On the contribution of the subtropical gyre to the meridional heat transport in an idealized OGCM

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ABSTRACT

We examine the physics of the oceanic meridional transport of heat by the subtropical gyre H_{GY} in an idealized OGCM. The contribution of the gyre to the net mid-latitude heat transport H is important to understand because, unlike sometime considered, it can be significant compared to the meridional overturning circulation and therefore it is useful to gain control on it, in order eventually to improve the simulation of the total heat transport. This work points out the sensitivity of H_{GY} to three properties of the model: the physics of the surface heat flux through the value of the relaxation time constant, the physics of the mixed layer through its depth, and the parameterization of lateral diffusion through the intensity of the diffusion coefficient.

The analysis shows that the larger the relaxation time constant, the larger the gyre contribution. Simultaneously, the contribution of the meridional overturning circulation increases, but the net effect is positive for the total heat transport. Nevertheless, recent estimate suggest a smaller relaxation time constant, which would produce a smaller gyre contribution. For a given value of this constant, we argue that a deeper mixed layer, a higher H_{GY}. This mechanism is used to explain important differences between previous idealized studies of the physics of H. At last, we show that the lowest the intensity of the lateral diffusivity in various parameterizations of meso-scale processes, the larger the heat transport contribution of the gyre. This substantial modification of the physics of H is systematically accompanied by a decrease in the contribution of the diffusive term and various impact on that of the meridional overturning. The net impact on H is therefore not systematic, we obtained a net raise only for a weak relaxation time constant and the opposite otherwise.

1. Introduction

One of the main role of the ocean in the Climate system is, in conjunction with the atmosphere, to redistribute the heat excess received in the equatorial regions towards high latitudes. In order to aid the estimation as well as the understanding of this meridional heat transport (H), related observation and modelling studies often divide it into baroclinic and barotropic components (relatively to the velocity field). In Climate model studies more specifically, the division is generally made between, first, a baroclinic contribution horizontally non-divergent associated with the meridional overturning circulation (H_{OV}), second, a rotational contribution (barotropic plus baroclinic) corresponding to the gyre circulations (H_{GY}) and, third, a part driven by the lateral diffusion terms (H_{DIF}). Hence, at a fixed latitude and time, H is given by

$$H = \rho_{sea} C_p LD \left\{ \overline{\overline{v}^{x} \overline{T}^{x}}^{z} + \overline{\overline{(v-\overline{v}^{x})(T-\overline{T}^{x})}^{x}}^{z} - K_L \overline{\overline{\partial_y T}^{x}}^{z} \right\} \quad (1)$$

$$= \qquad H_{OV} \qquad H_{GY} \qquad H_{DIF}$$

with ρ_{sea} and C_p the density and specific heat of sea water, L and D the basin width and depth at the given latitude, v the meridional velocity, T the potential temperature and K_L the lateral diffusivity. The symbol $\overline{X}^i$ represents the average over the axis i of the variable X and, as an illustration, H_{DIF} is corresponding to a Laplacian representation of the lateral meso-scale processes.

As a dominant factor for the oceanic poleward transport of heat, the annual mean contribution of the Atlantic ocean is in particular of great interest. In the modelling literature about this quantity, a recurrent question, pertaining to its improvement, is what are the control mechanisms of the physics and relative contributions of these three terms. Especially there are strong differences in function of latitude but also of model runs regarding the importance of the H_{OV} versus the H_{GY} contribution in the latitude band 25°N-45°N where H plays its largest role. In agreement with the estimate of Hall and Bryden (1982) at 25°N, the Atlantic model study of Sarmiento and Bryan (1982) exhibits a gyre contribution negligible compared to the meridional overturning circulation (MOC), and the idealized coarse resolution basin study of Bryan (1987) find it negligible everywhere. These results have led some author to consider H as a good proxy, where H is maximum, for the strenght of the MOC in ocean models (e.g., Bryan, 1991; Häkkinen, 1999). But in the idealized coarse resolution Atlantic basin experiment of Colin de Verdière (1989), H_{GY} reaches 60% of H_{OV} around 30°N. And the seasonal Atlantic CME study of Boning and Herrmann (1994) shows that, at 25°N, H_{GY} can be comparable to H_{OV} for certain month, whereas at 35°N it is stronger in annual mean (totally dominant for half the year). Therefore in model studies, the analysis of the contribution of the subtropical gyre circulation in addition to the MOC term appears to be necessary *a priori* in order to have a full understanding of the physics of H.

In addition, since realistic values of H are difficult to obtain in coarse resolution models, especially below 40°N, it is of interest to understand what modulation of the gyre contribution can one expect from different parameters, in particular at mid-latitudes, its region of maximum transport. Indeed, some studies have examined how to increase the MOC intensity in order to improve H (e.g., Döscher et al., 94; Washington et al., 1994) but the results were mitigated due to the counter-effect of the Veronis effect and its western boundary upwelling (cf. Böning et al. 1995; Lazar et al., 1999). Therefore, it is appealing to study the possibility of increasing the gyre contribution H_{GY} instead.

One factor controlling the importance of H_{GY} at mid latitudes (subtropical gyre) in ocean models was discussed by Wang et al. (1995) and Klinger (1996): it is the intensity of the restoring effect on the SST by the Newtonian damping at the air sea interface relatively to the ocean advection time scale (the ratio of this two term being called λ). In their simplified wind-driven subtropical ocean models, these authors find that the asymptotes of the meridional heat transport is proportional either to λ or λ^{-1} when λ respectively tends toward 0 or the infinity. This result, if extendible to OGCM, would permit to understand differences in the physics, and possibly the intensity, of the meridional heat transport at mid-latitude existing between models with comparable configuration but different restoring time scale. It is interesting to detail this question by considering the Newtonian relaxation towards zonally constant field as a simple paramaterization of the tendency of the winds to homogenize ocean temperature zonally. Looking at the impact of various value for the restoration coefficient corresponds therefore to studying different degree of ability of the atmosphere to constrain the zonal character of SST.

A second factor governing the intensity of H_{GY} in Climate OGCM is clearly identified as the horizontal resolution (e.g., Wunsch, 1996; Fanning and Weaver, 1997). The explanation being that an increased horizontal resolution results in a stronger western boundary current and interior return flow, consequently allowing a stronger meridional heat transport by H_{GY}. In this paper, we utilize a coarse resolution OGCM with idealized geometry in order, first, to estimate the applicability of the results of wind-driven models to a more realistic ocean dynamics and, second, to test the role of the lateral mixing as a potential third governing factor. Section 2 describes the numerical model and experiments and section 3 present a sensitivity analysis of the intensity of H_{GY} to the formulation of atmospheric heat fluxes and lateral mixing. Section 4 summarizes the results.

2. Numerical model and experiments

a. Model geometry and forcing

The idealized basin model used here is based on "OPA" the OGCM developed at LODYC and is described in Lazar et al (1999). It uses primitive equations in spherical coordinates. The domain is a 40° wide sector of the sphere extending from 60°N to the equator, where symmetrical conditions are imposed, and has a constant depth of 5000 m. Such a basin geometry is adequate to simulate idealized large scale circulation patterns, and is comparable to previous process study basins (e.g. Holland, 1971; Cummins et al., 1990; Lazar et al., 1999). It has a uniform one degree horizontal resolution and there are 30 levels with vertical spacing ranging from 10 m at the surface to roughly 500 m below 1000 m depth as indicated in Table 1 (Madec and Imbard, 1996).

The forms of the Newtonian heat and fresh water fluxes applied at the surface are:

$$Q = Q_{obs} + \gamma_T \quad (T_{obs} - T) \qquad (2)$$

$$E - P = (E - P)_{obs} + \gamma_S \quad (S_{obs} - S)\ ' \qquad (3)$$

where T and S are the temperature and the salinity of the upper-layer. Q_{obs} , $(E\text{-}P)_{obs}$, T_{obs} and S_{obs} are constant in time and longitude, they are issued from annually and zonally averaged climatologies of the southern hemisphere. The fresh water flux $(E\text{-}P)_{obs}$ is computed from the Bryan and Oort (1984) atlas, the net heat flux Q_{obs} and the penetrating solar radiation from the Esbensen and Kushnir (1981) atlas, and the temperature T_{obs} and salinity S_{obs} from the Levitus (1982) climatology. The coefficient γ_T is associated to the feedback of the SST on the atmospheric heat flux and is equal to 20 W m^{-2} K^{-1}. The coefficient γ_S has a value resulting in the same restoration time scale as for Q (around 24 days over the first 10 m). A penetrating solar radiation scheme is used. The wind stress forcing is computed from a southern hemisphere annual and zonal average of the Hellerman and Rosenstein (1983) atlas. The (in-situ) density is calculated using the Jackett and McDougall (1995) formulation.

b. Formulation of the subgrid-scale physics

In all experiments, an order 1.5 turbulent closure scheme (Blanke and Delecluse, 1993) is used to calculate the vertical viscosity A_V and diffusivity K_V. The minimum values for K_V and A_V are specified to be 10^{-5} and 10^{-4} m^2 s^{-1} respectively (values attained at low latitudes beneath the mixed-layer). The resulting K_V profiles vary slightly in the different experiments but they all exhibit the following gross depth-profile features at mid-latitudes: a value increasing slowly from 10^{-5} m^2 s^{-1} at the base of the mixed layer to 10^{-4} m^2 s^{-1} near 1000 m depth and 3×10^{-4} m^2 s^{-1} at mid-depth (near 2500 m) and rising faster in the abyss up to roughly 10^{-3} m^2 s^{-1} near the bottom. The mesoscale processes are parameterized either by Laplacian horizontal diffusion, either by isopycnal mixing (Redi, 1982) and the G&M parameterization term. K_L is either the horizontal diffusivity or the layer thickness and isopycnal diffusivity in runs using the G&M formulation. The reader is referred to Lazar et al. (1999) for a complete description of the mixing parameterizations.

c. Details of the experiments

The 7 experiments performed in this study are listed Table 1. All experiments use horizontal Laplacian momentum mixing with a viscosity A_H of $4\text{x}10^4$ m^2 s^{-1}. The reference experiment HN uses Laplacian diffusion with K_L equal to $2\text{x}10^3$ m^2 s^{-1}. In HRN K_L is 500 m^2 s^{-1}. HN40 and HN80 are similar to HN except for γ_T which is set to 40 and 80 $W.m^{-2}.K^{-1}$ respectively. HRN80 is identical to HN80 but with K_L at 500 m^2 s^{-1}. The last two experiments, GMN and GMrN, are similar to HN and HRN respectively, except that they parameterize the lateral sub-grid scale processes differently by using the G&M formulation with K_L of $2\text{x}10^3$ m^2 $s^{-1}$and 500 m^2 s^{-1} respectively.

All experiments were run to quasi-equilibrium using the acceleration technique of Bryan (1984) with a tracer time step of one day in the upper ocean increasing to three days at the deepest model level and a five minute uniform time step for momentum. Then we performed approximately fifty years of synchronous integration (equal and uniform two hour time step for tracer and momentum) to reach an equilibrium state with non-distorted physics. Experiments were considered equilibrated when the level average of the potential temperature and the salinity trends dropped below 0.1°C and 0.01 psu per millennium.

3. The physics of H_{GY} at mid latitudes

a. The contribution of H_{GY} and its distribution

Figure 1 presents the meridional transport of heat H and the three contributions of equation (1) for the reference experiment HN. The contribution of the gyre H_{GY} is maximum at mid-latitudes and reaches 0.7 10^{14} W. It is a considerable amount comparable to what carries out the overturning (0.9 10^{14} W) at the same latitude range and it represents more than a third of the total heat transport of 1.9 10^{14} W. By construction (*cf.* eq. 1), the contribution of H_{GY} should increase with the departure from the zonal mean of temperatures and/or meridional velocities. Since the gradients of these quantities are the strongest in and above the thermocline rather than below, this contribution is likely to be dominated by the upper ocean circulation. This is confirmed by its computation in the first 500 meter which produces more than 95% of the total H_{GY} (not shown). In order for the reader to associate better the heat transport with the circulation of idealized OGCM, Figure 2 presents the horizontal current vectors and the temperature field averaged over the upper 500 meters. It is sufficient to say that the flow field forms a tropical and a subtropical gyre which are also seen on the temperature field. As visible on this figure, the largest zonal gradients are in the western boundary, hence one can expect this region to dominate the gyre transport. Figure 3 displays the horizontal distribution of H_{GY} ($\rho_{sea}C_p D\overline{(v-\overline{v}^x)(T-\overline{T}^x)}^z$). It confirms that the contribution is mainly confined in the western upper ocean, and therefore suggest that the mechanisms by which the contribution of H_{GY} can significantly vary take place in this region of the basin. In order to assess the respective role of the temperature and velocity field in both this horizontal distribution and its modification in the other experiments, we computed the deviations from the zonal mean for the meridional velocity and the heat content, and plotted them vertically averaged ($\overline{\left(v-\overline{v}^x\right)}^z$, $\rho_{sea}C_p D\overline{\left(T-\overline{T}^x\right)}^z$) on Figure 4. As for the heat transport by the gyre, the velocity field is clearly dominated by the western boundary deviations (Fig. 4a) which are typically ten times larger (and opposite) than in the rest of the basin. In contrast, the west-east asymmetry in the intensity of the deviation is not as strong for the heat content deviation (Fig. 4b) and reaches a factor ±2 at maximum. This field illustrates the fact that isotherms are flat in the interior and the tropics and have larger slopes in the western boundaries. Note that if the heat transport core at mid-latitude in Figure 3 is shifted off the western shore (despite the current maximum), it is due to the cold tongue (due to upwelling) along the shore.

b. Sensitivity to the formulation of surface heat flux at mid latitudes.

Wang et al. (1995) and Klinger (1996) showed that H_{GY} in simple ocean models is dependent on λ, the ratio of the gyre advection time scale and the heat flux Newtonian restoring time scale. Specifically, two asymptotic regimes emerge from their studies, both with the heat transport tending towards zero either when λ tends towards zero or when λ tends towards the infinity. Their findings are quantitatively difficult to compare to OGCM results since they are highly idealized and we can present here only a qualitative comparison. In addition, in Climate OGCMs, the incertitude in the order of magnitude of the wind forcing is small and hence only the denominator of this ratio, γ_T, admits a wide range of values in different OGCM model studies (10-80 $W.m^2.K^{-1}$).

Before looking at numerical experiments, consider a thought experiment that can help to estimate the sensitivity to γ_T. The SST of our idealized model is forced by a surface heat flux equal to a constant term depending on latitude only plus a relaxation term to a purely zonal SST climatology. This choice is of course motivated by the zonal character of the real atmosphere heat forcing. Suppose that the mixed layer depth is kept constant, if one increase the relaxation constant γ_T toward an infinite value then the SST will become completely zonal as well as the temperatures over the whole depth of the mixed layer. Such a zonal mixed layer temperature will also tend to influence the underlying waters through vertical processes and to produce more zonal temperatures in the upper thermocline. Correspondingly, the upper ocean meridional currents should tend to weaken (the geostrophic meridional surface current will vanish) and depart less from their zonal mean. Since it is near the surface that the strongest temperature and velocity gradients and values are found, such a zonal upper ocean will be characterized by an extremely weak contribution of the gyre term H_{GY} (see eq. 1).

In an attempt to study the effect on H of the tendency the atmosphere to zonally homogenize the SST, Kamenkovitch et al. (2000) simply fixed the SST to a zonally constant value in an idealized global OGCM. As expected, their experiment, which is equivalent to the thought one detailed above, resulted in a negligible gyre contribution compared to experiments with a more realistic surface fluxes parameterization. To go beyond this result, it is necessary to quantify the sensitivity of the physics of the heat transport to various values of the restoring coefficient γ_T in the range commonly used in OGCM studies. Therefore we carried out two experiments with two larger values for γ_T of 40 and 80 $W\ m^{-2}\ K^{-1}$ respectively in experiments HN40 and HN80, and focused our attention at mid-latitudes where H is maximum (Fig. 1). As seen in Figure 5, and in agreement with the studies discussed above, the recirculation contribution felt down by 25% (-

1.5 10^{13} W) in the former (not shown) and by 40% (-2.8 10^{13} W) in the latter (Fig. 5). This result can be associated to the regime found in simple ocean models where the heat transport decreases toward zero with λ.

However, a closer look at the modification of the heat content and the velocity field shows that the process is more complex than foreseen. Figure 6 displays the same diagnostics of vertically averaged deviation as in Fig 4 but for HN80, as well as for the reference experiment superimposed. One see that the transport is practically unchanged, which means that the increase of the restoration on the temperature field didn't end up with a more zonal character of the flow. Hence it has to be the temperature field that became more zonal. It appears from Figure 6b that, whereas this effect is widespread in the mixed layer (not shown) the average over the water column shows it only over a limited region between 35N and 50N. This region corresponds grossly to the North Atlantic Drift (see Fig. 2) where the isotherms have a much stronger zonal character than at lower latitudes, but a explanation would require a more detailed analyzis. However we chose to limit our conclusion to the fact that OGCM and simpler ocean models are in good agreement regarding the sensitivity to the restoration coefficient of the gyre heat transport. But the effect does not dominate the entire basin and can instead be regional and limited to the temperature field without affecting the mass transport.

It is now interesting to study the resulting modifications of the total meridional heat transport H. Simple ocean models like those utilized by Wang et al. (1995) and Klinger (1996) lack a realistic overturning circulation and can not assess the accompanying evolution of H_{OV} and therefore of H. Instead, the OGCM study by Kamenkovitch et al. (2000) allowed to show that the zonally fixed SST and the collapse of the gyre contribution was not accompanied by changes of the contributions of the other components of the heat transport. Hence, in their study, the total transport decreased approximately by the amount lost by the gyre component. Interestingly in our simulations, H_{OV} raises (Fig. 7) with γ_T and partly compensates the drop of H_{GY} (the diffusive component H_{DIF} is weakly affected by these changes). As a result the diminution of H is a bit smaller (Fig. 8) : -2 10^{13} W from HN to HN80 at 30N. Note that this compensation phenomenon is possibly related to the fact that H is too constrained by the constant term Q_{obs} in (2) and it could be inherent to the expression of the atmospheric forcing.

In conclusion, since the decrease of H_{GY} following a rise of the restoring coefficient value is coherent among different model studies, we believe that it is a robust mechanism at play in ocean models. The simultaneous fall of the total transport following that of H_{GY}, observed in our experiments as well as in Kamenkovitch et al. (2000), is also robust and it is a relation that can be kept in mind when looking at the sensitivity of the heat transport to the parameterization of the atmospheric fluxes. Regarding the possibility of using this mechanisms to increase and hence improve the simulation of H in ocean models, Chu et al. (1998) find that realistic values of γ_T for northern (southern) mid and high latitudes are 70 $W.m^{-2}.K^{-1}$ (65 $W.m^{-2}.K^{-1}$). Such values are about twice those generally used in forced ocean studies and our results suggest that their utilization would in fact produce a smaller subtropical gyre contribution and tend to reduce the total meridional heat transport.

c. Sensitivity to the mixed layer formulation

For a given Newtonian restoration coefficient γ_T, the contribution of H_{GY} is determined simultaneously by the depth of the mixed layer. The deeper the mixed layer, the larger its heat content and the weaker the efficiency of the relaxation of the SST. Thus we suggest that the contribution of the gyre is likely to increase with a larger mixed layer depth. In our experiments, in the region where the recirculation transports most of the heat, namely at mid-latitudes, the mixed layer is 100 m depth. This is twice the mixed layer depth specified in the comparable basin of Bryan (1987). Our reasoning implies that the contribution of the gyre to the total heat transport observed by this author should be smaller than in our set of simulations. In addition, the relaxation coefficient γ_T used in this study was high (80 $W.m^{-2}.K^{-1}$). Using these arguments, one can better understand why the results of Bryan (1987) emphasize so much the role of the overturning in the northward heat transport at the expense of H_{GY} which was totally negligible. Similarly, it is possible to understand the apparently opposite results of Colin de Verdière study (1989) where H_{GY} provides an important contribution to H. Indeed, the mixed layer depth of this study is approximately the same as ours (with a first level 100 m thick) and its relaxation coefficient is set to 40 $W.m^{-2}.K^{-1}$ as in HN40. Its results (fig. 11 of the corresponding article) show a contribution of H_{GY} of about 60% of H_{OV}, like in HN40 (not shown), and correspond consequently to what we can expect of such values for the mixed layer depth and γ_T.

d. Sensitivity to the paramaterization of meso-scale processes

Considering the previous discussion, one of the mechanisms contributing to the sensitivity to lateral diffusion can be expected to work as follows. A stronger lateral diffusion coefficient tends to homogenize laterally any quantity in the basin. Hence, with a higher lateral diffusion coefficient, the departure from the zonal mean of both the temperature and the meridional velocity are expected to generally diminish, and consequently the contribution of H_{GY} to drop.

To check this reasoning, we first reduced the horizontal diffusion coefficient by a factor 4 in experiment HRN. As expected, the contribution H_{GY} experienced a drastic raise and almost doubled up to 1.2 10^{14} W (Fig. 5). By looking at the deviation fields, it appears that again the deviation of the flow has been much less affected compared to the temperature (Fig. 9) for which the mixing is weaker. One sees that this last field has significantly increased, in particular at mid latitudes by up to a factor 1.5 to 2 (corresponding grossly to the rise of the heat transport).

Regarding the other contributions, we observe a drop at mid-latitudes that cancels totally the gyre effect and even reduces the total transport. It is largely due both to the logical collapse of the diffusive heat transport H_{DIF} (Fig. 10), and also to the collapse of H_{OV} (Fig. 7) due to a decline of the overturning transport (Lazar et al. 1999).

Such an offset of the increase in the large scale circulation heat transport by the meso- scale process parameterization is very comparable to that observed in several sensitivity studies when horizontal resolution is enhanced (e.g., Cox 1985, Böning and Budich, 1992). Since a general default of ocean Climate models is to generate a too weak meridional heat transport at mid latitudes, it would be of interest to be able to raise H_{GY} more than the fall in H_{DIF}. To the opposite of the above mentioned studies, the idealized OGCM of Fanning and Weaver (1997) experiences a net increase of H due to the raise of H_{GY}, when the horizontal mixing is lessened or the resolution increased. These authors suggest that the singularity of their results is partly due to the differences with previous studies in basin geometry and integration time. In order to test if the decrease of the total heat transport is robust in our model or if we can obtain similar results to these authors study, we again reduced the horizontal diffusivity by a factor four but using the configuration HN80 (where the surface heat flux relaxation constant γ_T is 4 times stronger than in HN). Around 40°N, this simulation undergoes a tripling of H_{GY} passing from 0.4 10^{14} W to 1.2 10^{14} W, that this time it is not entirely counteracted by the equivalent fall of H_{DIF} and H_{OV}., resulting in a net (but small) raise of H (0.02 10^{14} W). The reason why there is a net increase at mid-latitudes for this case of strong Newtonian surface damping is not clear and would requires more analysis. But this result shows that the phenomena consisting in an offset of the large scale circulation heat transport by the meso-scale processes parameterization is not systematic but instead, for a given geometry and integration time, sensitive to the restoring boundary conditions. We therefore limit our conclusion to the facts that a decrease of the lateral diffusion 1) changes drastically the physics of H especially due the strengthened contribution of the subtropical gyre and 2) results or not in an increase of H depending upon parameters like γ_T for example.

In order to obtain a more complete picture of the sensitivity of H to meso-scale processes parameterization, we performed two experiments using the combination of isopycnal mixing and eddy-induced velocities (Gent and McWilliams, 1990; hereafter GM). GMN and GMRN are the companion experiments to HN and HRN since they employ respectively the same values for the lateral diffusion coefficient (used for isopycnal and layer thickness diffusions). The homogenization effect over the temperature field by lateral mixing, strong in HN, should now be very weak because the mixing is purely isopycnal in GMN. Simultaneously, the induced velocities will act to flatten isopycnal (Gent and McWilliams, 1990; Lazar et al. 1999) and therefore should limit the growth of the deviation from the zonal mean temperature. Hence it is natural to wonder what is the resulting effect on H_{GY}. To identify the different mechanisms at play in the switch to GMN and GMRN, we must compute H_{GY} and H_{OV} in the same way as before (therefore they still account for the large scale, or Eulerian-mean, circulation contributions) and additionally calculated the specific contribution of the eddy-induced transport velocities (Fig. 10) and the isopycnal diffusion (but not shown since always negligible).

Figure 5 shows that in fact GMN does not display any reduction of H_{GY}, which stays interestingly as intense as in HN with an equatorward shift of about 5°. The comparison of Figures 11, which displays the deviation field for GMN, and Figure 4 for HN is enlightening. The intensity of the current deviations in GMN is almost unchanged, as observed in the previous sensitivity experiments, and the distribution of the deviation of the temperature is also very close to HN at mid-latitudes. Hence, for a given lateral diffusion coefficient, whereas the switch to the Gent and McWilliams parameterization is very effective at modifying the intensity both the zonally integrated temperature signal and overturning transport (Böning et al., 1995; Lazar et al. 1999), it does not change the intensity of the subtropical recirculations v' nor the deviation from the zonal mean of the temperature T' (but the mean fields are strongly modified, not shown). In other words, the flattening effect of the parameterization on the isotherms damps T' with a similar efficiency to that of the Laplacian formulation at subtropical and mid-latitudes. This similitude can be placed in parallel with the similitude found by Lazar et al. (1999) between these two same experiments concerning the circulation and the temperature balance in the deep ocean. Whereas the previous study demonstrated that it was the quasi-geostrophic character of the deep circulation at these latitudes that was explaining the similitude, it is still unclear for us what is the rational of this present result.

Regarding the total heat transport, the effect of the switch to the GM parameterization is a strong reduction by more than 25% north of 30°N. It is in accord with the results of Kamenkovitch et al. (2000). The switch first reduces drastically the overturning circulation in GMN especially in the northern half of the basin (not shown) and the H_{OV} contribution to heat transport there consequently collapses. This effect on the Eulerian-mean overturning circulation is in agreement with previous study (e.g., Böning et al., 1995 and personal communication; Weaver ad Eby, 1997; Kamenkovitch et al., 2000) and a detailed explanation is provided by Lazar et al. (1999). The modification of H_{OV} is the main contributor to the collapse of H. Indeed, the eddy-induced transport contribution south of 45°N (fig. 10) appears to be very comparable to that of the horizontal diffusion in HN. North of 45°N, the eddy-induced advection contribution is much smaller than was that of the horizontal diffusion and it participates with H_{OV} in the weakening of the total transport.

We shall now compare the consequences of the reduction of the lateral mixing coefficient (isopycnal and layer thickness) from GMN to GMRN. Our discussion in this chapter is based on the increasing effect on H_{GY} when the lateral diffusion of temperature is lessened. Since the GM parameterization has in common with the horizontal diffusion to flatten isopycnals, the decrease of the layer thickness diffusivity in GMRN should similarly lead to an increase in the extrema of the velocity and temperature fields, and therefore raise the contribution of the gyre to the heat transport. This is what appears on Figure 5: H_{GY} doubles up to more than 1.2 10^{14} W very much alike the increase of H_{GY} in HRN. Again, the recirculation have not experienced a significant change but, like in HRN, the intensity of the temperature deviations have almost doubled (not shown).

Hence this result supports the conclusions drawn from the previous experiments concerning the sensitivity of H_{GY} to meso-scale processes parameterizations, regardless of the formulation. Regarding the overall effect on the total heat transport, these last two experiments present another scenario, showing how much it is dependent on the configuration of the model. Alike the previous runs, GMRN experiences a collapse of the contribution of the mesoscale process parameterization (Fig. 10) that tends to offset the increase of H_{GY}. But this time the overturning circulation increased instead of diminishing (not shown) in the northern half and consequently its transport of heat raised substantially (Fig. 7) partly compensating the fall of the eddy-induced transport. As a net result, the total transport of heat increased significantly of about one third (~+0.5 10^{14} W) at mid-latitudes. Hence, whereas these experiments underline the systematic tendency of meso-scale process parameterization to offset increase in the gyre heat transport contribution, they also show that the net effect on the total heat transport depends on the response of the overturning which is highly variable through the different experiments.

4. Conclusion

We used an idealized OGCM to study the physics of the meridional heat transport carried by subtropical gyres H_{GY}. After having showed that the main contribution of the gyre lies within the thermocline depth range (the deep ocean gyre carry a negligible net amount of heat), the analyze brought out the dependency of H_{GY} upon three factors: the relaxation constant γ_T of the Newtonian surface heat flux, the mixed layer depth and the lateral diffusion.

We find that the shorter the relaxation time, the smaller the gyre contribution. This result supports some comparable conclusions drawn from more simple ocean models (Wang et al., 1995; Klinger, 1996). It can be understood as the effect of the more intense surface damping of zonal variations of both the meridional velocity and the temperature field, since atmospheric variable have a strong zonal character. A recent study by Chu et al. (1998) indicates that oceanic Climate models generally utilize a too small value for γ_T at mid-latitudes. It would therefore signify that these models over-estimate the contribution of subtropical gyres in the meridional heat transport essentially at the expense of the MOC.

We then argue that this effect is modulated by the depth of the mixed layer which, when deeper, will reduce the surface damping effect and corresponds to a higher H_{GY}. Therefore, the parameterization chosen for the mixed layer is likely to play a particular role, through this process, in the distribution of the meridional transport of heat over the different transport components (gyre, overturning, diffusion).

Finally, it is showed that the contribution of the subtropical gyre increases and hence changes the physics of H if the intensity of lateral diffusion decreases, the lateral diffusion being either that of heat for Laplacian parameterization or of layer thickness for the Gent and McWilliams parameterization. This result is due to the fact that temperature can depart more from its zonal zonal average when the intensity of the parameterization of mesoscale processes is diminished. Regarding the impact on the total transport of heat, we found that there is a negative compensation by the fall of both the MOC and the diffusive transports. It can be compared with resolution sensibility studies that showed how eddy transport offset the increase of large scale circulation transport (e.g., Cox, 1985; Böning and Budich, 1996). Singularly, Fanning and Weaver (1997) showed an net increase of H for an finer horizontal resolution as well as for a weaker diffusion (due to the gyre transport). We could also obtained a net increase of H with less diffusion, but only in the case of a high value (closer to the observations) of γ_T. If similar sensitivity to diffusion exists in more realistic models, the heat transport is likely to be larger with reduced mixing and hence become closer to observations.

These results underline the importance of the choice of parameterization for surface forcing, mixed layer physics and meso-scale processes on the role of the subtropical gyre for the poleward transport of heat in coarse resolution ocean models. They suggest that a proper simulation of the gyre circulation is as important as for the meridional overturning circulation. More attention towards this quantity and the controlling factors discussed here, or their coupled model equivalents, may help to increase the understanding of the poleward heat transport in coupled ocean-atmosphere Climate models.

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FIGURE CAPTION

Figure 1. Different contribution to the meridional heat transport H for the reference experiment HN. H_{OV} stands for the meridional overturning circulation, H_{GY} for the recirculations contribution and H_{DIF} for the meso scale processes.

Figure 2. Experiment HN: vertical average of a) velocity vectors (1cm=1cm.s^{-1}), b) temperature (°C).

Figure 3. Experiment HN: vertically integrated meridional heat transport (c.i.=10^7 Watts.m^{-1})

Figure 4. Experiment HN: vertical average of the departure from the zonal mean for a) the meridional velocity (cm.s^{-1}), b) the temperature (°C).

Figure 5. Heat transport H_{GY} by the recirculations component.

Figure 6. Like in Figure 4 but for Experiment HN80. in b) the superimposed thin line corresponds to HN.

Figure 7. Heat transport H_{OV} by the meridional overturning component.

Figure 8. Total heat transport H for the 6 main experiments

Figure 9. Like in Figure 4 but for Experiment HRN.

Figure 10. Heat transport H_{DIF} by the lateral diffusion component. For GMN and GMRN, only the eddy-induced velocity contribution is presented (negligible isopycnal diffusion contribution).

Figure 11. Like in Figure 4 but for Experiment GM.

Table 1. Summary of the numerical experiments. Mixing coefficients are in m^2 s^{-1}.

Experiment	K_L	γ_T (W.m^{-2}.K^{-1})	lateral mixing formulation
HN	2 000	20	horiz. Laplacian
HN40	2 000	40	horiz. Laplacian
HN80	2 000	80	horiz. Laplacian
HRN	500	20	horiz. Laplacian
HRN80	500	80	horiz. Laplacian
GMN	2 000	20	G&M param.
GMRN	500	20	G&M param.

Table 1. Summary of the numerical experiments. Mixing coefficients are in m^2 s^{-1}.

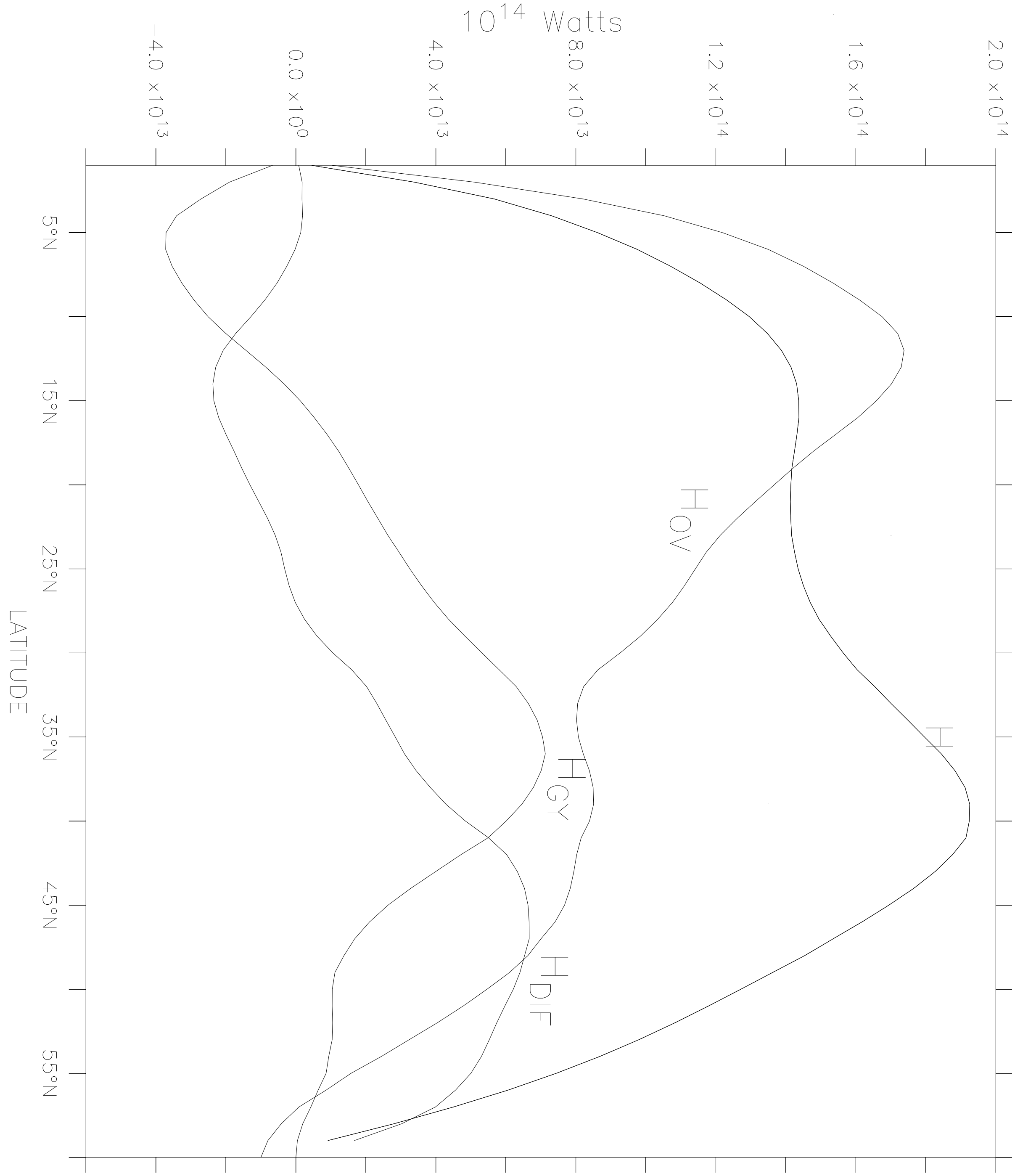

Figure 1. Different contribution to the meridional heat transport H for the reference experiment HN. H_{OV} stands for the meridional overturning circulation, H_{GY} for the recirculations contribution and H_{DIF} for the meso scale processes.

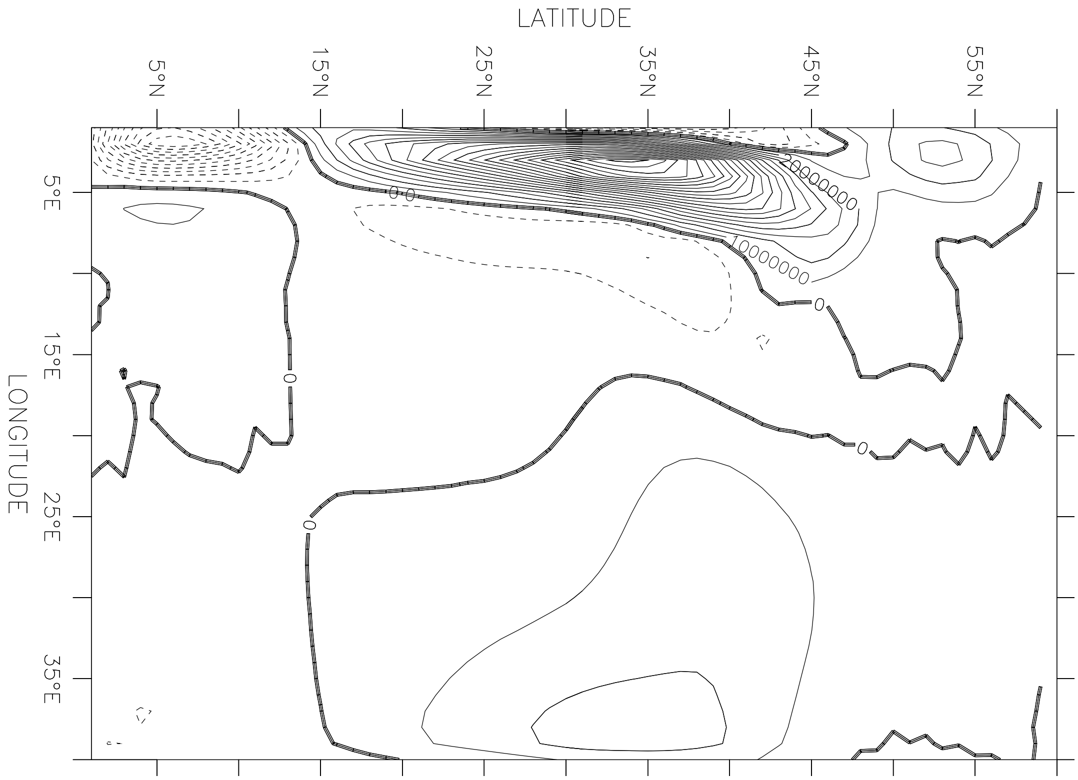

Figure 2. Experiment HN: vertical average of a) velocity vectors (1cm=1cm.s^{-1}), b) temperature (°C).

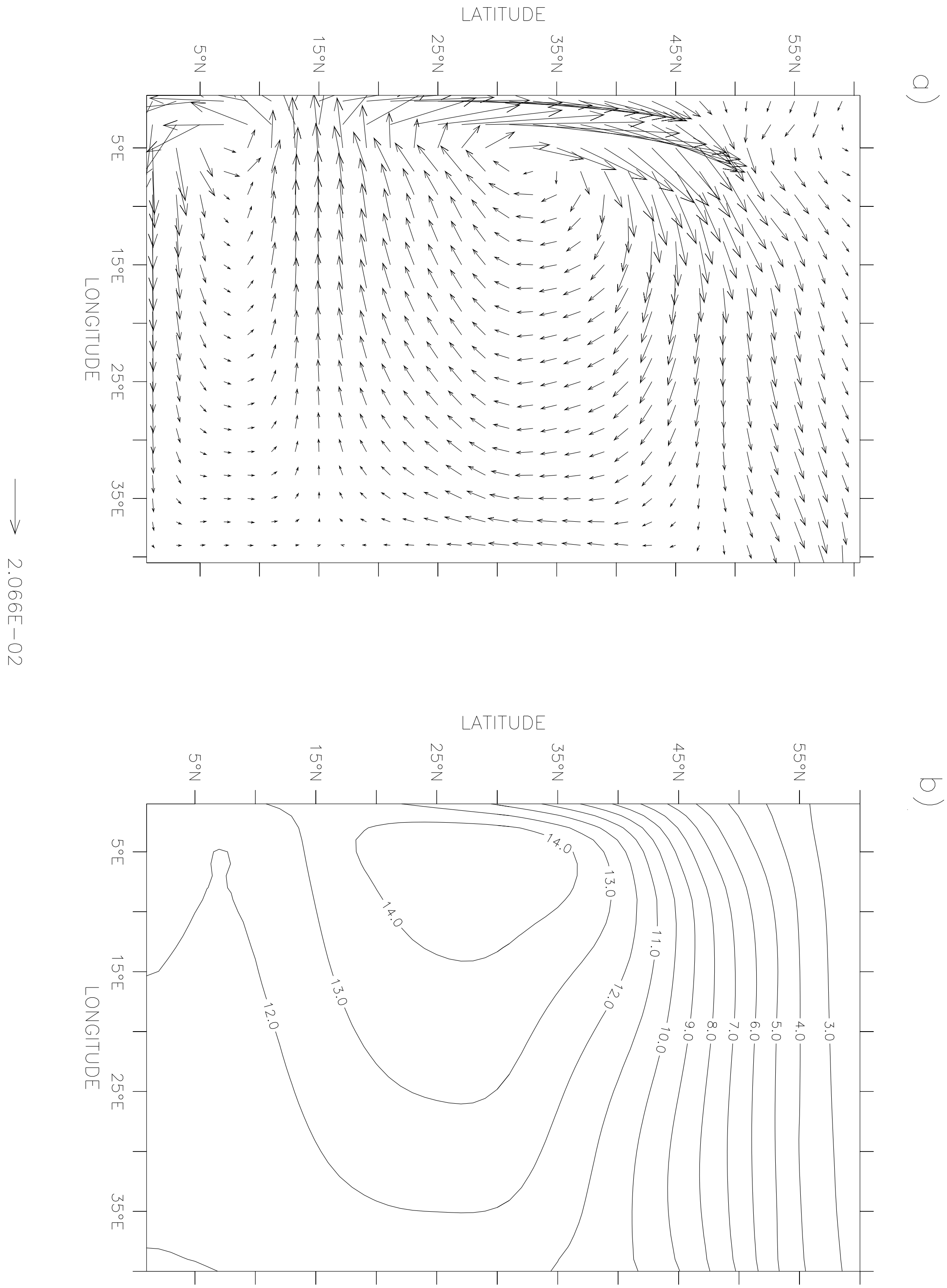

Figure 3. Experiment HN: vertically integrated meridional heat transport (c.i.=10^7 Watts.m^{-1})

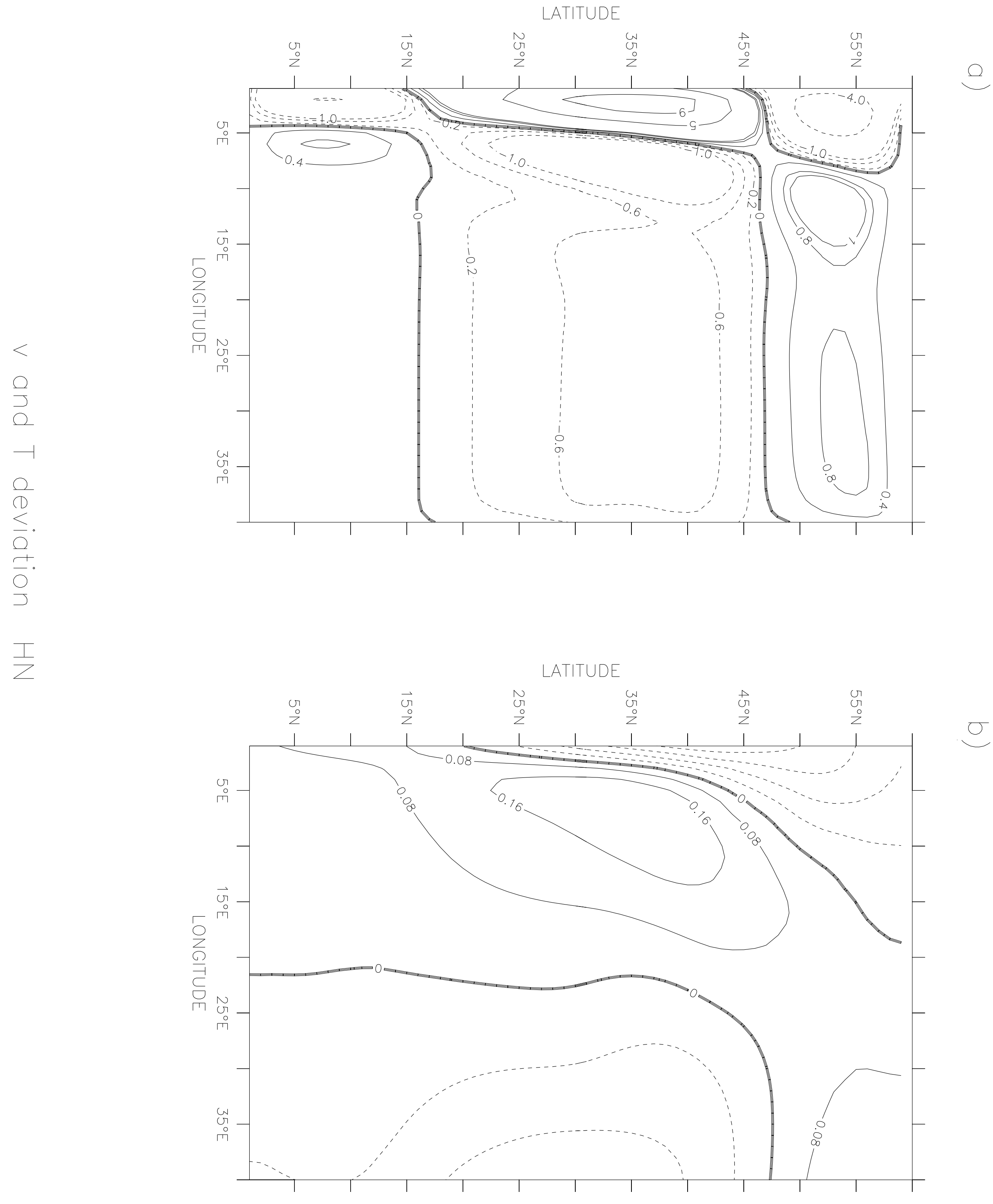

Figure 4. Experiment HN: vertical average of the departure from the zonal mean for a) the meridional velocity ($cm.s^{-1}$), b) the temperature (°C).

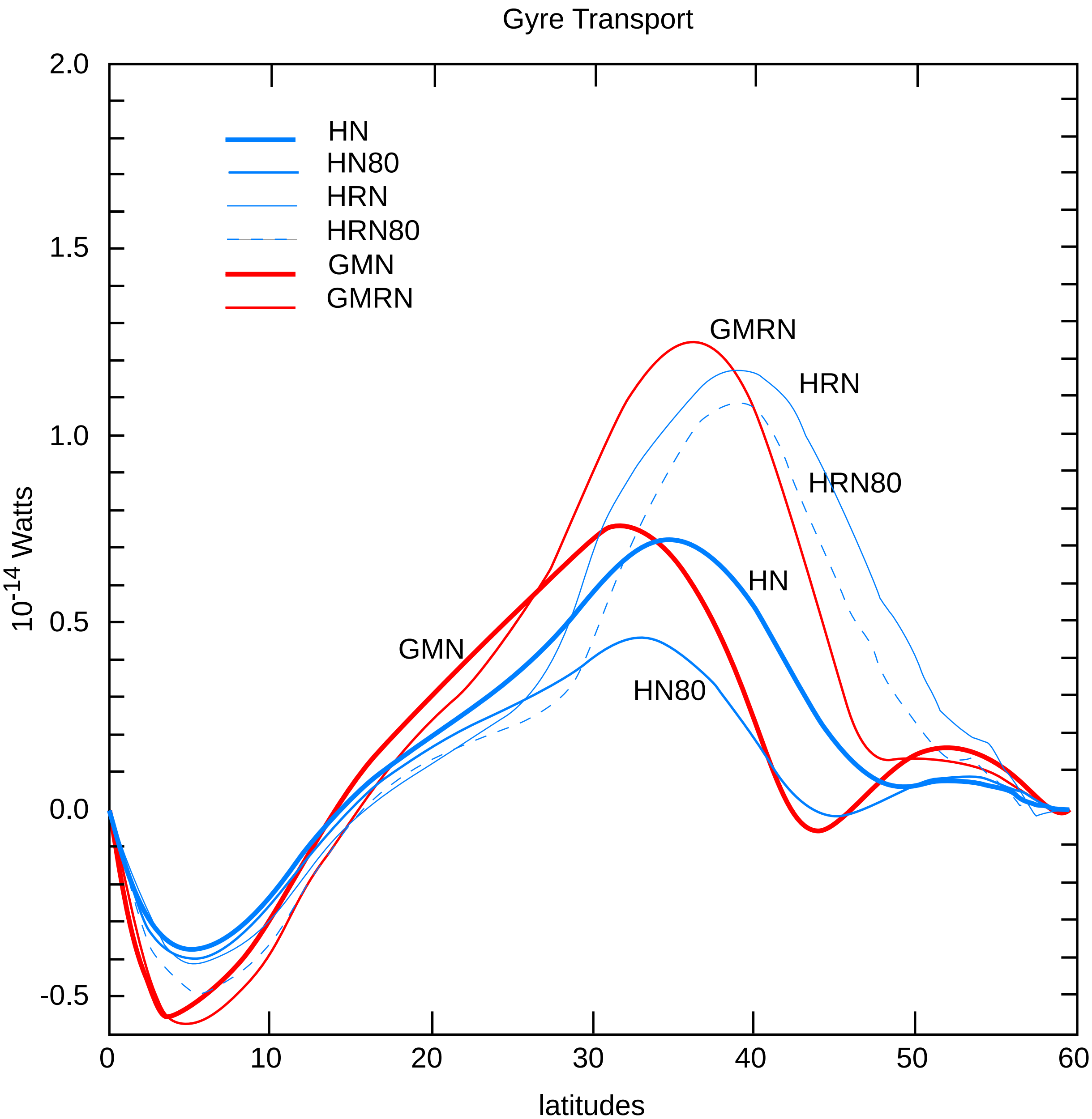

Figure 5. Heat transport H_{GY} by the recirculations component.

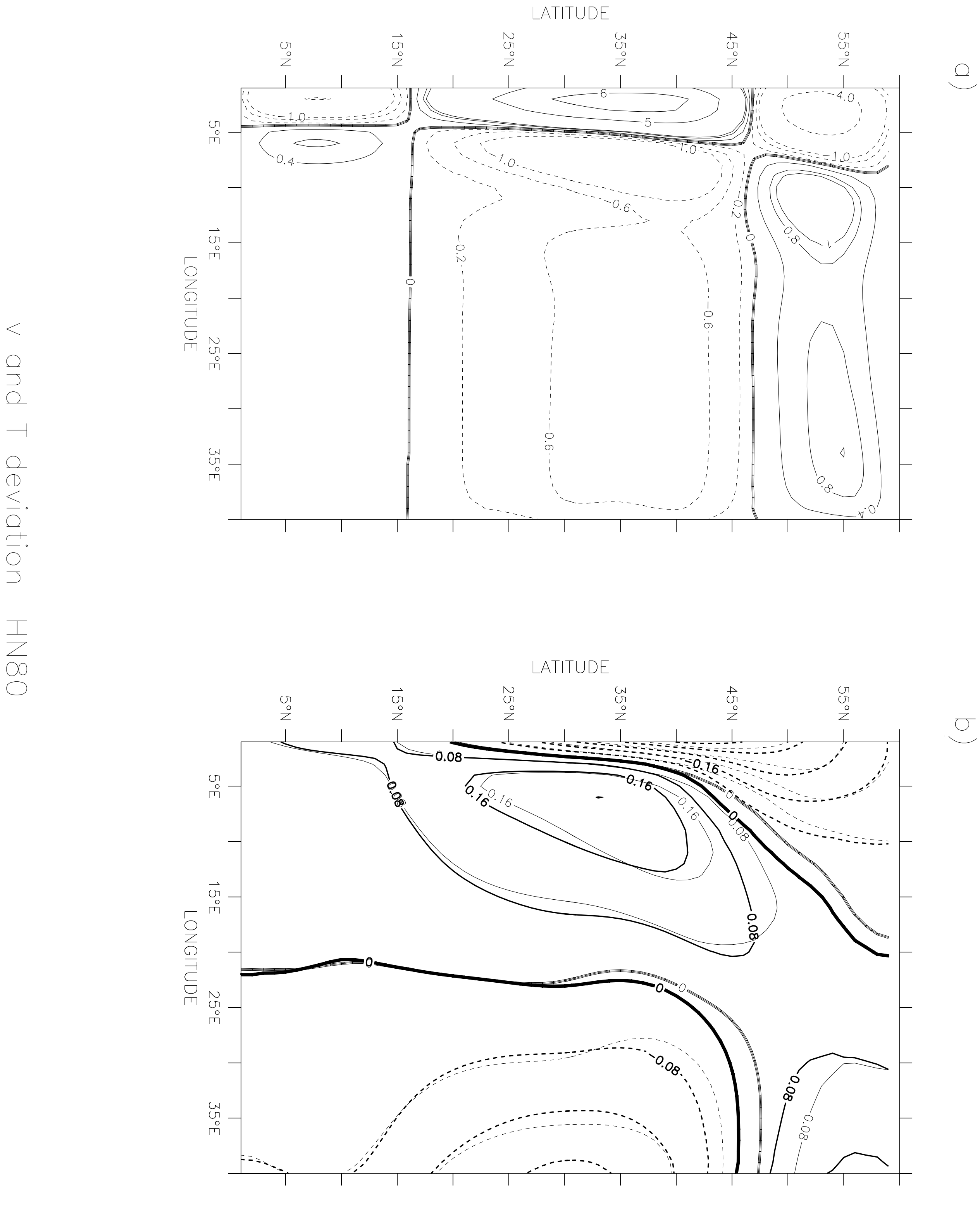

Figure 6. Like in Figure 4 but for Experiment HN80. in b) the superimposed thin line corresponds to HN.

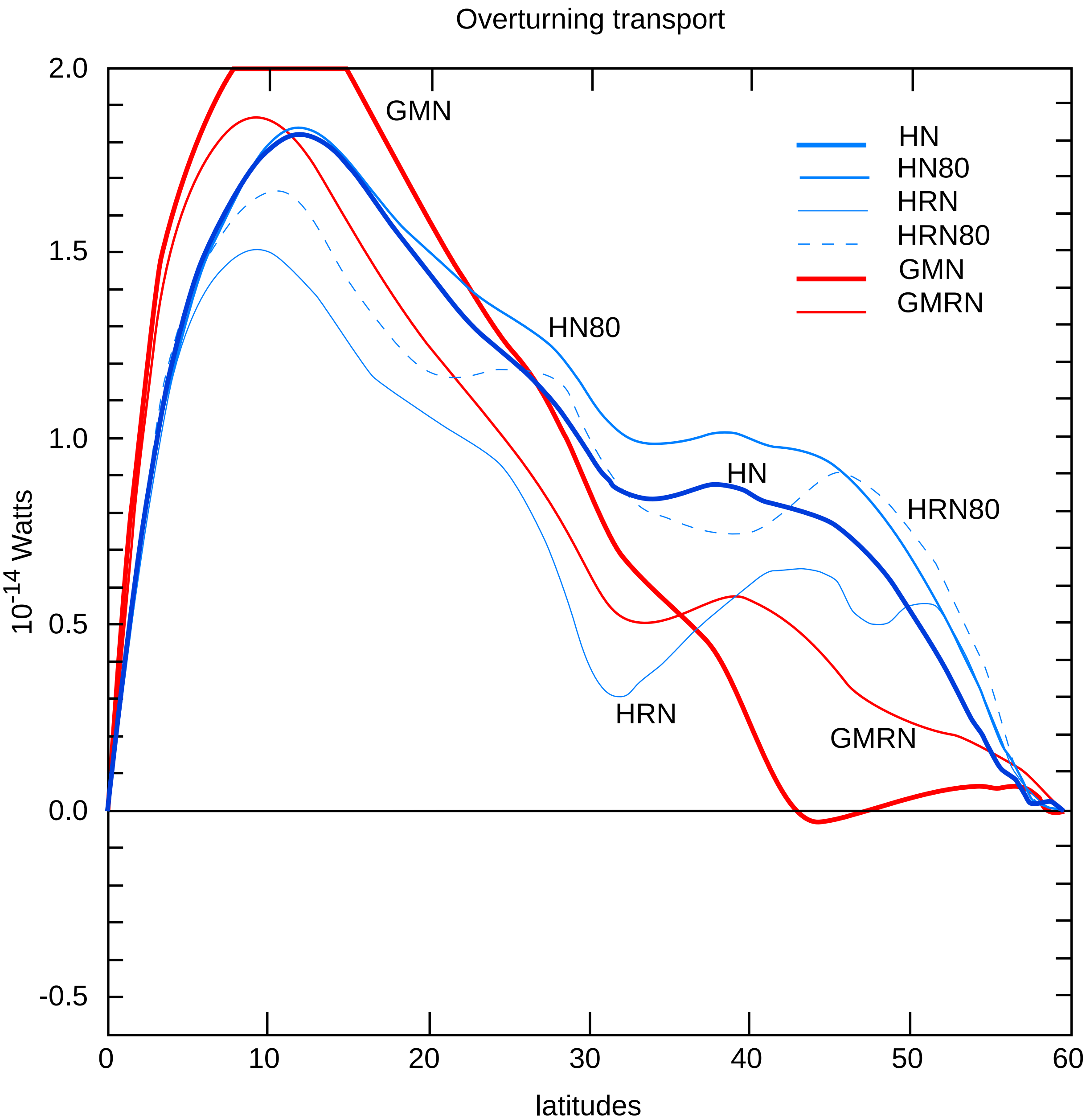

Figure 7. Heat transport H_{OV} by the meridional overturning component.

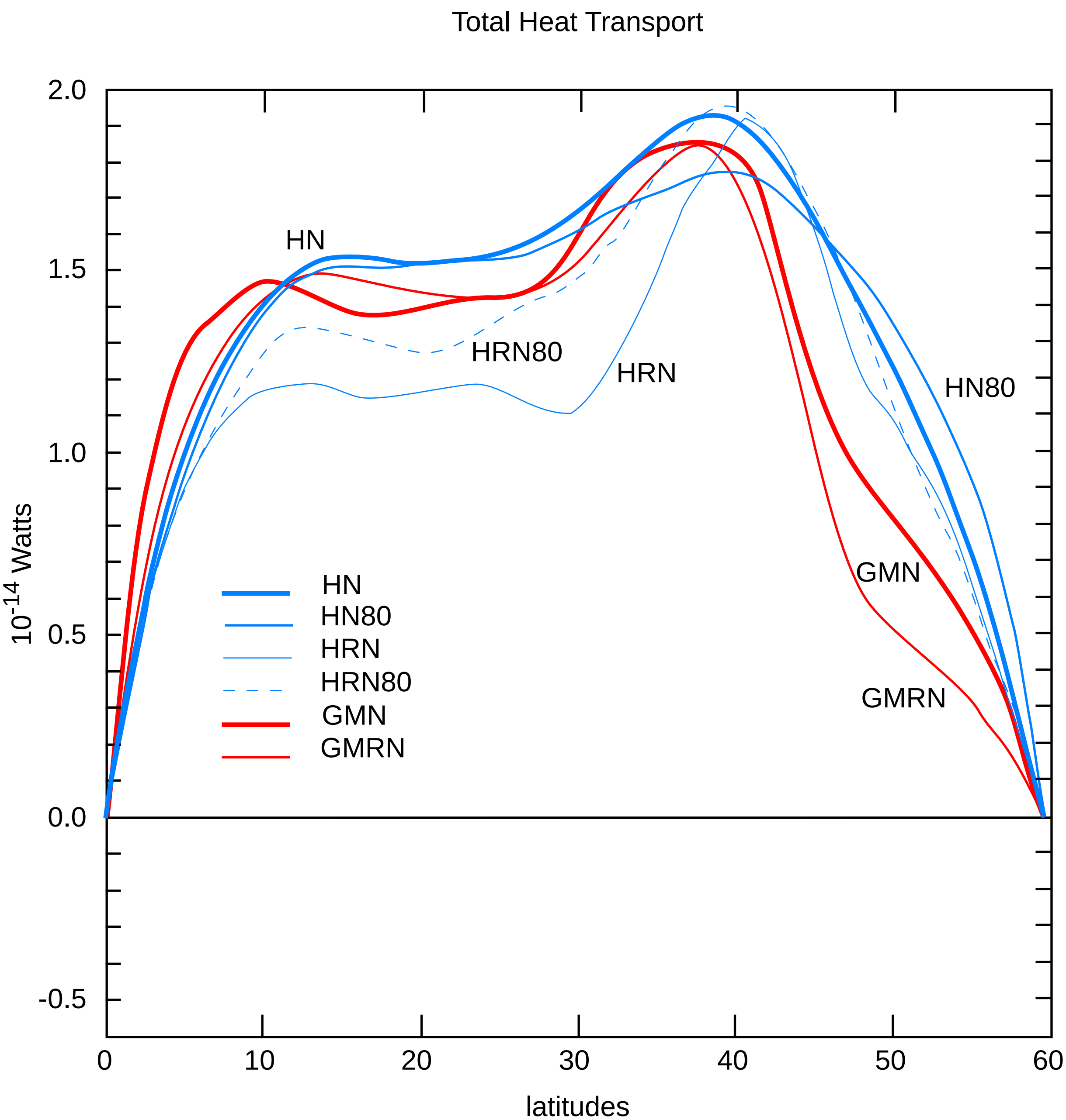

Figure 8. Total heat transport *H* for the 6 main experiments

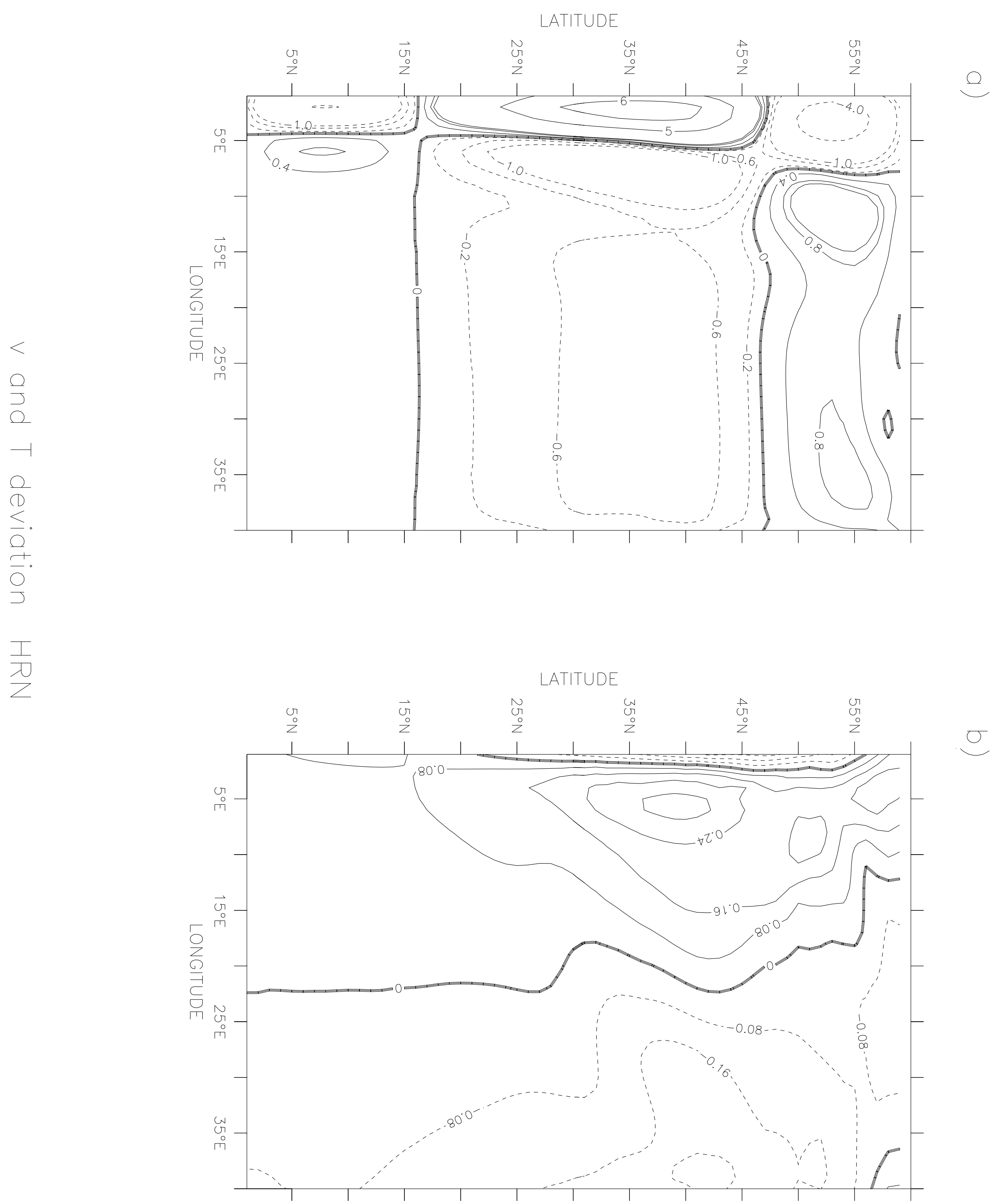

Figure 9. Like in Figure 4 but for Experiment HRN.

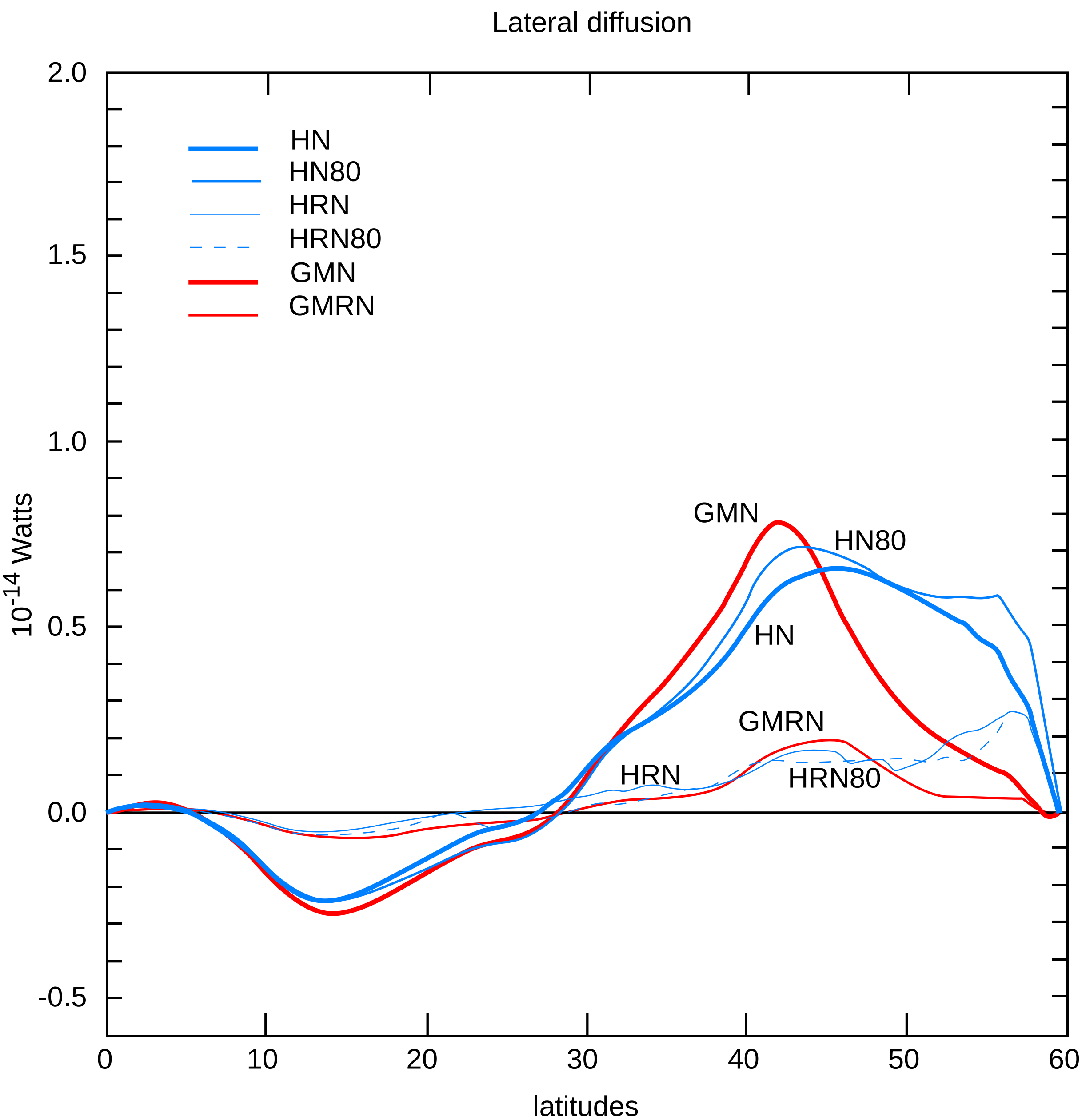

Figure 10. Heat transport H_{DIF} by the lateral diffusion component. For GMN and GMRN, the negligible isopycnal diffusion contribution is not shown and only the eddy-induced velocity contribution is presented.

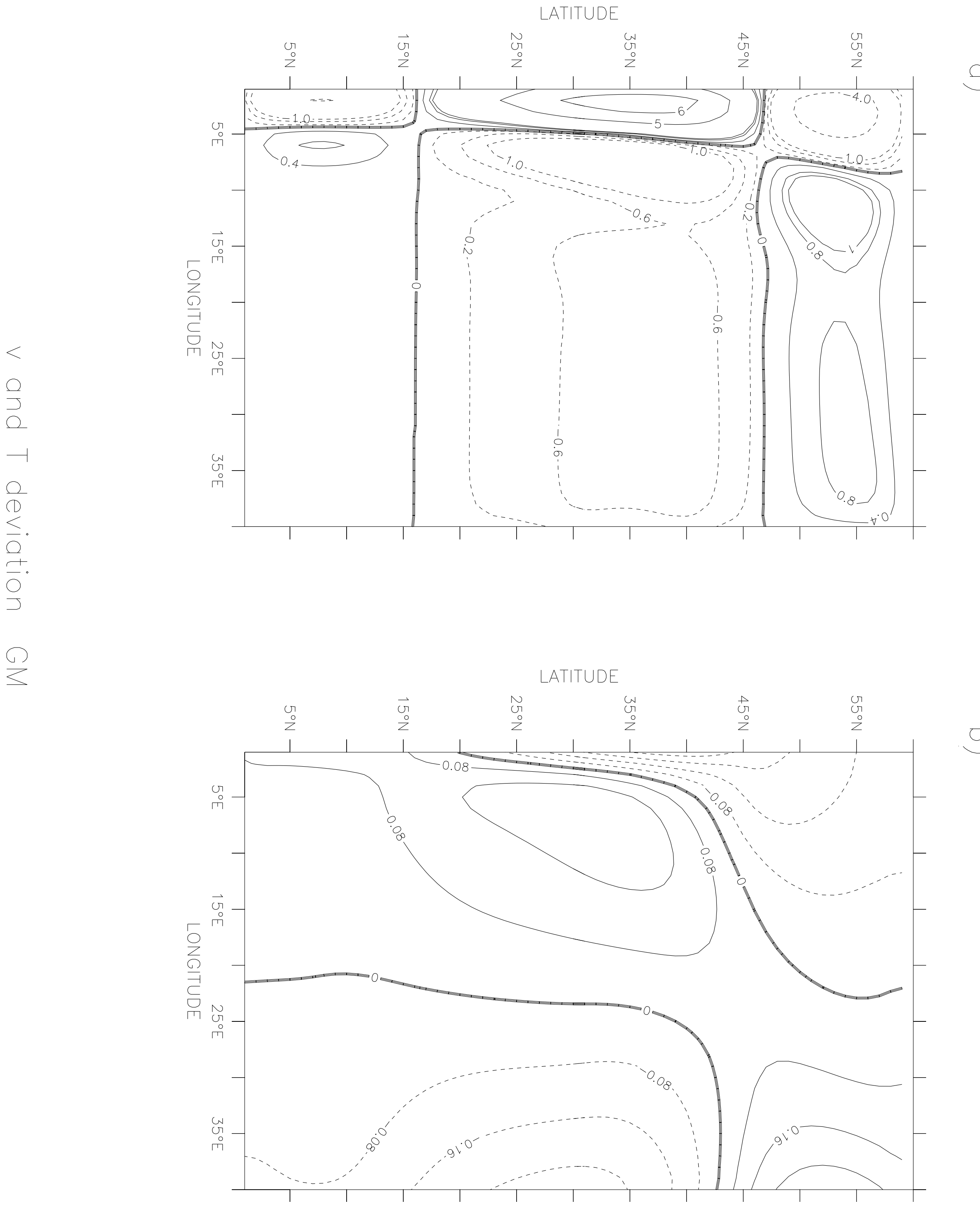

Figure 11. Like in Figure 4 but for Experiment GM.