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Interactive comment on "Control of phytoplankton production by physical forcing in a strongly tidal, well-mixed estuary" *by* X. Desmit et al.

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Control of phytoplankton production by physical forcing in a strongly tidal, well-mixed estuary. X. Desmit, J.P. Vanderborght, P. Regnier, and R. Wollast

Answers to Anonymous Referee #3

General comments:

We thank Ref. #3 for the very positive appreciation given in the first part of his general comments. We regret the confusion caused by an imprecise set-up or some ambiguous definitions, and hope that we succeeded in clarifying these points in the revised paper. First of all, we have deleted all references to the euphotic /mixing depth ratio. In our text, we have used the concept of "euphotic depth" in its purely physical meaning (i.e. the depth at which the irradiance is equal to 1% of the surface irradiance). Accordingly,

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"euphotic depth" is only depending on 2 parameters: the incident solar light (forcing function 1) and the light extinction due to turbidity (forcing function 2). The mixing depth is equal to the water depth in a well-mixed system (forcing function 3). As a result, the euphotic to mixing depth ratio is, in our mind, a simplified way to refer to the combined effect of all 3 physical forcings. But it is true that we never use it explicitly to get insight into the results: it is used as an indicative parameter only, is thus uninformative and is a potential source of confusion in our discussion. We have thus decided to discard it completely.

In addition to this change, we have added a more accurate description of averaged and time-varying values, and when they are respectively used. We have also added 3 complementary graphs that, we think, greatly support our conclusions about the overall importance of high-frequency variations of the light regime. Finally, we tried to make clear that water depth is always considered as a time-varying function in all simulations.

Specific comments:

(1) To address as precisely as possible the first specific comment of Ref. #3, the introduction has been modified in the following way (starting p. 38, l. 24): "It is indeed well established that the net phytoplankton production is determined by the ratio between critical and mixing depths, the former being defined as the depth at which vertically integrated photosynthesis equals vertically integrated respiration (Sverdrup, 1953; Grobbelaar, 1985; Cloern, 1987; Falkowski and Raven, 1997). In this production-loss balance, the first term (vertically integrated photosynthesis) not only depends on biological parameters: it is strongly linked to the light availability within the water column, which is itself controlled by physical forcing mechanisms. This control is particularly critical in turbid environments such as estuaries and coastal waters, which are often under the influence of significant particulate terrigeneous fluxes (Postma, 1980)." In the same way, the conclusion now reads (starting p. 52, l. 17): "In this paper, we have applied a simple model to assess the net phytoplankton growth in a system characterized by high-frequency variations of the physical forcing functions. In this type of system,

it is difficult to draw intuitive conclusions about the phytoplankton production-loss balance, because of the complex interactions involved. Simulation results show that, in shallow to moderately deep systems (<15m), this balance may be strongly affected by the short-term (˜ hourly) fluctuations of the light regime, in particular by those linked to SPM dynamics. This effect may even lead to a situation where a completely inverse long-term evolution of the biomass is predicted when the tidal fluctuation of the turbidity is not taken into account. We have also demonstrated that (...)."

(2) Thanks!

(3) The direct (in situ) measurement of kd is based on a formula given in Kirk (1994, op. cit.). Given that the vertical light profile is decreasing exponentially, the value of kd can simply be obtained by measuring the irradiance Ed at two different depths z1 and z2:

$kd = 1/(z2-z1) . \ln [Ed(z1)/Ed(z2)]$

Reference to Kirk (1994) is added in the paper.

(4) Self-shading by the phytoplankton is not explicitly accounted for in the model. In our test system (the Scheldt estuary), it generally plays a comparatively small role in the overall turbidity. Typical values of SPM concentration at our test sites are in the range 50-200 mg.L-1, whereas phytoplankton biomass is most of the time lower than 10 mg.L-1(dry weight). Another argument for not explicitly considering self-shading is that, as stated in our paper, phytoplankton cells are weakly affected (if at all) by settling and resuspension during tidal cycles. Algal concentration in the water column does not follow the typical tidal pattern of "ordinary" SPM, but only adds a baseline value to kd. It is thus not very demonstrative for the purpose of our paper.

(5) We appreciate very much that Ref. #3 draws our attention to the paper by Lucas & Cloern (2002) which is indeed very complementary to ours. Not mentioning this paper in our work is obviously a flaw that we are happy to correct in our revised version. Lucas

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and Cloern have indeed followed a very similar approach, looking at the effect of the variability, on a short time scale, of phytoplankton sources and sinks. A main difference is that, in their case, the tidal variability of the phytoplankton sink is (partly) caused by the influence of benthic grazers (which increases with decreasing water depth). In our case, we consider the variability of the phytoplankton source, due to the tidal variation of the turbidity and the diel variation of the solar light. We also like to quote the last sentences of Lucas and Cloern (1999b), for it adds a strong argument in favour of our approach based on the use of a simple, zero-dimensional model: "The large number of mechanisms co-operating in real estuaries is a compelling reason for using simple models; like laboratory experiments, models allow us to isolate and study one or a few processes at a time in a controlled fashion and help us generate new hypotheses for looking at complex real systems in new ways. Outcomes from simple models can also provide useful guidelines for constructing complex and comprehensive ecosystem models. In this case, a simple zero-dimensional model defines combinations of environmental conditions in which tidal-scale processes absolutely must be incorporated into estuarine ecosystem models."

In the same comment, Ref. #3 wonders if we have considered the effect of fluctuating Z_{max} in our results (in the same way as Lucas and Cloern did in the paper cited above). The answer is definitely yes, and we are sorry that this was not clear enough in our paper. We therefore insist here that all simulations have been performed with a time-varying water depth Z_{max}, using a time-step value of 30 minutes. In the first set of simulations, the variation is purely sinusoidal. The tidal range is equal to 6m (i.e. the amplitude is 3m, see technical comment 2!) The water depth at mid-tide (what we confusingly called the "mean value", and have renamed "average value" in our revised paper) is comprised between 6 m and 20m in the various simulations (see Fig. 3 and 13). In the second set of simulations, the tidal variation of Z_{max} is also considered, using the results of a 1D hydrodynamic model, as stated in the text.

Finally, Ref. #3 suggests that we illustrate the variation with time of the euphotic:mixing

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ratio, as well as the way this ratio varies versus kd and Zmax. We have tested this approach and must sincerely conclude that none of the graphs obtained brings a convincing support to our demonstration. We thus have decided not to add those representations in the final version of the paper, also because the concept of euphotic:mixing ratio has been discarded from the paper...

(6) We appreciate the positive comment of Ref. # 3 concerning Fig. 11 and 12. The reason why we have chosen to represent the light intensity at 20 cm is that the variation with time of PAR at this depth is already quite different from the purely sinusoidal signal that is observed at or near the surface. Taking PAR at 20 cm is thus illustrative of the complexity of the light field within the water column. Moreover, the irradiance at 20 cm has a similar shape as the one displayed by the depth-averaged irradiance. But we prefer to avoid the use of depth-averaged irradiance, a concept that has no clear physical or biological meaning and might be misleading in our case.

(7) Figure 12 is a representation of the time-varying GPPz (integrated over the water depth) in the first set of simulations (the one using "simple" sinusoidal forcing functions for Zmax, E0 and kd). It has been computed for an average depth of 8 m (i.e. a depth oscillating with tide between 5 m and 11 m). It should however be noted that the value of Zmax is irrelevant as far as GPPz is concerned, as long as it is always larger than the euphotic depth. Because the relation Zmax $>$ Zeuphotic is a preliminary hypothesis in our model, we have not mentioned the specific value of Zmax when presenting the results of GPPz.

(8) We have followed the suggestion of Ref. #3 who, together with Ref. #1, would like to see a new figure combining Fig. 11 and 12. We have also added a third panel that represents the values of the (chlorophyll-specific) GPPz integrated over one day, computed for 5 consecutive days. We think that this additional figure allows an easy and informative comparison between the varying and constant kd cases for the first set of simulations. It also supports much more convincingly our conclusion that using a constant kd may lead to a severe under-estimation (of about 30%) of the daily GPPz.

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We also follow the suggestion of showing the long-term trajectories of computed phytoplankton biomass, not only for the varying kd cases (Fig 13), but also for the constant kd case (new figure). It shows that the deviation between the varying and constant case may become exceedingly large in the long-term, because of the cumulative effect of the difference in phytoplankton growth. The trajectories are also increasingly divergent when the average water depth is decreasing. This demonstrates the fact that, as suspected by Ref. #3, a negative biomass growth can be predicted instead of a positive one, if the short-term variability of kd is ignored in the case of relatively shallow waters. In our case, it can be seen on the figure that the average depth under which varying and constant kd models predict an opposite sign for phytoplankton growth is slightly higher than 6 m. Differences in the model response tend to vanish for an average depth greater than 15m.

(9) As stated in our answer to Ref. #2 (specific comment #1), a reference to May et al (2003) with an accompanying comment has been added in our text.

(10) We agree with Ref. #3 that we have not clearly demonstrated that the "euphotic to mixing depth ratio is the principal controlling factor of phytoplankton dynamics in this type of estuary". We therefore have deleted this statement, together with other references to this ratio. We have followed the suggestion of Ref. #3 and "have compared the 2 (shallow and deep) varying kd simulations with new simulations using constant, mean kd." In all cases, the tidally-driven variation of the water depth has of course been considered. The results show that constant and varying kd cases do not produce similar results at all. This does not reach the point where the conclusions are totally inverted (chlorophyll decreasing at the shallow site and increasing at the deep site). But the long-term trends are clearly affected, especially at the shallow site. For some intermediate depth (not represented on this graph), it is expected that the long-term trends have an opposite sign depending on kd (constant or variable). We can thus "safely conclude that fluctuating turbidity is a significant factor regulating the observed bloom dynamics". We have also followed the suggestion of Ref. #3 of looking at a case

where Zmax is kept constant (new figure), and also added the case where E0 is taken constant (i.e. where an average value of the surface irradiance is applied during the day hours instead of a fluctuating one, new figure). Thus all forcing functions are now treated equally with respect to "averaging" the short-term variations. Results show that neglecting the variability of turbidity is by far the most important source of error in the estimation of net phytoplankton growth. Neglecting the tidal variation of water depth is a minor source of deviation, for shallower system only (< 8m). Using an average irradiance is even less critical.

(11) We understand why Ref. #3 is confused with some aspects of our text, because we are not looking at the variations of the euphotic to mixing depth ratio per se (see our discussion above). Concerning the Scheldt, we are not talking about mean values for the forcing functions (except of course when we test the effect of using an average kd instead of a time-varying one). We are thus not exploring 2 different concepts!

Minor technical issues:

(1) "Suspended particulate matter (SPM) dynamics" has been replaced by "Short-term suspended particulate matter (SPM) dynamics" (p. 39, l. 23).

(2) Ref. #3 is perfectly right when he says that we have used the term "tidal amplitude" in a wrong way. We actually mean tidal range, and have corrected this confusion where needed in the text.

(3) Yes, we mean average Zmax (see also our answer to question #5). The average Zmax is thus varying between 6m and 20m depending on the simulations, but the tidal range is the same in all cases (6m).

(4) We think that Fig. 9 gives a clear indication of the various time scale that have to be taken into consideration when looking at the dynamics of kd: not only the sub-tidal scale, but also the longer term (neap-spring cycle). It also shows that the average turbidity at the shallow site is higher than at the deeper one. We thus would like to

keep this figure in our final version.

New references:

Lucas, L.V. and Cloern J.E.: Effects of tidal shallowing and deepening on phytoplankton production dynamics: a modelling study, Estuaries, 25, 497-507, 2002.

Lucas, L.V., Koseff, J.R., Cloern, J.E., Monismith, S.G. and Thompson, J.K.: Processes governing phytoplankton blooms in estuaries. I: The local producion-loss balance, Mar. Ecol. Prog. Ser., 187, 1-15, 1999b.

May, C.L., Koseff, J.R., Lucas, L.V., Cloern, J.E. and Schoellhamer, D.H.: Effects of spatial and temporal variability of turbidity on phytoplankton blooms, Mar. Ecol. Prog. Ser., 254, 111-128, 2003.

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