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Discussions

On the permeability of barrier layers

J. Mignot[1], **C. de Boyer Montégut**[2], **and M. Tomczak**[3]

[1] IPSL/LOCEAN, UPMC/CNRS/IRD/MNHN, Paris, France
[2] Laboratoire d'Océanographie Spatiale, IFREMER, centre de Brest, France
[3] School of Chemistry, Physics and Earth Sciences, Flinders University of South Australia, Adelaide, Australia

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Correspondence to: J. Mignot (juliette.mignot@locean-ipsl.upmc.fr)

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Abstract

We present a revisited 2-degree resolution global ocean climatology of monthly mean Barrier Layer Thickness (BLT) first proposed by de Boyer Montégut et al. (2007a). In addition to using an extended data set, we present a modified computation method in order to take into account the observed permeability of Barrier Layers (BL). We name permeability the fact that barrier layers can, in some areas, be very patchy regarding the space and time scales that are considered. This patchiness may have important consequences for the climatic impact of BLs. Differences between the two computation methods are weak for robust BLs that are formed by large-scale processes. The former approach can however largely underestimate the thickness of short and/or localized barrier layers. This is especially the case for the ones formed by mesoscale mechanisms (under the ITCZ for example and along western boundary currents) and patchy barrier layers detected equatorward of the sea surface salinity subtropical maxima. Complete characterisation of regional BL dynamics therefore requires the description of BL robustness through the determination of both BLT and BL permeability.

1 Introduction

Generally, the base of the oceanic mixed layer coincides with the top of the pycnocline. When a barrier layer (BL) is present the density change responsible for the pycnocline is produced by a salinity change, the mixed layer salinity being lower than the salinity in the layer below. The BL is then defined as the layer between the pycnocline and the thermocline, which is found at greater depths. In this case, the temperature in the BL, immediately below the surface mixed layer is thus either the same or slightly higher than the temperature in the mixed layer itself. BLs received their name (Godfrey and Lindstrom, 1989) from their property of inhibiting turbulent and entrained heat exchange between the atmosphere and the cold subsurface ocean.

An early analysis of the distribution of the barrier layer for the global tropical ocean

(Sprintall and Tomczak, 1992) was based on the first available version of the World Ocean Atlas (Levitus, 1982). De Boyer Montégut et al. (2007) and Mignot et al. (2007) recently extended the analysis to the global ocean, using a much larger and not already interpolated observational data base (more than 500 000 temperature and salinity profiles from the period 1967–2002 and Argo profiles collected from 1996 until January 2006). These studies show the barrier layer thickness (BLT), derived as the mean or the median from all available observations, for the four seasons. They allow researchers and others to identify ocean regions where heat exchange between the atmosphere and the subsurface ocean is inhibited.

Yet, when one of us (M.T.) investigated occurrences of barrier layers in the eastern Pacific Ocean as part of the science program of voyage S216 on SSV Robert C. Seamans of the Sea Education Association, it became evident that stations with barrier layers alternated with stations where a barrier was not found (Fig. 1). The observed patchiness has the potential to modify the importance of the BL on air-sea heat exchange, since the BL can only effectively obstruct the heat transfer if it is sufficiently persistent or if it is continuous over a sufficiently large area. If the barrier layer is dotted with "holes", its role as an inhibitor of heat transfer can be greatly reduced, to the extent that the area available in the "holes" may allow turbulence and entrainment to act in the normal way.

To investigate this issue further, we propose to repeat the analysis of de Boyer Montégut et al. (2007a) with a slightly amended methodology. The 2007 analysis determines the BLT as the median from all available observations, including stations with no barrier layer. This methodology was directly inspired from the computation of the mixed layer depth by de Boyer Montégut et al. (2004). However, while the mixed layer, as a fluid surface boundary layer, is a permanent feature of the ocean, BLs are not necessarily present in the ocean. They can appear or disappear according to the space and time scales of their formation and destruction mechanisms. BLs distribution at a specific grid point is thus not necessarily gaussian but rather skewed toward high values. The former approach on a $2^\circ \times 2^\circ$-monthly grid therefore possibly underestimated the BLT when it really occurs. In this work, we determine the median thickness of all stations that effectively exhibit a barrier layer. In addition, we calculate the ratio R of the number of stations where a barrier layer exists to the total number of stations. This ratio can be considered as a measure of BL persistence. We define the permeability of the barrier layer as the quantity 1-R. Our goal is to estimate the BL robustness on a global scale regarding our time/space resolution. In some areas, thick BLs may occur but were not obvious in our previous studies as they are not persistent and/or do not occur on a large enough scale. This new study allows a better identification of such permeable BLs that should then be considered carefully regarding their possible climatic impact on air-sea interactions

The following section presents the new data set and the new methodology in more detail. The results are presented in Sect. 3 and conclusions are given in Sect. 4.

2 Data and methodology

2.1 Data

The present study is based on the collection of about 750 000 instantaneous temperature and salinity profiles measured between 1967 and September 2008 (Fig. 2). They were obtained from the World Ocean Database (WOD) 2005 at the National Oceanographic Data Center (NODC) (Boyer et al., 2006), the World Ocean Circulation Experiment (WOCE) database (WOCE Data Product Committee, 2002), and the ARGO data base (from Coriolis Global Data Assembly Center, www.coriolis.eu.org). The previous study by de Boyer Montégut et al. (2007a) was based on the same data base but included only data until January 2006 for the ARGO data base and until end of 2002 for the NODC (WOD2001) and WOCE data bases.

The 2007's study did not include statistical information. The major reason for this was the relatively small number of profiles available at some places (Fig. 2a in de Boyer Montégut et al., 2007a), which put the significance of the statistics into question. Since about 100 000 new ARGO profiles are currently collected every year, part of this problem could be overcome by prolonging the period covered: more than 200 000 additional profiles are available when extending the period from January 2006 to September 2008.

2.2 Methodology

As in de Boyer Montégut et al. (2007a) and Mignot et al. (2007), we compute the BLT for each profile based on the difference between two depths: $D_{T-02}-D_\sigma$. $D_{T-0.2}$ is the depth where the temperature has decreased by 0.2°C as compared to the temperature at the reference depth of 10 m. D_σ is the depth where the potential density σ_θ has increased from the reference depth by a threshold Δ_σ equivalent to the density difference for the same temperature change at constant salinity:

$$\Delta_\sigma = \sigma_\theta(T_{10}-0.2, S_{10}, P_0) - \sigma_\theta(T_{10}, S_{10}, P_0) \tag{1}$$

T_{10} and S_{10} are the temperature and salinity at the reference depth 10 m and P_0 is the pressure at the ocean surface. If the difference $D_{T-02}-D_\sigma$ is positive, the pycnocline is shallower than the thermocline and a BL occurs with BLT=$D_{T-02}-D_\sigma$ Note that the layer comprised between the surface and $D_{T-0.2}$ can be isothermal but this is not general, as shown by the presence of subsurface temperature maxima in de Boyer Montégut et al. (2007a). If the difference $D_{T-02}-D_\sigma$ is negative, the pycnocline is deeper than the corresponding thermocline. No BL occurs in this case but rather a vertically compensated area (de Boyer Montégut et al., 2004).

In order to reduce these individual data over the 2°×2°grid, we first repeat the method employed in de Boyer Montégut et al. (2007a) and Mignot et al. (2007) by defining the BLT as the positive values of the median of *all* differences $D_{T-0.2}-D_\sigma$ available for each grid mesh. This estimation thus mixes together profiles with real BL events and profiles where no BL is present ($D_{T-0.2}-D_\sigma \leq 0$). The interpretation of this climatology is that for each grid point, the likelihood that a profile has a BLT larger than the given value is 50% and equals the likelihood that its BLT is smaller than the given value.

It is obvious that this methodology underestimates the barrier layer thickness that really occurs, although it is impossible to tell to what degree, since the monthly charts do not contain information about the number of stations without a barrier layer. In other words, they do not include information on the BL patchiness as observed in the central Pacific (Fig. 1). Therefore, we propose to compare this analysis with a slightly amended one: for each grid mesh, we now select profiles that do exhibit a significant BL before computing the median. The selection criterion, applied to each profile, is arbitrarily fixed to

$$\begin{cases} D_{T-0.2} - D_\sigma > 5\,\mathrm{m} \\ D_{T-0.2} - D_\sigma > 10\%(D_{T-0.2}) \end{cases} \tag{2}$$

Note that in the previous approach, for clarity of the figures, we had arbitrarily chosen to shade grid points where the final median value met these criteria (see figures in de Boyer Montégut et al., 2007a and Mignot et al., 2007). But all profiles were used for the computation and the data product (http://www.locean-ipsl.upmc.fr/~cdblod/blt.html) includes all final values. Here, the computation excludes profiles that do not meet these criteria. Note also that the first condition cannot simply be $D_{T-0.2}-D_\sigma>0$ because of the vertical resolution of data (5 to 10 m for ARGO floats). The second condition is particularly needed in the extra-tropics where isopycnal and mixed layers are relatively deep so that an absolute difference of 5 m does not have the same meaning and impact as in the Tropics. In order to give more robustness to the statistics, we only consider grid points where at least 5 profiles are available. In both approaches, no kriging of the final data is applied in order to keep a point-wise interpretation of the comparison.

In addition to the BL thickness itself, the second approach provides statistics on the amount of profiles with a BL satisfying the criterion (Eq. 2) compared to the total number of profiles available at the specific grid point with both $D_{T-0.2}$ and D_σ defined. This ratio R can be interpreted as a measure of the BL persistence: it gives information on the robustness of the measured BL as compared to the totality of the measurements that were done at the location. We define the BL permeability as the quantity (1-R)

expressed in percent. The more the BL is patchy regarding the space/time scales considered, the greater the BL permeability is.

3 Results and discussion

3.1 BL permeability

Figure 3 shows monthly maps of BL permeability on the global 2°×2° grid. In several areas, BL permeability is less than 25%, i.e. the majority of available profiles does indeed show a significant BL thickness. In these areas, the BL can thus be considered as a robust, impermeable feature and the heat transfer from the atmosphere to the ocean is quasi-permanently hindered for the observed month. In the Tropics, these areas are essentially the ones that Mignot et al. (2007) highlighted as the thickest and the most persistent: the Bay of Bengal and the southeastern Arabian Sea (BLT peaking in February), the eastern tropical Indian Ocean (November), the northwestern tropical Atlantic (in boreal winter), the Pacific warm pool and the South Pacific Convergence Zone (SPCZ) (BLT peaking in austral autumn and winter) and the western Mediteranean Sea (in winter). As detailed in Mignot et al. (2007), these BLs are due to the large scale advection of various freshwater sources (rivers and seasonal precipitations). Thus, they extend over macro-areas and they are logically rather impermeable. They are also expected to have a real and robust impact on air-sea exchanges. (The quantification of the latter is beyond the scope of the present paper).

Permanent differences between D_{T-02} and D_{σ} are also detected at high latitudes in winter (North Pacific, Labrador Sea, Norwegian Sea and Austral Ocean south of 50° S). As discussed in de Boyer Montégut et al. (2007a), these differences are due to the layering of different water masses rather than air-sea interface physics. Their low permeability results from this large scale characteristic. However, their climatic impact is probably limited by another factor: the fact that they occur at relatively great depths, since the winter mixed layer is deep at these latitudes (below 100 m in the North Pacific and 200 m in the Labrador Sea). Therefore, we do not comment further on the potential climatic role of the BLs detected in these regions.

Next, Fig. 3 also contains areas where the BL permeablity is comprised roughly between 25 and 60%. In particular, permeability index under the central and eastern Pacific ITCZ away from the warm pool is around 25–40% in boreal summer This value suggests that two to three summer profiles collected in this area out of four exhibit a BL. Another way to see this value is that BLs detected in this area persist over slightly more than half of the sampling time, that is one month here. In this case, air-sea interactions are hindered by a BL during 60–75% of the sampling period. Note that our study does not indicate whether this BL period is continuous over the observed month, and followed by a continuous period where no BL is present, or whether the BL is present intermittently on a daily time scale for example. These two extreme cases might have themselves different climatic impacts as discussed in Sect. 4. Nevertheless, this permeability ratio can be linked to the BL formation mechanism: under the ITCZ, mesoscale turbulent activity is thought to play an important role in generating BLs (e.g. You, 1995 1995, Cronin and McPhaden, 2002). Since this activity is not resolved by our $2^\circ \times 2^\circ$ monthly grid, we do expect a relatively high permeability ratio (it increases to up to 75% in boreal winter). It becomes evident here that the notion of permeability cannot be separated from the time and space scale of the study.

Another major area of permeable tropical BL is the southern Arabian Sea in summer, studied recently by Thadathil et al. (2008). This BL area was already detected in Mignot et al. (2007) but it had not been commented because of its small thickness. The present analysis emphasizes that it is not necessarily thin but rather permeable (about 50% or more). Durand et al. (Barrier layer in the Arabian Sea during summer monsoon, in preparation) show that during this season, BL formation is linked to the southward displacement of a high salinity front and its associated mesoscale instabilities. This mechanism is consistent with a relatively permeable BL. Note also the intermediate permeability ratio of the winter BL located offshore of California and already mentioned in de Boyer Montégut et al. (2007a).

Winter BLs located equatorward of the subtropical SSS maxima were one of the major findings of Mignot et al. (2007). It was shown that their formation mechanism is still under discussion, with the relative influence of the large scale layering of different water masses on the one hand, and of seasonal vertical turbulent mixing on the other hand not being well established. These BLs clearly appear in Fig. 3 with intermediate permeability indexes, but generally less than 50%. This tends to confirm some influence of turbulent mixing below the 2°-monthly scales, at least that subsurface advection of salty waters is not the only factor inducing the formation of these BLs.

Figure 3 also reveals several grid points where the permeability index amounts 60 to 90%. This corresponds to very permeable BLs, which probably have a relatively limited impact on air-sea heat exchange and thus climate. Indeed, in this case, the exchange of heat between the mixed layer and the ocean interior is perturbed by an intermittent BL, but it is not permanently blocked. Figure 3 shows that such intermittent BLs are potentially present in all regions of the globe, in any season in the Tropics and mostly in winter in the mid to high latitudes. They are also detected along the western boundary currents in summer, especially along the Gulf Stream. In this region, indeed, BLs may occur due to mesoscale eddies coming from instabilities of the current and bringing fresh water lenses from the north (de Boyer Montégut et al., 2007a and references therein). This formation mechanim is again consistent with the transient feature revealed by Fig. 3.

Finally, the figure still reveals areas where no BLs are ever detected (permeability above 90%). These are essentially the winter midlatitudes (compensation areas) and the summer northern midlatitudes (except along the western boundary currents as indicated above).

3.2 BL thickness

We compare now the BLTs given by the approach developped here (Fig. 4) with the one developped in de Boyer Montégut et al. (2007a) and Mignot et al. (2007) updated with the new data set (not shown – see supplementary material http://www.

ocean-sci-discuss.net/6/799/2009/osd-6-799-2009-supplement.pdf). The first thing to note is that the new computation retrieves many more observed barrier layers than when all stations are used to compute the final median value of the BLT, and that BLs computed by the new approach are naturally generally thicker than the ones computed by the former method (Fig. 5). Differences are mostly evident in areas where the BL permeability (Fig. 3) is intermediate to high (40 to 90%). Indeed, in these regions, a large proportion of profiles without barrier layers pushes the median toward a very low value of BLT if they are included in the computation. On the other hand, a low permeability (say less than 30 to 40 %) means that the majority of the collected profiles are captured by the criterion given in Eq. (2), so that the two methods become equivalent. And when a BL is too permeable (more than 90%), it is most probably very thin, so that both approaches also give similar values. Therefore, the major breaking point of this new product concerns BLs of intermediate permeability. In this case, the 2007 method takes a large amount of profiles that do not present a significant BL into account so that it strongly underestimates the resulting BLT.

In the Tropics and subtropics, the maps of differences (Fig. 5) are rather patchy. Consistent with the discussion above, differences are small (generally less than 5 m) in the tropical Indian Ocean, the Pacific warm pool, under the SPCZ and in the northwestern tropical Atlantic. They can amount to 10–25 m in the central equatorial Pacific and 5–10 m in the central equatorial Atlantic (under the ITCZ). In the Indian Ocean, some significant differences are visible in the Bay of Bengal in May, in the northern Arabian Sea in February and March and in the southern Arabian Sea in August. Figure 3 revealed a higher permeability ratio during these specific months than during the rest of the year. As reviewed in Mignot et al. (2007), these months correspond to the end of the thick BL cycle at the corresponding location, so that it is not surprising to detect less BLs, particularly towards the end of the month. In this respect, this new approach of the BLT computation can also give insight into the characterization of BL seasonality. Finally, we note differences up to 30 m thickness for BLs located equatorward of the subtropical SSS maxima in winter.This amounts to 40 to 70% of the BLT computed by the new approach.

Large differences (Fig. 5) are also found at mid to high latitudes in winter. In these areas, BLs can indeed be very thick (over 1500–200 m, de Boyer Montégut et al., 2007a), so that incorporating or neglecting profiles where a BL is absent makes a strong difference in the resulting BLT. Noticeable differences are also seen along the western boundary currents in the northern hemisphere all year long.

To conclude, this new BLT climatology (Fig. 4) is probably more physical than the previous one (de Boyer Montégut et al., 2007a), but it should not be considered without the associated permeability ratio (Fig. 3).

4 Summary and conclusions

This study presents an amended climatology of the global barrier layer thickness of de Boyer Montégut et al. (2007a). In addition to using an extended data set, we propose a modified computation method in order to take into account the observed permeability of barrier layers. We name permeability the fact that barrier layers can, at least in some areas, be very patchy in space and in time. This permeability may have important consequences for the climatic impact of BLs.

The new computation method is based on an a priori criterion of BLT applied to individual profiles before reducing the data set on a regular grid. It differs from the previous approach where reduction on the grid consisted of taking the median of *all* individual differences $D_{T-02}-D_{\sigma}$, without considering whether it corresponds to a BL (i.e. $D_{T-02}-D_{\sigma}>0$) or not. The new computation goes along with a measure of the ratio R of the amount of profiles that exhibit a significant BL over the total amount of available profiles, for each grid point. 1-R is a measure of the BL permeability relative to the space and time scales that are considered. The monthly mean differences $D_{T-02}-D_{\sigma}$ computed with the new method and using the extended data set, as well as the monthly permeability ratio, can be downloaded from http://www.locean-ipsl.upmc.fr/~cdblod/blt.html. They show that BL phenomenon potentially occurs nearly everywhere but with diffierent permeability indexes. If the latter is high (over 75 to 90%), then the potential impact of the BL for air-sea interactions and climate is likely to be negligible.

One major finding of this analysis is the link between the BL's formation mechanism and the associated permeability index. Note that Tomczak (1995) already mentioned a possible link between BL formation and its persistence in the tropical western Pacific Ocean. Our global product confirms this link for well-known BLs and gives insight in potential formation mechanisms in other areas. In the tropical Indian Ocean (except for the southern Arabian Sea), the western tropical Pacific and Atlantic, BLs are formed by large-scale, mostly advective, processes and they are thus rather impermeable. In these areas, the analysis showed very weak differences (less than 5 m) with the previous climatology (de Boyer Montégut et al., 2007a). On the other hand, BLs under the ITCZ and in the Arabian Sea in boreal summer develop under the action of mesoscale, turbulent processes that are not resolved by our time and space scales. These BLs were thus logically associated with a larger permeability index. The former computation largely underestimated these BLs and their detection through the new climatology constitutes a major improvement. Concerning the BLs detected equatorward of the subtropical SSS maxima in winter, their intermediate permeability index gives confidence in the fact that some turbulent activity probably plays a role in their formation. A similar distinction could be made at mid to high latitudes: Strongly impermeable BLs due to the layering of fresh and cold waters over warmer and saltier waters are found at high latitudes in winter while more permeable BLs are found at mid latitudes in areas of strong turbulent activity (along the Gulf Stream in particular).

The climatic implications of BL permeability depend to some degree on the way in which the data are grouped for the statistics. Our study groups them into bins of 12 months. Two extreme situations are then possible, with a whole range of intermediate situations as well. At one end of the scale, the barrier layer might exist and blanket the area for two weeks and disappear for the remaining two weeks of the month. At the other end, it might only exist for one day, be broken down during the next day, reappear on the following day, just to be broken down again, and so on. In both cases, its "permeability" – as derived in our study – will be the same (50%), but its consequences for air/sea heat exchange could be quite different. Permeability as we present it here is an attempt to estimate the life time of monthly BLs and thus their robustness relative to this timescale (one month). One way to gain better insight into the problem of quantifying the climatic impact of BLs would be to base the analysis on shorter time intervals, for example weekly bins. Shorter bins however reduce the number of observations in each bin and render the statistics unsafe. The final answer can probably only be obtained through time series with sufficiently high resolution in time. Maybe a detailed assessment of barrier layer permeability requires dedicated field studies in regions of interest that can generate time series capable of resolving processes at time scales of days. With such data in hand, an absolute timescale giving the expectancy lifetime of the BL could be defined. This notion is indeed probably as important as the BL spatial extent in order to evaluate its climatic impact.

Sprintall and McPhaden (1994) carried out such an analysis using mooring data at 0°, 165° E. They estimated the dominant timescale of BLT in the western equatorial Pacific to be around 12–25 days. It is however difficult to link this result with our study because our definition of permeability is also relative to our space resolution (2°). Indeed, variability of barrier layer persistence in time is of course not the only cause for high barrier layer permeability. Variability in space can produce high permeability as well, and our method is unable to distinguish between the two situations. In the observations obtained in the the central Pacific by SSV Robert C. Seamans, a barrier layer was present at 7 stations and absent at 10 stations (Fig. 1), yielding a permeability of about 59%, somewhat larger than but not inconsistent with the value derived from the climatology for March (Fig. 3). With an average station spacing of 40 nm (70 km) the resulting permeability could be interpreted as the result of variability in space, perhaps reflecting the localized character of tropical rain storms. However, SSV Robert C. Seamans being a sailing vessel crossing an ocean with moderate to low winds it took the ship more than a week to cover the 1250 km, so some of the observed variability could be the result of changes in time as well.

Finally, we suggest that another parameter of BLs be considered, on top of the thickness and permeability: the intensity of the salinity stratification is probably is crucial parameter for the robustness of the BL and its efficiency in limiting the heat exchange betweenthe surface and the cold deeper ocean.

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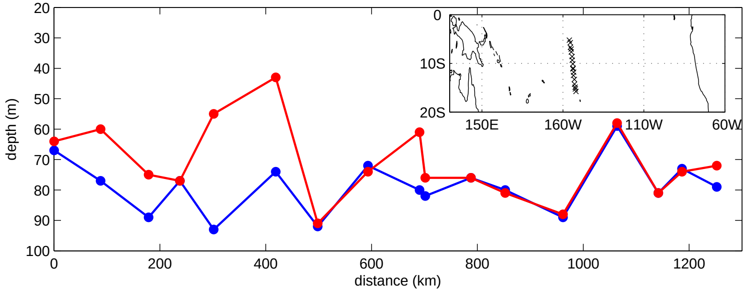

Fig. 1. Thermocline (blue) and pycnocline (red) depths measured in the central Pacific from 5° S to 15° S along approximately 155° W during the science program of voyage S216 on SSV Robert C. Seamans of the Sea Education Association (map in the top right corner, the crosses indicate the stations, the voyage was undertaken southward). The measurements took place between 17 April and 26 April 2008. The thermocline and pycnocline depths are defined as the depths $D_{T-0.2}$ and D_{σ} respectively in de Boyer Montégut et al. (2007a) (see Sect. 2.2). Stations where the pycnocline is shallower than the thermocline are stations where a barrier layer was detected.

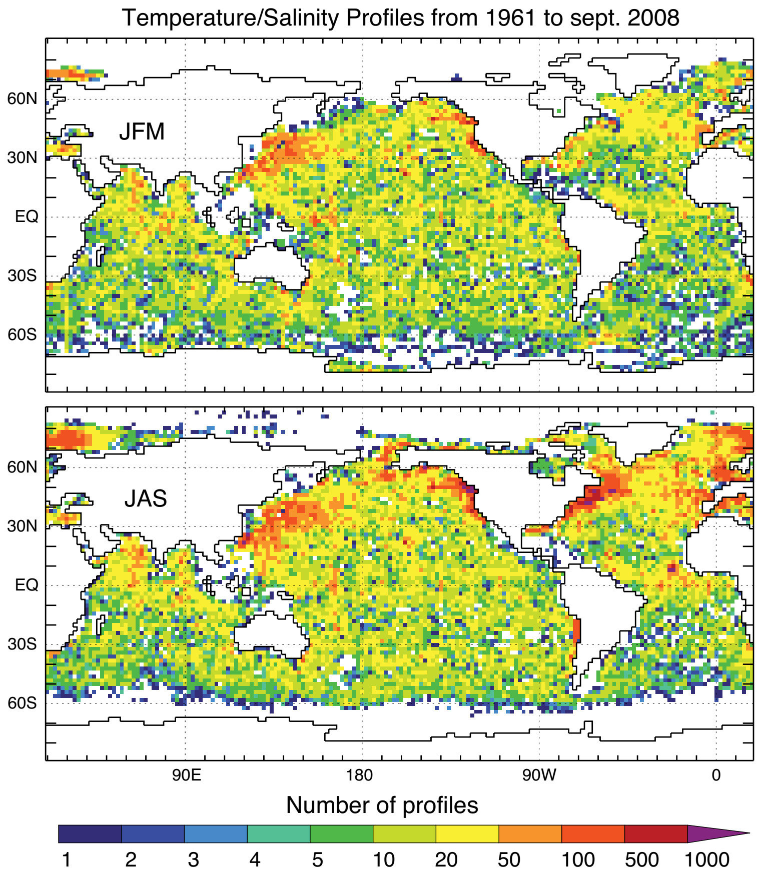

Fig. 2. Distribution of profiles including both temperature and salinity data in each 2° by 2° mesh box. JFM and JAS indicate the two seasons January-February-March and July-August-September, respectively. This figure should be compared with Fig. 2a in de Boyer Montégut et al. (2007a).

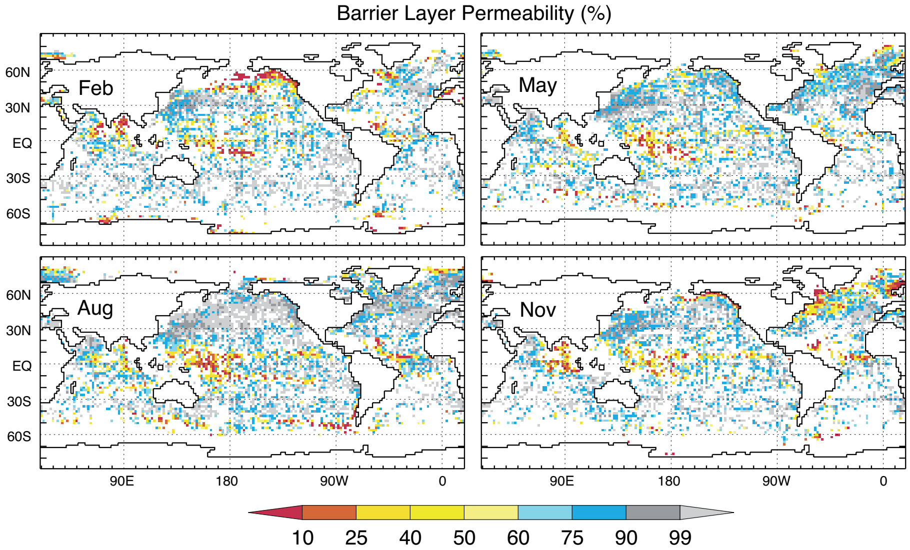

Fig. 3. Selection of 4 monthly maps showing the BL permeability measured as 100*(1-*R*), where *R* is the ratio of the number of profiles where a significant BLT is detected over the total number of profiles available at this location with D_{T-02} and D_σ both defined. Light grey oceanic areas show grid points where BL permeability is 100%, i.e. no BL was ever detected. White areas show grid points where less than 5 profiles where available with both D_{T-02} and D_σ defined. See Fig. A1 in the supplement (http://www.ocean-sci-discuss.net/6/799/2009/osd-6-799-2009-supplement.pdf) for the full 12 monthly maps.

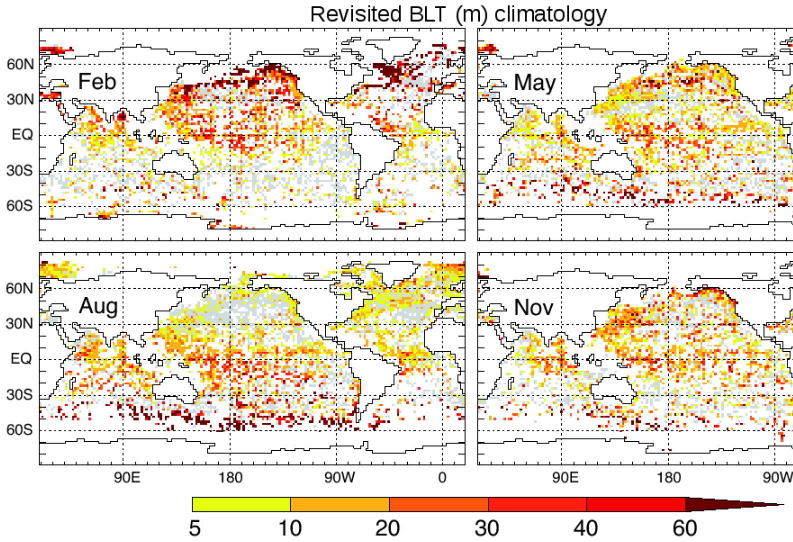

Fig. 4. Selection of 4 monthly maps of the difference $D_{T-02}-D_\sigma$ computed as described in Sect. 2.2: for each grid mesh corresponding to a square of $2^\circ \times 2^\circ$, we plot the median of all differences that are larger than 5 m and 10% of D_{T-02}. Light grey oceanic areas show grid points where no BL was ever detected. White areas show grid points where less than 5 profiles were available with both D_{T-02} and D_σ defined. See Fig. A2 in the supplement (http://www.ocean-sci-discuss.net/6/799/2009/osd-6-799-2009-supplement.pdf) for the full 12 monthly maps.

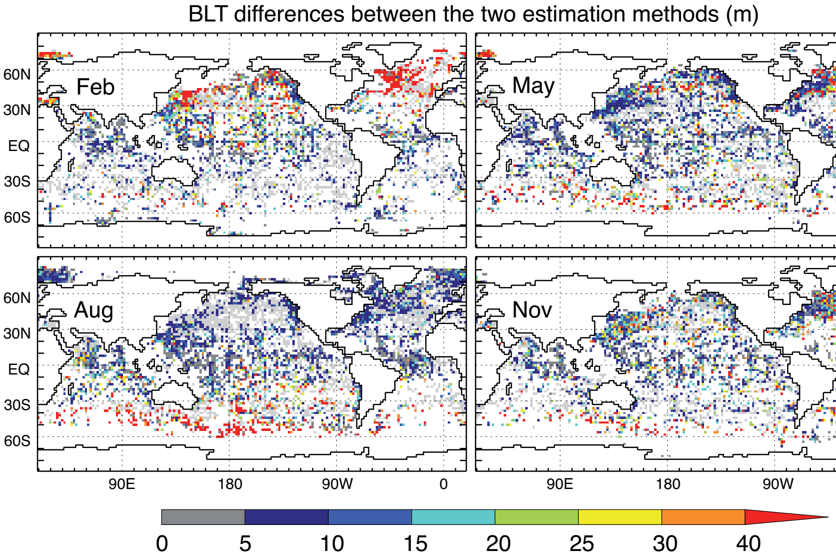

Fig. 5. Selection of 4 monthly maps of the BLT differences between the two computation methods. See Sect. 2.2 for more details. See Fig. A3 in the supplement (http://www.ocean-sci-discuss.net/6/799/2009/osd-6-799-2009-supplement.pdf) for the full 12 monthly maps.

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