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Ocean Science Discussions

Interactive comment on "Sea surface salinity variability from a simplified mixed layer model of the global ocean" *by* S. Michel et al.

S. Michel et al.

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3. MLD estimate

3.a. MLD estimate variability

Referee 1: *A deliberate choice was made to use a mixed layer depth in the model that is estimated in a rather complicated, non-linear way from the observed SST variability and fluxes. It is really hard to figure out whether these estimates are reasonable or not (and I am more concerned with their variability, because of the assumption of what happens to SSS when there is entrainment, see below). This could have been tested a little further with sensitivity studies. For instance, one can fear that the errors on the heat fluxes (roughly to give a range on the order of 40 to 80 W/M2) would have in some situations huge impact on the estimated mixed layer depth (MLD). It would be relevant* *to have a few time series of what these smooth climatological MLD seasonal variability looks like in different areas (and not just the two March and September maps. Is the variability rather smooth, or does it present large sea-saws.*

We have validated the MLD estimate from our inversion technique through various sensitivity studies. We preferred not to describe these experiments in this paper, as it is already rather long. In brief, we tested the MLD sensitivity to several inversion schemes (direct computation, sequential method, minimisation), with several datasets (fluxes from the SOC climatology, ERA15 and ERA40 reanalyses), several time-steps (hourly, daily, monthly) and several depth steps in the minimisation method. Using the latter method, the results appear reasonably robust. We concluded that a daily forcing frequency and a 1-meter time-step are sufficient to reproduce the MLD seasonal evolution over most of the global ocean.
The parameterisation used in case of detrainment ensures the mixed layer (upward) retreat is reasonably slow, while the (downward) entrainment is slow by nature. Thus, the MLD evolution is generally smooth and does not present any sea-saw features.
The MLD temporal variability has been examined in details over several subdomains of the global model (as alluded to on page 60). In particular, a detailed study of the North-East Atlantic is presented in a previous paper, which has not been published yet: Michel, Chapron and Tournadre: “Heat budget in the North-East Atlantic from a simplified mixed layer model forced by meteorological and altimeter data”, submitted to Ocean Dynamics in 2005 (hereafter SCT 2005).
The draft of this paper can be downloaded from this FTP site:
ftp://ftp.nbi.ac.uk/pub/general/smic/Thesis/article_OceanDynamics.pdf
See in particular the monthly maps of MLD from January to April in the North-East Atlantic (Fig. 5 of the latter paper), which compare reasonably well with the climatological thermocline (Fig. 4) and pycnocline (Fig. 6) depths from De Boyer-Montegut et al, 2004. The MLD time-series in the POMME area (Fig. 7) are in close agreement with these two climatologies, whilst being less smooth due to the finer temporal resolution. Also the simulated MLD appears very similar to the high resolution measurement

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during the POMME experiment (Gaillard et al, 2005).

The modelled MLD and corresponding heat balance have also been analysed in the Kurushio Extension Region and over the whole North Pacific. Readers interested in these validation studies can access the Ph.D. manuscript by S. Michel (in French) from the previous FTP site:
ftp://ftp.nbi.ac.uk/pub/general/smic/Thesis/These_revision_chap4.pdf

As noted by the referee, our MLD estimate is dependent on the accuracy of the net air-sea heat flux, as well as on the other forcing data. The accuracy of the surface heat flux from the ECMWF model is estimated around 10 W.m^{-2} on average (Uppala, 1997: Observing System Performance in ERA. ECMWF Re-Analysis Project Report Series). An order of magnitude of the associated MLD error can be inferred by considering the effect of a 10 W.m^{-2} error on the daily mean flux. If we assume the SST variation can be as high as 1 degree C during 1 day, the uncertainty on MLD is equal to (from Eq. 1):
$dT/dt = Q_{net}/(C_p \rho_0 h)$
$h = Q_{net}/(C_p \rho_0 dT/dt)$
$dh = dQ_{net}/(C_p \rho_0 dT/dt)$
$dh \sim 10/(4000 \times 1020 \times 1/60/60/24) \sim 0.2m$
Thus an error in the range of 40-80 W.m^{-2} would lead to a MLD uncertainty of the order of 1-2 m. This can be a critical error for SSS reconstruction where the ML is particularly shallow (in the range of 10-20 m), as in the equatorial band. But this error is acceptable over most of the global ocean, where our MLD estimate is generally at least 50-100 m.
However, the surface heat flux is not the only process which affects MLD. Other processes have a strong impact on MLD and their associated errors can be much higher than those of the surface heat flux (mainly error in geostrophic current, wind stress, SST variations).

3.b. Vertical entrainment representation

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Referee 1: *Then, in integrating the SSS equation to have the seasonal SSS fields, a fairly large assumption was made on the vertical advection (both for T and S). It is barely described, but acts as a strong negative feedback on actual variability towards the climatology in case of detrainment. Other assumptions could have been made, which would have a less drastic effect. Based on that, it is not surprising that the "winter hemisphere" SSS looks rather close to the observed one. The actual S which is entrained is taken from a climatological monthly profile at the actual depth of entrainment. This comes from a climatology which is known to have some serious month-to-month noise. What is the impact of that on the results? Again, this is a function of the amplitude of changes in MLD, and when entrainment actually occurs, and how often this happens.*

We have to concede that the vertical mixing representation in the model is relatively crude. But we would like to point out a few objections to the referee's comments. We are convinced this representation mimics efficiently the effect of vertical mixing, averaged over the mixed layer thickness. In the model, vertical entrainment is basically separated in two distinct regimes:
1) In case of (downward) **entrainment**, the mixed layer water is mixed with the lower layer water, according to the equation:
$(dS/dt)_e = w_e(S(z=-h) - S(z=0))/h$
where $w_e > 0$ is the entrainment velocity
2) In case of (upward) **detrainment**, only the MLD is modified (h decreases), while the ML properties are unchanged.
Thus entrainment acts a feedback toward the properties of the lower water, which are indeed taken from a monthly climatology in our simulation. In case of entrainment, **SSS is not relaxed toward its climatological value, but toward salinity in the deeper layer**. This process generally increases SSS, as can be seen from the annual mean effect in Fig. 9d, because salinity is generally higher at depth. The simulated SSS is relaxed toward the SSS climatological value only if the MLD is lower than the depth of the upper level in the climatological fields (10 m for the World Ocean Atlas used here).

Moreover, this feedback is strong only if the velocity w_e is high and the MLD h is shallow. Our simulation shows that w_e is mainly controlled by the rate of MLD variation *dh/dt*.
dh/dt values are of the order of 1-10 m.day^{-1} (10^{-5} to 10^{-4} m.s^{-1}).
h varies in the range of 10 to 1000 m.
S(0)-S(-h) can be as high as 35 psu, but is generally lower than 5 psu.
Therefore, the impact of entrainment depends crucially on the MLD estimate, which comes from the SST inversion in our simulation. The reliability of the SST inversion appears more critical than the accuracy of the salinity climatology. Regarding the noise in the in situ analysis, the salinity time-series are interpolated to obtain daily values, what reduces the impact of month-to-month "bumps".
Finally, vertical entrainment is not important everywhere in the global ocean. From the RMS of the entrainment impact on salinity (Fig. 10d), it is mostly significant in two types of areas:
- the tropical bands where the MLD is permanently shallow,
- the subtropical northern Atlantic (North of 40N) and Pacific (North of 50N) and the ACC, where the MLD is strongly variable (see RMS value in Fig. 5b).
The maps of annual mean SSS from the climatology and from the simulation (Fig. 14) are reasonably close over most of the ocean, not only where vertical entrainment has a strong impact. This shows our model performs well, with or without the relaxation toward the climatology due to downward entrainment, and is efficient over a broad range of oceanic regions.

3.c. Sensitivity of the MLD estimate

Referee 2: *Page 51: The semi-implicit numerical method may be unconditionally stable but this does not guarantee accuracy. Does the 1 day time step affect the accuracy of the MLD solution?*

No, the time-step on the MLD inversion does not impact significantly on the solution. The 1 day time-step was chosen to be equal to the frequency of the forcing data, as we use daily means for air-sea fluxes and SST input. 6-hourly data are also available

from the ERA40 reanalysis, which would enable to address the diurnal cycle. But we want to focus on longer time-scales, from 1 day to the annual cycle.
We may interpolate the input data linearly in time, to compute the MLD at a higher frequency. But as our MLD estimate depends on the variation rate of SST, not on SST itself (see Eq. B3 and B4 in appendix B), and on the time-mean of fluxes, this would not make a large difference. Several sensitivity experiments were performed, using either a higher (hourly) or a lower (monthly) frequency. In areas where the inverted MLD is stable (i.e. following a closed annual cycle), these experiments produce roughly the same results as with the original (daily) frequency.
Our inversion technique appears more sensitive to the choice of the depth step for the minimisation (in case of downward entrainment). We found that a 1-meter step leads to a sufficient accuracy, whereas a 10-meter (or higher) value may provide very different results.

3.d. Comparison to the T02 thermocline depth

Referee 2: *The comparison of the mixed layer depths in Fig. 3 shows some very large differences where the mixed layers are deep (e.g. in the Southern Ocean) with the slab model much deeper than the T02 De Boyer-Montegut depth. One might expect the T02 depth to be deeper than the actual well mixed depth (e.g. if salinity stratification controls the depth of vertical mixing) but is it not clear how the slab depth can be so much greater than the T02 depth. Are the authors confident that these differences are not due to inaccuracies in the MLD inversion at high latitudes?*

The MLD obtained from the inversion is **almost systematically larger** than the T02 thermocline depth. This is true not only in the Southern Ocean, but also over most of the global ocean, with the exception of the lowest latitudes. In Fig. 3, the scale is twice larger for our MLD estimate than for the T02 depth. These scales were chosen to highlight the similarities in the spatial structures, despite very different values in the two fields.
As explained at the beginning of Sect. 3, the model MLD is an "effective depth". It

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ensures the consistency between the model variables (SST, SSS) and the forcing data (wind stress, heat flux, geostrophic current). But there is no reason why it would be systematically higher or lower than any particular "physical depth", such as T02. Every MLD estimates from observed data rely on an arbitrary definition. In the case of T02, the depth is based on a temperature decrease of 0.2 degree Celsius from its value at 10 m. Other authors used a threshold as high as 1.0 degree Celsius, or the maximum of the vertical gradient. Each definition can be appropriate in a particular context and is equally valid, but none of them is universal. Our model estimate does not require any such empirical criterion, but arises naturally from the model formulation.

If the vertical mixing penetration is controlled by the salinity stratification, the thermocline depth does not reflect the MLD. The penetration of air-sea fluxes is limited by the lowest of the thermocline and halocline depths. Our model formulation ensures that the resulting depth h always characterises the fluxes penetration.

In Figs. 3 and 4, the only areas where the simulated MLD appears clearly shallower than the T02 depth are located in the ITCZs. These are precisely the regions where we can expect salinity barrier layers (e.g. the Fresh Warm Pool in the western tropical Pacific). In these areas, the model MLD is still consistent with the surface forcing, while the thermocline depth is not representative of the mixed layer.

At high latitudes, Figs. 3 and 4 show very high MLD values both in the Northern oceans and in the ACC. Such values are probably overestimated, as the inversion accuracy decreases with increasing latitude (as seen from Figs. 6, 7 and 8). As stated in Sect. 3.3, this inaccuracy is due to combined factors: lower accuracy in the forcing fields, weaker stratification and absence of sea-ice representation. Moreover, because of the lack of in situ temperature data in polar oceans, the T02 depth is not expected to be accurate either in these regions.

3.e. Representation of vertical mixing

Referee 2: *Page 57: I don't see how the lack or correlation in tropical areas can be attributed to the lack of a mixing mechanism in the model. As I understand the slab*

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model it has no knowledge of specific vertical mixing processes but infers the amount of vertical mixing from the SST observations. The other explanations offered seem more likely.

Our slab mixed layer model does not depend on any vertical mixing parameterisation, as the MLD is inferred from the observed effect of the vertical mixing on SST. Thus the model does not contain any details on how this mixing impacts temperature. However, this representation of vertical mixing could be improved.
For example, we could impose a **temperature profile** within the mixed layer, rather than a simple step function. By doing so, the thermal stratification at the mixed layer base would be modified. The vertical temperature gradient is expressed:
$[SST - T(z = h)]/h$
and would be replaced by:
$[T(z = h - dz) - T(z = h + dz)]/2dz$
Hence the impact of vertical entrainment would generally decrease.
This is not an additional mixing mechanism, but a refinement of the model representation of vertical mixing.
In the horizontal direction, some mixing mechanisms could be added to replace or enhance the simple Laplacian operator used in the present model configuration. For instance, to take into account the effect of **eddy activity**, we could use a variable diffusivity (κ) computed from the TKE. Thus the diffusivity would increase with wind stress and current velocity. Additionally, we could include in the model the effect of **lateral induction**, due to horizontal transport across the mixed layer base. This would require a computation of the ML slope, which would be become significant only if the model resolution is increased.
Therefore, an improved representation of the vertical mixing and/or additional horizontal mixing mechanisms could lead to a better correlation between the simulated and observed MLDs. The second explanation (inconsistency between SST and forcing fluxes) is also likely to play an important contribution. But sensitivity experiments are necessary to separate the effects of mixing and forcing.

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3.f. Representation of horizontal mixing

Referee 2: *Page 59 Line 24: The implication seems to be that the choice of a small horizontal mixing coefficient (section 2.3) is having an impact rather than the absence of a particular mixing mechanism.*

The small horizontal mixing coefficient (κ =2000 m.s^{-2}) is probably adequate in most areas having a weak eddy activity. But in strongly turbulent areas, horizontal diffusivity should be increased, as suggested in the previous paragraph. Where horizontal diffusion is underestimated, the model compensates by adjusting the vertical mixing to fit the input SST evolution. As the vertical mixing intensity is controlled by the MLD, the depth h is the free parameter which enables the model to reproduce the observed SST. Thus the low estimate of horizontal mixing can lead to overestimate the MLD variability. Moreover, the vertical entrainment generally cools the mixed layer, because upward retreat does not impact the ML temperature while downward entrainment includes colder deep water into the ML. As a consequence, underestimating horizontal mixing can also produce too cold a mixed layer temperature. Therefore, the model results could be improved by enhancing the horizontal Laplacian diffusivity (κ) or adding a mixing mechanism to parameterise the effect of eddies. Both the MLD variability and the SST cold bias are expected to be reduced.

3.g. Method of MLD estimation

Referee 4: *I think the formulation of mixed layer depth should be introduced and expanded upon in a separate paper. A good portion of the present paper is devoted to validating the mixed layer depth formulation. This distracts from the main purpose of the paper, discussion of the factors involved in mixed layer salinity evolution. It would be nice to have a more expansive treatment of the mixed layer depth formulation elsewhere. I am not convinced by the authors' arguments for the need for the mixed layer depth formulation as opposed to using a monthly climatology. Stating that in situ mixed layer depth product is based on subjective criteria (p 54) or arbitrary criteria (p 77)*

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does not do justice to in situ mixed layer climatologies. In the in situ calculations of De Boyer-Montegut et al., a definition of mixed layer is put forth, and then calculations performed. I would not term this arbitrary or subjective, even if the definition, of necessity has some subjectivity. Similarly the present paper presents a definition of mixed layer depth and then performs the calculation. The definition includes terms partial derivative of h with respects to input variable (dTh) and partial derivative of h with respects to time. I would need to be convinced that these parts of the definition are not also arrived at with some degree of subjectivity. And is there an initial mixed layer depth? If so, how is this calculated?

Once again we believe that the computation of the mixed layer salinity budget should not be separated from the estimation of the mixed layer depth. The two issues are strongly related, as the MLS budget can not be interpreted without knowing how the MLD is estimated. But we agree that the long discussions about the MLD in Sect. 3 divert the reader from the main results, which deal with the salinity budget analysed in Sect. 4. Thus, in the revised version of the paper, we will summarise Sect. 3 as much as possible, in order to focus on the findings in Sect. 4.
As we pointed above, the MLD formulation has already been described in a previous paper (SCT 2005, to be re-submitted). The inversion method is explained in details and its evolution is analysed in the North-East Atlantic. In this article, we also compare the results obtained by using the MLD climatology computed by De Boyer-Montegut et al. (2004). Their T02 thermocline depth is used as an input to the slab mixed layer model, instead of using our MLD estimate from the SST inversion. We computed the surface heat budget from each simulation and we find that the thermal balance is reached over a larger area when using our synthetic MLD (Fig. 19). We also find that the SST variability is better reproduced with our MLD estimate, both at daily and at seasonal scales (Figs. 20, 21). Thus, in terms of mixed layer budget and temperature, the simulated MLD appears more reliable than the in situ climatology. This result was expected, as it confirms that our inversion method is efficient in reconstructing observed SST variations.

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Nonetheless, we agree with the referee that the criteria used to define MLD from water properties are not “arbitrary”. Some degree of subjectivity is necessary to extract an exact depth value from a vertical profile which is supposed to be continuous, but is always described with discrete data. De Boyer-Montegut et al. (2004) selected their temperature criterion after a very careful examination of the MLD statistics obtained with several thresholds ($\Delta T =$ 0.2, 0.5 and 0.8^{o}C). Among these 3 values, $\Delta T =$ 0.2 leads to the best trade-off between all the regions of the global ocean. But nothing in their analysis ensures that $\Delta T =$ 0.1 or 0.3 would not perform better. The choice of the test values for the threshold is the only thing that makes this climatology “subjective”. In our simulation, the MLD definition is implied by the model formulation. No parameter is needed, but the result is ultimately dependent on the choice of the input data, as well as on the simulation time step. Thus one could think that our MLD estimate is more “arbitrary” than an in situ estimate. The main point is this MLD only exists to ensure the consistency between forcing data and model properties.
Finally, the initial MLD is taken from the final time step of a previous simulation, which was initialised using the T02 climatology. We found that a 1-year simulation is long enough to enable the model to adjust to the forcing and input data over most of the global ocean. Thus a longer “spin-up” would not make a significant difference in terms of MLD seasonal cycle.

3.h. Impact of SST errors on MLD

Referee 4: *The authors state (p. 53) that SST data from satellites have high resolution and accuracy. It is hard to dispute the high spatial coverage, but accuracy is another matter. How accurate are satellite SST and how do SST errors affect the mixed layer depth formulation? Further, would the errors inherent in the present papers formulation of mixed layer depth be small enough to justify using the formulation? A change of 10 meters over the course of the model run is potentially a large error (or is it real?) in areas where the mixed layer depth is shallow. Finally, do the daily variations of the mixed layer depth (vs. error) justify the need for mixed layer depth calculation at less* *than the monthly resolution of the climatogies? All of these questions could probably be easily addressed in a separate paper.*

The accuracy of SST satellite data is much higher than a few years ago, even if it is still far lower than in situ data. For blended satellite products (such as GODAE High Resolution SST, see http://www.ghrsst-pp.org), the accuracy is considered to be better than 0.1^{o}C over the whole ocean.
Note that we used the SST from the ECMWF model, which assimilates satellite data, rather than direct remote sensing products. Moreover, our SST climatology is computed from 12 years of the ECMWF reanalysis. Thus, errors in the input SST are considerably reduced compared to raw satellite data. Additionally, the time evolution is smoother than in a monthly climatology. This enables us to compute daily SST variations with an acceptable level of confidence. We are convinced that no other dataset, either from in situ observations, models or satellite data, would provide a significantly better accuracy over the global domain.
Meanwhile, this accuracy might still be too low in highly sensitive areas. For instance, in areas where the MLD is very deep, even a weak error in SST can imply a strong change in the controlling processes. Thus a negative SST error could be converted into strong downward entrainment, while a positive SST error could be translated into a strong MLD decrease, enhancing the impact of solar heating.
To simplify the estimation of the SST error impact on MLD, we can consider the case where horizontal processes are negligible. The model equation for temperature is thus reduced to:
$dT/dt = Q_{net}/(C_p \rho_0 h) + w_e(T_d - T)/h$
$h = [Q_{net}/C_p/\rho_0 + w - e(T_d - T)]/(dT/dt)$
If we consider a case without entrainment, with a 100 W.m^{-2} surface heating and a 0.1^{o}C temperature variation during 1 day, the impact of a 10% error on the MLD would be:
$\delta h = [Q_{net}/C_p/\rho_0]/(dT/dt)^2 \delta(dT/dt) \sim$ 2 m
If we consider a case with negligible heating and entrainment only, with a 10 m MLD

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variation during 1 day, a 1^{o}C temperature gradient and the same temperature error as previously:
$\delta h = w_e(T_d - T)/(dT/dt)^2 \delta(dT/dt) =$ 10 m
Both of these errors are acceptable if the MLD is not shallow, i.e. deeper than 100 m. The simulated MLD is generally around 200 m at subtropical latitudes and as high as 1000 m at subpolar latitudes (Figs. 3, 4). Thus, over most areas the impact of SST errors on MLD is acceptable. Only in tropical regions and particularly in the equatorial band, such errors could become critical. In our paper, we warn the readers that the model results are "less reliable" at low latitudes, even if this is difficult to quantify. The MLD errors computed above are based on high estimates. Therefore, the accuracy of the MLD can be considered to be lower or equal to 10 m.
MLD daily variations have an order of magnitude of 10 meters per day. Thus the error on one particular day can be critical, but it would be compensated on the following days. Overall, the MLD evolution appears reasonably smooth, but it exhibits much more detailed variations than a monthly climatology (see Fig. 7 in our previous article SCT 2005).
Therefore, we believe it is worthwhile to compute the MLD estimate from the model, instead of using an in situ estimate. And we think the errors on the input data are low enough to obtain a reasonable MLD at a daily frequency.

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