of the variations in the Ekman transports being too week as will be the zonally-integrated heat transport across this latitude. Whether, and to what degree, this deficit in present model simulations may also be of significance for the amplitude of the baroclinic response, remains to be investigated.

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