Ocean Sci. Discuss., 4, S131–S142, 2007
www.ocean-sci-discuss.net/4/S131/2007/

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.

Received and published: 24 April 2007

4. Mixed layer salinity balance

4.a. Areas of model validity

Referee 1: *Also a comment is made at the beginning of 4. to use criteria to select areas where the salinity budgets are relevant. However, these areas are not clearly selected on the following figures.*

Referee 4: *I see figures 9, 10, 11 as the heart of the paper, along with table 2. On page 60 the authors state that figures 6, 7, and 8 together show those areas for which the model results do not meet stated criteria. However, it is hard to relate the information from these 3 different figures to the interpretation of figures 9, 10, 11. Either an additional figure showing all areas where the criteria are not met, or a masking of values in*

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figures 9, 10, 11 in these areas would help with the interpretation of these figures.

We agree the 3 criteria proposed at the beginning of Sect. 4 are not used explicitly in the examination of the salinity budget. From the results described in Sect. 3, the MLD estimate validity appears dubious in two types of regions:
- in the equatorial band (5S-5N), due to the absence of Ekman advection in its vicinity and higher uncertainty on the surface fluxes,
- over polar regions (roughly South of 60S and North of 70N), due to the lack of sea-ice impact and improper vertical mixing representation.

In the final version of the paper, we will mask these areas on the subsequent global maps (Figs. 9, 10, 11) and ensure they are consistent with the global budget presented in Table 2.

4.b. Diapycnal mixing in the North Pacific

Referee 4: *Figure 11 shows diapycnal mixing as the major factor in salinity balance in the mixed layer for much of the North Pacific. Yet, as the authors state, significant convection in the North Pacific occurs only on the margin (Sea of Ohkotsk). So, how to explain the dominance of diapycnal mixing in the North Pacific? Could it have to do with the formulation of the mixed layer depth calculation neglecting the salinity barrier layer which can be important in this area?*

In our model, the diapycnal mixing term acts as a residual term, when no other process can explain observed SST variations. In the North Pacific, we believe this term is overestimated because the temperature vertical gradient is insufficiently accurate in the World Ocean Atlas 2001 climatology, due to a lack of in situ data. This is shortly explained on page 78, line2, but we will try and make it clearer in the final version of our article.

From Eq. 1, it can be seen that the vertical entrainment term, thus diapycnal mixing, is expressed as:

$$\Gamma(w_e)w_e(T_d(z=h)-T(z=0))/h$$

Then the intensity of vertical entrainment is affected by errors in the climatological temperature T_d, which in turn affects the simulated MLD *h*.
In contrast, we do not think the MLD formulation in the model neglects the effect of salinity barriers. Where salinity barriers are important, they impact the observed SST, As a consequence, their presence is reflected in the simulated MLD. As explained in Sect. 3, this depth is not a thermocline depth, but an estimate of the effective penetration depth for the surface fluxes, which can be controlled by salinity barriers as well as by temperature stratification.

4.c. Impact of freshwater flux on SSS

Referee 4: *The authors state (p67) "Moreover precipitations produce shallow mixed layers, while evaporation induces thicker mixed layers, thus the impact of P on SSS is generally stronger than the impact of E." This needs more explanation. Why does precipitation produce shallower mixed layers? Why do shallower mixed layers have a stronger impact on mixed layer salinity or SSS?*

Precipitations decrease salinity in the surface layer, thus decreasing its density and increasing its buoyancy. This process enhances stratification and produces a shallower mixed layer. In very weakly turbulent environment, precipitations can even create a thin surface layer made of freshwater (“rain cells”), which acts as a shield against the downward penetration of solar heat flux.
Conversely, evaporation increases SSS, reduces stratification at the ML base and produces unstable water column, which tends to increase the MLD. It can be seen from the equation governing salinity in the ML (Eq. 2) that the shallower the MLD, the stronger the freshwater flux impact:
$(dS/dt)_{freshwater} = (E - P - R)S/h$
As shown on Figs. 13 and 14, precipitations-dominated areas are generally associated with small MLDs (such as ITCZs in the tropical band), whereas evaporation-dominated areas are associated with relatively large MLDs (e.g. centres of subtropical gyres). For example, the simulated MLD is around 20 m below ITCZs and around 100 m in

the subtropical gyres of the winter hemisphere. Thus the impact of a -10 mm.day^{-1} precipitation in ITCZs would be approximately -0.02 psu.day^{-1}, while the impact of a +10 mm.day^{-1} evaporation in a subtropical gyre would be +0.004 psu.day^{-1}.
This mechanism will be detailed more thoroughly is the final article. Note that the only adverse effect in the model lies in the vertical entrainment term. As MLD increases, the salinity difference between the ML and the deeper layer ($S(0) - S_d(z = h)$) increases too. Thus the vertical gradient ($(S - S_d)/h$) can be enhanced, but only if stratification increases faster than linearly with depth. In this case only, a deeper MLD can imply a stronger impact of one of the model processes (i.e. the vertical entrainment term).

4.d. Advection in the Arabian Sea

Referee 4: *The authors state (p75) "The local maximum is due to the advection of salty water from the Bay of Bengal" when talking about the Gulf of Oman. The Gulf of Oman has an outlet to the Arabian Sea, not the Bay of Bengal.*

We were really thinking of the Bay of Bengal, which is located to the East of the Indian subcontinent, not of the Gulf of Oman, which is the northern part of the Arabian Sea, to the West of India.
During dry periods of the monsoon cycle, a westward current brings salty water from the Bay of Bengal, round the tip of India, into the Arabian Sea (G. Reverdin, personal communication). This current lies along 5N and is clearly seen in the SSALTO-DUACS analysis from December to March. Its signature can be seen on the map of geostrophic advection RMS value (Fig. 10b). We believe this current carries intermittently salty water from the southern Bay of Bengal. This would explain the salinity maximum obtained in the simulation around 15N-65E, which has no counterpart in the in situ climatology. The climatology only represents a weaker and more wide-spread SSS maximum in the Gulf of Oman (around 20N-60E), which is due to the input of high salinity water from the Persian Gulf. This is an example of the model ability to produce finer SSS features than the climatology.

5. SSS variability in the simulation

5.a. High frequency of forcing

Referee 1: *I have also a general question on the strategy retained to keep in the average year some residual of the day-to-day variability (see table 1, if I understand it correctly). This introduces high frequencies which confuse the issues and might have resulted in some strong variability in MLD and from that in the frequency of entrainment. I feel that we need to have some guarantees that this is not a major issue. I am mentioning that, because the modelled variability appears rather large in some areas compared to what is expected (but Fig. 13 indicates small day-to-day increments; actually, is this figure really relevant?).*

We agree that the resulting SSS variability is probably overestimated in some regions. However, the main reason for this does not lie in the forcing data, but in local instabilities of the MLD inversion. Some day-to-day variability remains in the forcing data, but we have shown it does not impact the simulated MLD and SSS to a great extent.
The forcing data have been prepared by computing an average year with a daily time step, from 12 years (1990-2001) in the case of meteorological variables and from 4 years (August 2001-August 2005) in the case of geostrophic velocities. Thus the daily fields may still contain some high-frequency variability, which can be considered as natural “white noise” superimposed on the slow seasonal cycle.
In the real ocean, the mixed layer integrates rapid variations from the atmospheric forcing over its thickness. Thus the mixed layer responds on time scales much longer than the characteristic time scales of the atmosphere. The deeper the ML is, the slower it reacts to changes in air-sea fluxes. For our model to be realistic, it has to mimic this behaviour. We find the simulation results are consistent with the real ML dynamics. This can be seen from all three fundamental quantities in the model:

1) MLD

The MLD evolution at a given location is generally smooth, as detailed above when addressing the MLD estimate variability (see SCT 2005). No rapid oscillations are obtained. This is partly due to the inversion algorithm, which ensures a continuous evolution of MLD and limits the rate of MLD decrease in case of detrainment.

2) SST

In our previous article cited above, the sensitivity of the model to the forcing frequency has been investigated. We performed a simulation in which all the forcing data has been smoothed with a 30-day running mean. Thus day-to-day variability is removed from the forcing and only monthly variations are represented. This simulation is called “MLDmon” and is compared to the simulation analysed in this article, called “MLDday”. In MLDday, the components of the heat budget exhibit much more high-frequency oscillations, in particular the entrainment term. This can be seen in the heat budget time-series in the POMME area (Fig. 18 of SCT 2005). However, these oscillations do not result in large fluctuations in the simulated SST. Indeed, the SST variability in MLDmon and MLDday has a similar distribution and the values are only slightly higher in MLDday. This is found in terms of day-to-day increments (Fig. 20c,e of SCT 2005) and in terms of standard deviation of SST (Fig. 21c,e of SCT 2005). Moreover, the impact of using another MLD estimate (the thermocline depth from De Boyer-Montegut et al, 2004) is much more dramatic. When using this in situ MLD (simulations “T02day” and “T02mon”), the model produces a SST variability with a very different distribution and much higher values, as the depth is generally shallower.

3) SSS

The SSS variability at daily time scales appears much weaker than the seasonal variability. Indeed, the RMS value of day-to-day increments is generally around 0.01 psu, while the standard deviation of the simulated SSS is around 0.5 psu. If we consider a purely seasonal cycle with an amplitude ΔS, its standard deviation is:

$$\sigma_M = \Delta S/2^{3/2}$$

The corresponding day-to-day increments have a RMS value of:

$$\sigma_D = \Delta S \times 2/365$$

Thus the relationship between the two standard deviations is:

$$\sigma_D = \sigma_M \times 4 \times 2^{1/2}/365 \sim 0.02 \times \sigma_M$$

As a consequence, the average value of $\sigma_M \sim$ 0.5 psu corresponds to $\sigma_D \sim$ 0.01 psu, showing the variability is dominated by the seasonal cycle. Nonetheless, σ_D is much higher in some areas (exceeding 0.1 psu) and its global distribution (Fig. 13) is considerably different from σ_M (Fig. 12b). Thus daily fluctuations add a significant contribution to the total variability.

We think Fig. 13 is relevant to illustrate this result, but its colour scale should be changed to enable the comparison with the total variability displayed in Fig. 12. Roughly, a factor of 50 could be applied to the scale in Fig.13, as σ_D = 0.01 corresponds to σ_M = 0.5. Other diagnostics of the high-frequency variability are equally valuable, but this one does not rely on any filtering of the time-series.

5.b. Uncertainty of in situ SSS

Referee 2: *Page 44, line 12: Concerning the estimation of uncertainties for the error covariance matrix. Could the authors clarify whether this problem is due to lack of data, or some other reason, and why is this a particular problem for optimal interpolation?*

The uncertainty on salinity is more difficult to estimate than for other variables, simply because less observed data are available. In some areas, particularly in the Southern Ocean, salinity is known from only a couple of measurements over the last decades. See for example the SSS data distribution in the World Ocean Atlas 2005:
http://www.nodc.noaa.gov/cgi-bin/OC5/WOA05F/woa05f.pl

For assimilation methods, as well as for optimal interpolation, error covariance is generally set to the observed RMS variance multiplied by a constant coefficient. For example, in Gaillard et al (2005), the optimal interpolation of the POMME data is based on a Kalman filter, with a prediction error taken as a percentage of the climatological variability.

Thus, if the number of observations is reduced by a factor 10, the error estimate increases by a factor $10^{1/2} \sim 3.2$. The global SST is known from about 10 times as many measurements. As a consequence, a global analysis of SSS would have an error estimate approximately three times higher than the corresponding SST analysis.

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We have cited the case of optimal interpolation, because this is the usual method used to reconstruct the salinity distribution at a global scale, from in situ measurements. The phrase on page 44, line 12 will be formulated more clearly as:
“Data assimilation and optimal interpolations rely on the estimation of uncertainties, which is still particularly difficult in the case of salinity, due to a critical lack of data in many regions.”

5.c. Resolution of salinity climatologies

Referee 4: *The authors state (p. 43) that "only global climatologies can be generated, with a resolution limited to 1 degree in space". In the references to this paper is a reference to Boyer et al. of a 1/4degree global climatology.*

The paper by Boyer et al. (2004) presents a global climatology of temperature and salinity with a 0.25 degree resolution. This is actually an update of the World Ocean Atlas 2001 (Boyer et al., 2002) which is used in our simulation. The same in situ database has been used, but a new objective analysis method provides a better representation of small structures and isolated areas. However, in the case of salinity, improvements are impeded by the lack of in situ measurements, which increases the noise level at higher resolution. Thus over most of the global ocean, the climatological SSS is not significantly different in the 1 degree and 1/4 degree analyses.

5.d. Global annual salinity variation

Referee 4: *This would help the reader understand the magnitude of the equivalent annual salinity variation of -.38 (page 68). Is this an average annual variation? This is a huge variation. The authors state that the ECMWF reanalysis precipitation is in excess of evaporation over a given year. The authors could calculate how much of the salinity variation is due to this P-E imbalance. It is perfectly acceptable to have a freshening over the global ocean for a year. But I don’t think the magnitude of the change is realistic. In 100 years the mixed layer would be pure freshwater if that annual rate of change continued. And adding the ice covered areas would reverse this freshening?*

What does this say about the model results? Are errors so large as to be unrealistic? I don't think so, but I need to be convinced of this.

The phrase the referee is writing about is on line 8, page 68: "The total tendency indicates a net freshening by $-1.05 \times 10^{-3} psu.day^{-1}$, equivalent to an annual variation of $-0.38 psu.year^{-1}$."
This is an annual variation, averaged over the ice-free global ocean surface. This value should not be considered as a result from the simulation, but as a quantification of the salinity balance closure. Clearly, the balance is not closed over this nearly global area, but we do not expect it to be so. First, because nothing in the model ensures that the global balance would be closed. The input data are taken from various sources and the formulation does not guarantee local balance. Second, because the area over which this average is computed is not global. High latitudes regions are not included, but they have a potential for acting as huge sinks or sources of salt (if the amount of sea-ice tends to decrease or increase, respectively).
The impact of the E-P imbalance on the SSS balance can be estimated approximately using mean values of MLD and SSS. The mean MLD is around 200 m and the mean SSS is 35.0 psu. From Eq. 2 we get:
$dS/dt = (E - P)S/h$
In the ECMWF reanalysis, the E-P global budget is almost zero. But we can consider the mean error on E-P to be of order 0.1 mm.day^{-1}. The associated error on SSS would be $0.02 \times 10^{-3} psu.day^{-1}$.
Conversely, the global annual variation from the simulation would correspond to an E-P imbalance of $6mm.day^{-1}$. This is certainly larger than the mean E-P error expected over the global ocean.
But our results suggest that if polar regions were included properly, the global SSS balance would be much smaller, or even reverse sign.

5.e. Errors in daily variation

Referee 4: *This extends to daily variations. Are the errors in daily salinity calculations* *acceptable? The daily changes in salinity due to the different factors are very small. Are they significant compared to errors? This is not a trivial question, and I don't know how the authors can answer the question. But some answer beyond simple comparison with in situ climatologies is important. The authors mention in the perspectives section that daily salinity variations can be compared to PIRATA and TAO salinity measurements if the model is run with one years worth of forcing. But I think the comparison can and should be made with the run of the model already completed, if only to validate the magnitudes of the daily variations.*

Validating the daily SSS variations is indeed a difficult task, given that very few observed datasets are available at this frequency. Buoy arrays such as PIRATA and TAO are the only source of daily salinity data we can think of, but they are restricted to tropical areas. The ARGO profilers provide an almost global coverage, but the analysis frequency is weekly at the best. GCMs can access both a global coverage and daily frequencies, but they still use a relaxation to a climatological salinity in the surface layer. Thus none of these data sources can be compared to the daily variations from our model.

Moreover, validating precisely the SSS daily variability is beyond the scope of this paper. We aim at assessing the model performance at a global scale and we focus on the seasonal cycle, whilst describing quantitatively the variability at higher frequencies. The simplest way of validating the daily variations is based on the seasonal evolution, which arises from the accumulation of day-to-day variations. The seasonal cycle appears to be realistic over most of the domain, as seen from monthly SSS maps compared to the climatology (not shown). Additionally, the annual mean SSS is overall well preserved in the simulation (Fig. 14). Besides this simple qualitative validation, we propose a more quantitative assessment below.

We show that the daily SSS variability, as estimated from the RMS of daily increments (Fig. 13), is generally lower by one or two orders of magnitude than the seasonal variability (Fig. 14). For instance, in tropical regions where seasonal variability often exceeds 1.0 psu, daily variability is around 10^{-2} psu. We can consider the global SSS

imbalance ($1.05 \times 10^{-3} psu.day^{-1}$) as an estimate of the mean error in daily variations. Then the daily variability (Fig. 13) is significantly greater than this error over most of the global ocean, except in deep subtropical areas, away from the influence of all major driving forces.
In conclusion, validating accurately the daily SSS variability against in situ data would require a paper on its own. However, we are fairly confident that:

- the daily variations are significantly higher than model errors,
- they are accurate at the first order, as they lead to a realistic seasonal evolution.

5.f. Simulated and climatological SSS variability

Referee 4: *The authors state (p. 71) that simulated variability is higher than in situ climatology variability because of the daily forcing used. But the simulated values in this comparison are monthly means, just like the in situ climatology. Even if there are large daily variations, the mean monthly value should average out to be similar to the in situ climatology. So, I don't think the difference in variability of the monthly means can be explained by the daily forcing.*

Referee #4 is right to point that daily fluctuations are cancelled out in the monthly averages, from which the monthly variance is computed (shown in Fig. 12b). However, as noted by referee #1, "high frequencies [in the forcing data] [] might have resulted in some strong variability in MLD and from that in the frequency of entrainment". This can be extended to the other processes represented in the model, not only vertical entrainment. Non-linear impacts of the high frequency forcing can result in strong MLD and SSS variations at lower frequency.
The model sensitivity to the forcing frequency was investigated in our previous article (SCT 2005), by comparing simulations using daily data and monthly smoothed data. We concluded that high frequency variability in the forcing have a generally modest impact on the simulated SST, though it can be significant is particular areas (Fig. 21 of SCT 2005). Note that SST variability can be either enhanced or reduced by a higher forcing frequency.

Where vertical entrainment dominates, the variability of ML temperature and salinity tends to decrease. Indeed, faster fluctuations in the surface fluxes allow MLD to adjust more rapidly. Indeed, vertical entrainment is activated more frequently and ultimately damps variations of the ML properties by relaxing them toward the deeper layer properties.

Other non-linear effects explain the model response to high frequencies in the input data. For each process which intensity depends on MLD, the model response is not linear, Thus it can be seen from Eqs. 1 and 2 that air-sea fluxes, Ekman advection and vertical entrainment have non-linear behaviour. As a consequence, the seasonal variations arising from the combination of these processes are can be higher (but also lower in some areas) with a daily forcing than with a purely seasonal forcing. Therefore, we expect a stronger SSS variability in the simulation than in the monthly climatology, particularly in regions where freshwater fluxes and/or Ekman advection control the ML salinity. Conversely, this variability could be weaker in areas where vertical entrainment is the dominant process.

Interactive comment on Ocean Sci. Discuss., 4, 41, 2007.