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## Global tidal residual mean circulation: Does it affect a climate OGCM?

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[1] A global description of the ocean tidal residual mean circulation (TRMC) is provided and its effect on a global ocean climate model is evaluated. The TRMC is computed from a global barotropic tidal model based on pure hydrodynamical equations and forced by the major tidal constituents. It thus includes both Stokes drift and non-linear tidal dynamics. The TRMC map exhibits remarkable basin scale structures in the Indonesian archipelago-Australian region and on the Malvinas shelf. Regions of largest transport are characterized by sites of high tidal amplitudes, abrupt topography and western boundaries. Yet transport magnitudes remain at a few tenths of a Sverdrup. This TRMC is introduced as an external forcing in an ocean climate model. At equilibrium, the thermohaline structure and the poleward heat transport of the ocean are almost insensitive to the TRMC. It is concluded that the TRMC is negligible for climate purposes in an ocean climate model. **Citation:** Bessières, L., G. Madec, and F. Lyard (2008), Global tidal residual mean circulation: Does it affect a climate OGCM?, *Geophys. Res. Lett.*, 35, L03609, doi:10.1029/2007GL032644.

### 1. Introduction

[2] Tides play a major role in the ocean overturning circulation [Munk and Wunsch, 1998]. They generate internal waves which dissipate in the interior ocean and this dissipation induces vertical mixing that contributes to sustain the thermohaline circulation [Wunsch and Ferrari, 2004]. This process has been incorporated in several climate Ocean General Circulation Model (OGCM) [e.g., Simmons et al., 2004; L. Bessières et al., Improved tidally driven mixing in a numerical model of the ocean general circulation, submitted to *Ocean Modelling*, 2008, hereinafter referred to as Bessières et al., submitted manuscript, 2008]. In all cases, the introduction of tidally driven mixing leads to an improvement of the thermohaline structure and the circulation of the simulated ocean. Nevertheless tidal mixing is not the only aspect that can influence the ocean. Though quasi-periodic, tides also generate a mean circulation, the tidal residual mean circulation (TRMC). This circulation is due to both Stokes transport and non-linear tidal dynamic [Longuet-Higgins, 1969; Zimmerman, 1979]. The TRMC is extremely difficult to extract from observations, as it is almost impossible to isolate it from the mean wind and thermohaline driven circulations. Nevertheless, TRMC can be evaluated using numerical models. In coastal

oceanography, its importance is well known, in particular its effect on the transport of sediments [Hoitink et al., 2003; Ménesguen and Gohin, 2006]. At regional scales, several studies have shown that the TRMC can be the main contributor to the mean circulation [e.g., Le Provost and Fornerino, 1985; Sentchev et al., 2006]. Furthermore, Schiller [2004] has shown that the TRMC contributes significantly to an inter-basin exchange. He found that it is responsible for a transport of  $\sim 0.7$  Sv from the Pacific Ocean to the Indian Ocean, i.e. 7% of the total transport of the Indonesian Throughflow (ITF). To our knowledge the effects of the TRMC at global scale has never been addressed, and even more the global TRMC itself has never been described. The aim of this paper is to provide such a global description and to test its effect on a global ocean climate model.

[3] Section 2 provides a description of the TRMC at a global scale, computed from a barotropic tidal model. In section 3 the TRMC is introduced in a climate OGCM as an external forcing and the ocean response is investigated.

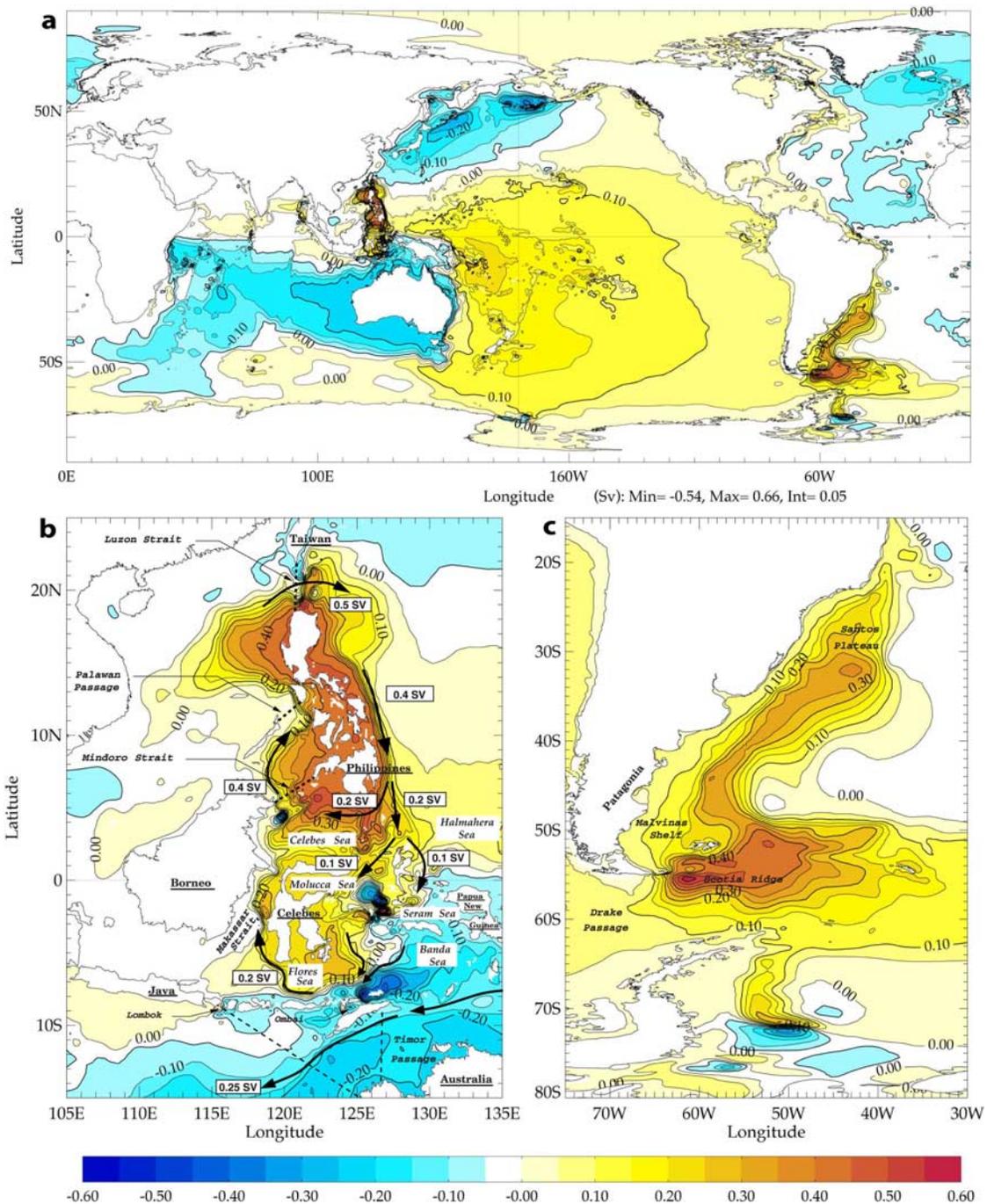
### 2. Global Tidal Residual Mean Circulation

[4] In order to compute the barotropic TRMC at a global scale, the Toulouse Unstructured Grid Ocean model (T-UGOm) has been used to generate the global ocean tides. The external mode of T-UGOm is identical to MOG2D-G non-linear hydrodynamical barotropic model [Carrère and Lyard, 2003; Lyard et al., 2006]. The finite element space discretisation (triangular  $P_1 \times P_1$  elements) allows us to adapt the model resolution with respect to the local dynamical constraints (e.g. classical wavelength criterion) and coastal geometry (e.g. local slope criterion). The resolution varies from  $\sim 10$  km along the coasts and in steep topography or shallow water areas, to 200 km in the deep ocean. The domain includes all marginal seas as well as tides under Weddell and Ross Sea ice-sheets. Tidal dissipation is introduced with both a quadratic bottom friction and an internal wave drag dissipation parameterization. The simulation has been forced by the tidal potential of the major tidal constituents, namely  $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_1$  and  $O_1$ . This set of components explains more than 90% of the observed barotropic tidal signal.

[5] We have chosen not to use data assimilation in order to maintain the consistency of the pure hydrodynamical equations. This is important as the signal we want to extract (TRMC) is weak compared to the tides themselves. Even without assimilation, the results show a very good global accuracy [Lyard et al., 2006]. Rms differences of 4.0 cm ( $M_2$ ) and 1.2 cm ( $K_1$ ) are found when compared to the best altimetry derived global models, such as GOT00 or FES2004 [Lyard et al., 2006]. The residual mean transport has been computed as the averaged instantaneous model transport over a one year period. The resulting 2D vector

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**Figure 1.** (a) Global barotropic stream function (BSF) associated with the tidal residual mean transport. Units in Sverdrup. Positive and negative transports respectively match the clockwise and counter-clockwise sense of currents. Zooms have been added (b) in the Indonesian archipelago and (c) in the Malvinas shelf area, where TRMC induced transports are the most significant.

field has been decomposed into a potential function and a barotropic stream function (BSF) associated with the divergent and rotational parts, respectively [Lynch, 1987]. The transport reconstructed from the divergent potential function is almost zero everywhere, demonstrating that a one year average is long enough to reduce the aliasing effect associated with the presence of several tidal components to a negligible level. The TRMC is thus entirely described by the BSF. Then, the BSF has been interpolated onto a global

geographic mesh of  $1/8^\circ$  i.e. a resolution comparable to the smallest finite element used. This choice of a BSF formulation has been motivated by its capacity to preserve transports, especially when interpolating on an OGCM grid with different resolution and bathymetry.

[6] The BSF associated with TRMC is shown in Figure 1a. Its intensity ranges from  $-0.54$  Sv to  $0.66$  Sv (Positive and negative transports respectively match the clockwise and counter-clockwise sense of currents). Areas of largest

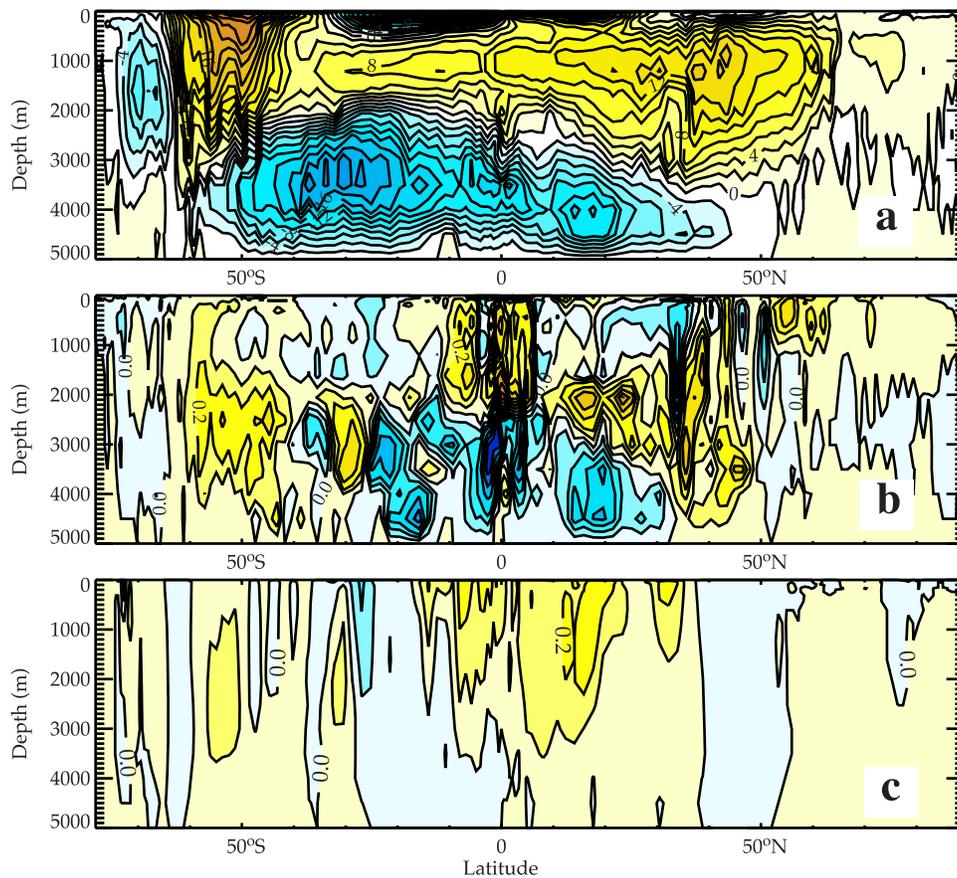
transports are located around the Philippines (0.4 Sv), Australia (0.2 Sv) and over the Malvinas shelf (0.3 Sv). All these locations are characterized by: (1) sites of large amplitude M2, K1 and M4 constituents ( $>75$  cm), (2) abrupt topography such as continental slopes and (3) western boundaries. In addition, barotropic flows along boundaries induce recirculation gyres as they have to loop back. The global map reveals a set of remarkable cells which circulation loop around these locations. Weaker but still significant cells appear along the Kurill and Aleutian Islands and north of the undersea ice shelf of Weddell Sea. A clockwise cell is also centred around the Salomon and Vanuatu Islands which fills the whole South Pacific Ocean area, but it is quite anecdotal in terms of transport. Barotropic currents associated with the TRMC range between 0 and  $14 \text{ cm.s}^{-1}$ , with a typical value of  $1 \text{ cm.s}^{-1}$ . The maximal values that exceed  $10 \text{ cm.s}^{-1}$  are found in two narrow and shallow places: Magellan straits and Tatar straits (between Sakhalin Island and Russia).

[7] Two of the three largest TRMC cells are located between the Pacific and Indian Oceans, a key position for water mass exchange (cf. Figure 1b). The northern cell is centred on the Philippine and Celebes archipelagos (the clockwise residual mean transport is: from 0.2 Sv up to 0.4 Sv). In this area the largest residual mean transport is found along the Philippine trench (0.4 Sv) with a peak in magnitude in the Luzon Strait (0.5 Sv), which represents 10% of the eastward volume transport estimated by *Tian et al.* [2006] in this strait. The transport along the Philippine trench flows southward down to the Celebes Sea where the circulation splits into two branches. A westward branch (0.2 Sv) loops back and re-circulates northward. The second branch (0.2 Sv) follows the eastern route of South Pacific subthermocline waters via the Molucca (0.1 Sv), Halmahera and Seram (0.1 Sv) Seas down to the Banda Sea. At Flores Strait the circulation loops back and re-circulates in the Makassar Strait (0.2 Sv) up to the Luzon strait. The southern cell is centred around the Australian continent with a westward extension into the Indian Ocean (the induced counter-clockwise residual mean transport is:  $-0.2$  Sv). This circulation splits into two branches before entering the ITF. A northern branch (0.1 Sv) circulates north of Papua New Guinea before supplying Lombok and Ombai Straits. The southern branch supplies Timor Passage via Torres Strait (0.1 Sv). Finally, the overall flow pattern in the ITF is only due to the southern cell. This ultimately leads to a transport of  $\sim 0.25$  Sv between Australian northern coasts and the archipelago of Indonesia. The total mean transport in the ITF is  $\sim 10$  Sv [Gordon, 2005]; therefore the TRMC in the ITF represents about 2.5% of the data-estimated transport, which is lower than the  $\sim 7\%$  estimated by *Schiller* [2004]. The higher resolution of the tidal T-UGO model (15 km coastal resolution) compared to *Schiller* [2004] model ( $\sim 50$  km) provides a more detailed description of the Indonesian archipelago region. This is particularly apparent in the area between Borneo and the Philippines where the narrow and shallow Strait of Mindoro is open, north of Palawan Passage. This strait also carries the return branch of the tidal residual mean transport (0.4 Sv) associated with the Philippine and Celebes archipelagos. Therefore, in this study the spatial structure of the TRMC is basically different than the one of *Schiller* [2004].

[8] The third main cell of TRMC has a semi-basin extension in the South West Atlantic Ocean. The patterns of the circulation draw a clockwise loop around the Malvinas shelf and the Scotia Ridge, and are correlated with the topography features. The flow is northward, offshore from the Patagonian coast up to the Santos Plateau where it loops back and re-circulates southward along the shelf break (its residual mean transport is:  $+0.3$  Sv) (cf. Figure 1c). Areas with the highest magnitude are found near the Malvinas shelf break (0.3 Sv) and around the Scotia Ridge (0.4 Sv). A peak in magnitude is found downstream of Drake Passage (0.55 Sv). Yet, the tidal residual mean transport remains two to three orders of magnitude smaller than the transport associated with the Western boundary current and the Antarctic Circumpolar Current ( $136.7 \pm 7.8$  Sv) [Cunningham et al., 2003].

[9] These results are extremely difficult to validate, as it is almost impossible to identify the TRMC in observations of the mean wind and thermohaline driven circulations [Le Provost and Fornerino, 1985]. In addition, simple time averaging of the velocity data obtained at a fixed mooring station might lead to a spurious material transport [Katsumata and Hibiya, 2003]. TRMC maps computed from barotropic tidal models are also rare in the literature, except for coastal areas [e.g., Ménesguen and Gohin, 2006] or those showing only the Stokes drift [Sentchev et al., 2006]. However, an indirect validation can be made for the two components of the TRMC: the Stokes drift and the non-linear tidal dynamic component. The Stokes drift component is well represented by the model since its accuracy is directly correlated with the accuracy of tidal constituents. The non-linear tidal dynamic component should be also well reproduced. Indeed, the T-UGOm solution for the quarter-diurnal tidal constituents is in good agreement with observations. A rms difference of 0.3 cm is found when compared to bottom pressure records deriving from BPR data base. Since the quarter-diurnal tides are produced by the same non-linear processes as the residual mean current, we have some confidence in the present results.

[10] It must be emphasized that the described TRMC does not take into account of the transport associated with the propagation of internal waves. Nevertheless, such a contribution may be considered as negligible for two reasons. The former is that a residual mean transport associated with the propagation of internal waves would require non-linear effects, the origin of which is different from the one of wave breaking and is much more localized (e.g., wave-topography reflexions or wave-wave interactions). So, internal waves do not necessarily develop such non-linearities, making such a transport hypothetical. The latter reason is that, if such a transport would happen, the fraction of tidal energy that would be dedicated to it would not range more than from about 20 to 30% of the barotropic tidal energy. Indeed, the fraction of tidal energy dedicated to internal waves ranges from about 1/4 to 1/3 of the total tidal energy that is dissipated in the ocean [Munk and Wunsch, 1998], furthermore only 2/3 of this fraction is likely to radiate away from the generation site [St. Laurent and Garrett, 2002]. Therefore, we assume in this study that the baroclinic contribution to TRMC is negligible. Yet, it must be noticed that the baroclinic tidal contribution associated with internal wave breaking has been taken into



**Figure 2.** Meridional overturning stream functions (MSFs) for the global ocean from the ocean general circulation model ORCA2-LIM, after 1500 years of run. Units in Sverdrup. (a) Numerical experiment RES including the forcing induced by the tidal residual mean circulation (TRMC). The contour interval is 2 Sv. (b) Differences between the experiments RES and NoRES (NoRES is a control run without TRMC). The contour interval is 0.1 Sv. (c) Meridional overturning circulation induced by the TRMC alone. The contour interval is 0.1 Sv.

account in the OGCM via a tidally driven mixing parameterization (Bessières et al., submitted manuscript, 2008).

### 3. Climate OGCM Response

[11] In order to explore the effects of the TRMC on the large-scale ocean circulation, we have used a climate OGCM derived from NEMO ocean modelling framework [Madec et al., 1998]. The model configuration is ORCA2-LIM: on a horizontal  $2^\circ \times 2^\circ$  Mercator tripolar grid; 31 vertical levels (with a 10 m resolution in the upper 100 m, increasing to 500 m near the bottom). The physics and the forcing are described by Iudicone et al. [2008]. The physics includes a sea-ice model; a free surface formulation; lateral mixing evaluated along isoneutral surfaces; an eddy-induced velocity; vertical mixing computed by a turbulent kinetic energy closure scheme; a diffusive bottom boundary layer; convection processes parameterized by locally enhancing the vertical diffusivity; and a synchronous time step of 5400 sec. In addition, the model uses a partial-step representation of the bottom topography and tidally driven bottom intensified mixing (Bessières et al., submitted manuscript, 2008). At the surface the model is forced by heat and fresh water fluxes, using bulk formulae and monthly climatologies of wind stress, air temperature, humidity,

cloud cover and precipitations. A restoring term to sea surface salinity is also added.

[12] As for the eddy induced velocities [Gent and McWilliams, 1990], the TRMC is introduced in the model as an external forcing, so that its associated currents are added to the eulerian velocities on the tracer advection. Interpolation consistent with the OGCM grid is required. Directly imposing with tidal residual mean transports would have led to spurious divergent quantities when interpolating, since the OGCM grid has a different spatial resolution and topography. This problem vanishes when the BSF is interpolated. Indeed, potentials are easily conserved when interpolating. As a result, extrema of the previously discussed gyre structures have not been altered, except those around the Kurill and Aleutian Islands whose spatial scales are too close to the model grid spacing. Attention has been paid to preserve the initial potential for each island accounted for in the climate OGCM. In particular, the ITF transport associated with the TRMC is exactly the same in ORCA2-LIM as in T-UGOm. The barotropic currents associated with the TRMC are then reconstructed in the model from the BSF via numerical derivations. In order to quantify the climate OGCM response to TRMC forcing, two experiments have been performed, one with the TRMC forcing (RES) and the other

one without (NoRES). An integration over 1500 years was sufficient to reach a steady state i.e. at which time the trends in globally averaged potential temperature and salinity were respectively less than  $0.02^{\circ}\text{C}$  and  $0.001$  psu per millennia.

[13] The meridional overturning stream function (MSF) diagnosed for RES experiment (Figure 2a) is in agreement with what is expected with this configuration [Judicone *et al.*, 2008; Bessières *et al.*, submitted manuscript, 2008]. The TRMC barotropic forcing is associated with an overturning circulation which is represented as MSF in Figure 2c. This resulting overturning forcing has the same order of magnitude as the BSF ( $O(0.1)$  Sv). Its spatial structure shows a set of meridional cells whose location and regional extension are correlated with the main gyres of the TRMC. The OGCM response to the TRMC forcing is presented in term of MSF difference between RES and NoRES (Figure 2b). Its order of magnitude ( $O(0.1)$  Sv) is the same as that of the overturning forcing (Figure 2c). The spatial distribution of the ocean response is not associated with an intensification of the meridional overturning cells. Instead, these structures seem to be located in maximal gradient areas, where small displacements induce strong differences. Therefore, the weak ocean response indicates that the TRMC has only a slight effect on the global meridional overturning circulation.

[14] Quantitative arguments based on TRMC forcing analysis show that the meridional heat transport (MHT) should be negligible. Firstly, barotropic flows along boundaries induce re-circulation gyres as they have to loop back. Gyres are known to be less efficient in conveying heat than the meridional overturning circulation. In the case of the Gulf-Stream, the circulation induced along the western boundary is about  $O(40)$  Sv near the surface and the associated heat transport is approximately  $O(0.1)$  petawatt (PW). Since the TRMC induced re-circulation gyres are about  $O(0.1)$  Sv over the whole water column, the TRMC induced MHT can not be higher than  $O(0.01)$  PW. Secondly, the overturning circulation due to the North Atlantic deep waters induces a  $O(10)$  Sv meridional mass transport associated with a  $O(1)$  PW MHT [Ganachaud and Wunsch, 2003]. If we consider that the MHT is proportional to the strength of the overturning circulation times the temperature difference across the pycnocline, the  $O(0.1)$  Sv meridional mass transport induced by the TRMC should not lead to a MHT higher than  $O(0.01)$  PW. Consequently, neither the gyre circulations induced by the TRMC nor the overturning ones are likely to modify the MHT beyond a hundredth of a PW. After computation, the difference in the MHT between the RES and NoRES cases is smaller than a hundredth of a PW, as expected (not shown).

[15] Largest changes in heat content are found in the Atlantic Ocean, south of Greenland, where a difference of  $-0.2^{\circ}\text{C}$  is found in the first hundred meters between RES and NoRES. This results from a  $O(10)$  km horizontal displacement in a strong temperature gradient area, which does not affect deep water mass formation in Labrador Sea. Almost everywhere else, differences of heat content in the first hundred meters remain below  $0.05^{\circ}\text{C}$  of magnitude. For example, the TRMC transport increase of  $0.25$  Sv in the ITF leads to a slight raise of the equatorial thermocline by about  $0.5$  m in the Pacific Ocean, which is proportional to

the raise occurring when the ITF is opened/closed in the model [Gorgues *et al.*, 2005].

#### 4. Conclusion

[16] The residual mean circulation induced by tides (TRMC) has been computed at a global scale and its effect on an OGCM has been investigated. The computation of the TRMC has been obtained from an accurate barotropic tidal model. The circulation spreads over large-scale gyres, whose intensities range from  $-0.54$  Sv to  $0.66$  Sv, which can be large compared to coastal circulation but remains negligible for mean large-scale circulation. These gyres generate an overturning circulation of weak amplitude ( $\sim 0.2$  Sv), which is introduced as an external forcing in an ocean climate model. The effects of this forcing on the global meridional overturning circulation are negligible. Therefore, the TRMC can be neglected in current ocean components of earth system modelling for climate purposes. Concerning the particular case of the ITF, it reinforces the idea that tidally driven mixing remains the major way for tides to affect water-masses properties [Koch-Larrouy *et al.*, 2007].

[17] Nevertheless, local non-linearities may still lead to regional modifications of the ocean state. In this regional scope, a higher resolution TRMC would better account for the bathymetry variations, which are central for resolving the patterns of the TRMC at a local scale. Although the present version of the TRMC remains sufficiently accurate for large-scale studies, it could be improved for coastal and regional studies.

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