Reply to anonymous Referee #1

Referee comment: *What are the sources for the forcings, the boundary and the initial conditions (both physics and biogeochemistry? (page 8404)*
Author's response: We agree that this information should be added.
Changes to the manuscript: This information has been added to section 2.2 Experimental setup.

Referee comment: *Model has been spun up for three years. Is there any reference to show that this time is enough, particularly for the deeper part of the domain? Or did the authors make some test to check this? (page 8405)*
Author's response: This was tested in an earlier version of the model and this is described in Hansen (2008), where it was shown that the model did not have any significant drift beyond the first three years. Reference: Hansen, C. (2008): Simulated primary production in the Norwegian Sea – Interannual variability and impact of mesoscale activity, PhD Thesis.
Changes to the manuscript: The reference to Hansen (2008) has been included in the text.

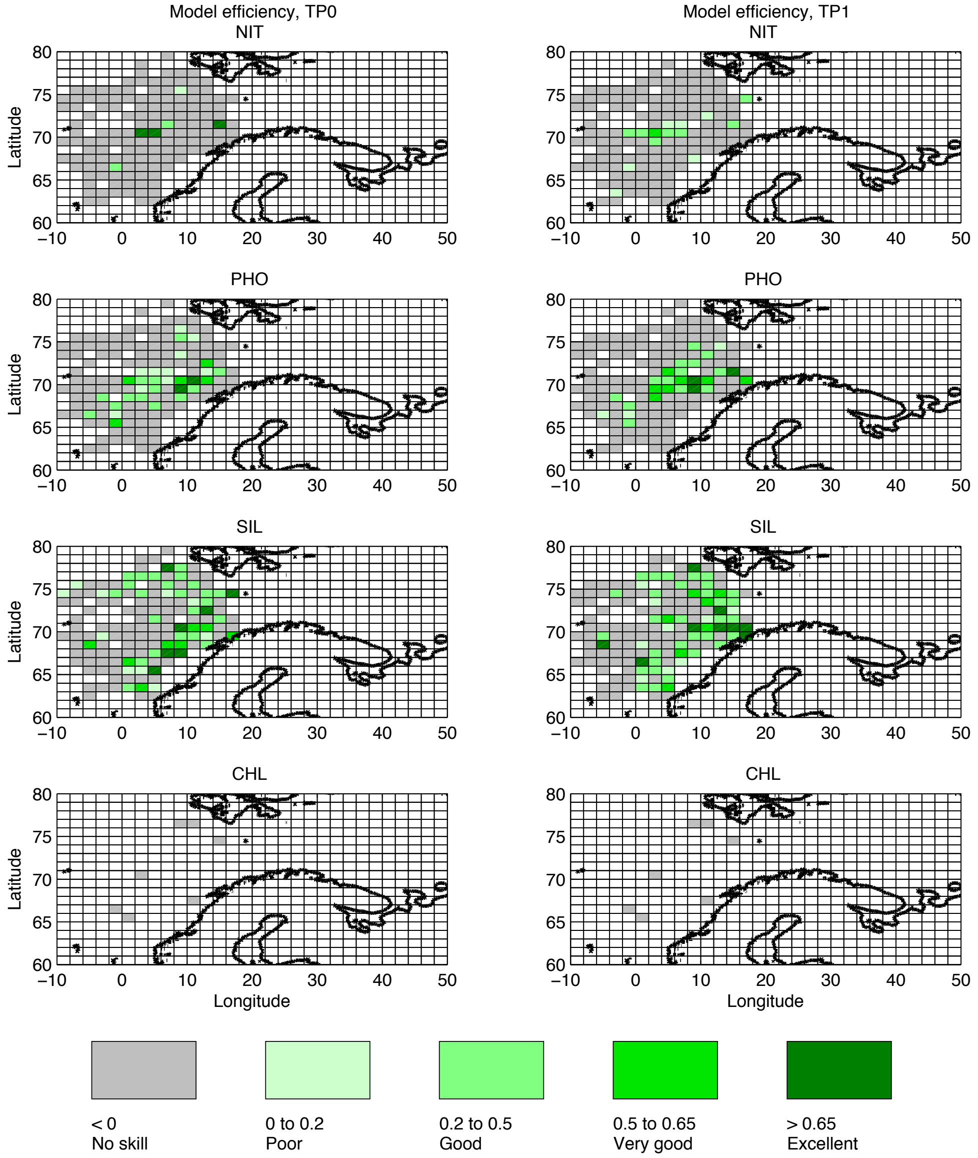
Referee comment: *After equation 3 (page 8404) authors write the value for "g" for Meso-zooplankton. Although the equivalent reference value for microzooplankton is reported in table 2, I would recommend the authors to report the standard value here as well for clarity*
Author's response: We agree with the referee
Changes to the manuscript: The value for microzooplankton is provided in the text as well.

Referee comment: *Authors did not explain the meaning of "mu_z" in equation 5. I assume this is the maximum mortality rate. If this is the case, I suggest authors to use the latin letter "m" instead of the greek letter "mu" because authors (in agreement with most literature) already use the greek letter "mu" for growth of the phytoplankton (equation 1 and 2) therefore it is misleading having the same symbol representing growth in one equation and mortality in another one.*
Author's response: Here we followed the symbols used in the ECOHAM user guide, but we agree that it does make more sense to use m for mortality,
Changes to the manuscript: The symbol has been changed to m in the equation and table 2 and defined in the text below eq. 5 as well.

Referee comment: *It is unfortunate that authors do not take full advantage of the spatial resolution of the model and the data and presents results lumped for the whole domain or at most for just 2 areas. I acknowledge that spatial coverage of the data can be limited particularly in winter, but figure 3 highlights that spatial pattern of uncertainty could be investigated in a more detailed way than the one authors already discussed contrasting two subdomains (NWS and BAS). Furthermore authors describe different performance of the model in the deeper domain (below 500m) compared to the upper domain (page 8407): nevertheless figures 4 and 5 show only the synthesis of the model-data comparison across the whole domain. I suggest authors to show also the outputs from upper and bottom domain separately, particularly because authors state "[Upper] Silicate has no skill in the years 1999 and 2000." while figure 4 shows good to very good skill for silicate in those years. This leads to think that the good results for nutrient simulation highlighted in figures 4 and 5 could be biased by good initialisation of the model in the deep basins where the dynamics are limited in a 10 years period. I would also suggest authors to mention the residence time of the basin, in order to give the opportunity to readers that are not expert of the area (like myself) an idea of the relative importance of endogenous dynamics versus boundary forcings. Similarly, authors show vertical profiles for Chl and nitrate, but they discuss also phosphate and silicate. I suggest authors to add similar plot to figures 9 and 10 for P and Si (perhaps as supplementary information or removing the June panel from figure 9 and 10 to limit the number of figures).*

Author's response: Thank you for this suggestion, the spatial component is indeed very interesting and should be taken greater advantage of. And the paragraph on page 8407 was confusing and in the last sentence about silicate it should have explained that the skill for silicate is lower in 1999 and 2000 compared the year before and after. We have removed this sentence in the new version.

Changes to the manuscript: As a result of your suggestion we changed figure 6 and 7 (figure 7 and 8 in the new manuscript) to be spatial maps of bias and model efficiency respectively. We chose to include only the upper 100 meters in these figures. For nutrients this is where we see the improvement and although the bias is better at depth, we do not see much difference between the model performances for different parameters (see figures R1 and R2 below). Figures R1 and R2 are for the depths 100 to 500 meters, for the depth 500 to 1500 meters there was almost no differences between the runs. Part of the good results at depth is probably due to good initial conditions and relaxation at the boundary. Paragraph 3.1 has been modified for more clarity and the information about residence time has been included. In addition Figures 9 & 10 has been updated to include phosphate and nitrate as the reviewer suggested. Here we also found an error in the code for the plots (the previous plots showed accumulated nutrients from the surface to depth, not nutrient concentration in a certain depth interval), we have corrected that as well, the correction resulted in less smooth curves than in the previous figures, it also becomes clear that there are no clear improvements at depth, so those claims have been removed from the manuscript.


Model efficiency, TP0

Model efficiency, TP1

NIT

PHO

SIL

CHL

Figure R1. Percentage bias in the 100-500 meters intervall for the model simulations compared to all available observations from the period 1998-2001 in 2x1 degree boxes from the simulations with the fine-scale model with the original (TP0) and final set of parameters (TP1).

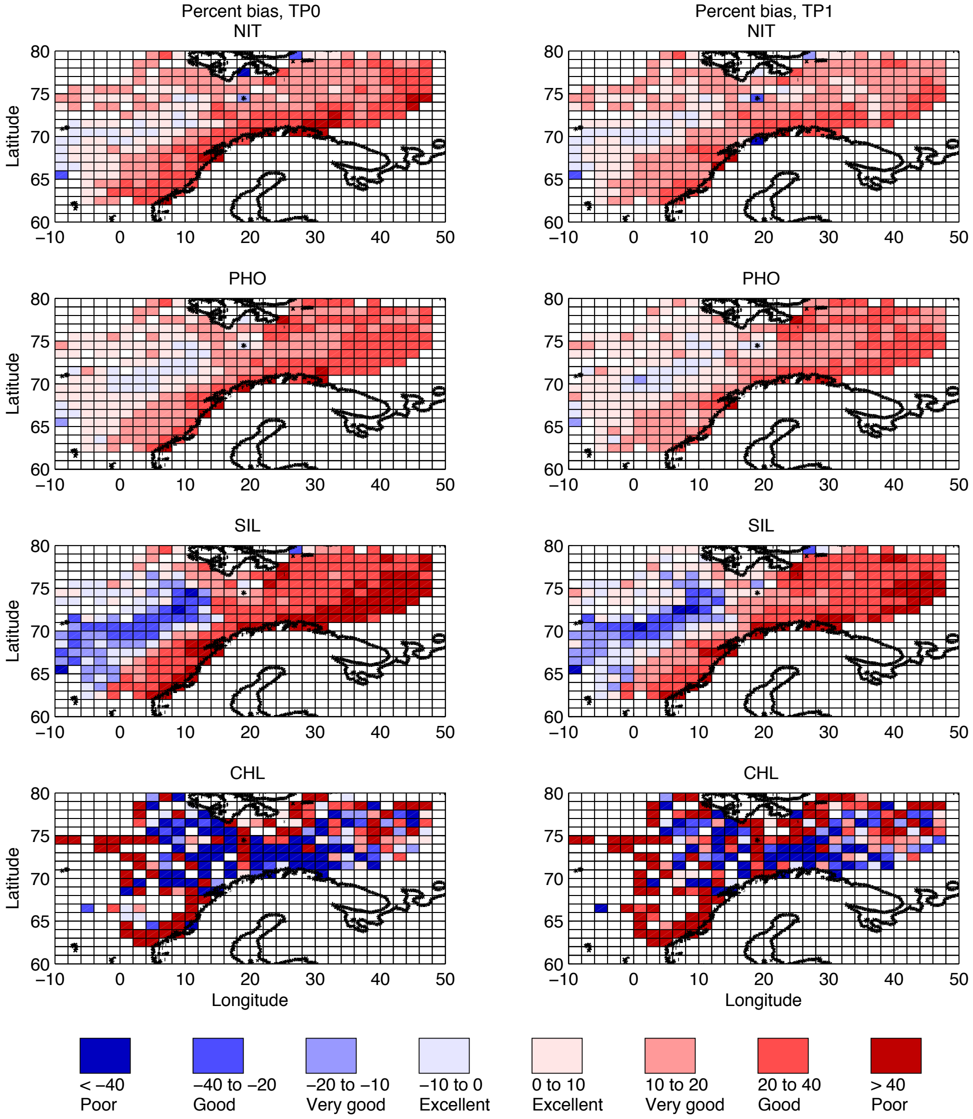


Figure R2. Model efficiency in the 100-500 meters intervall for the model simulations compared to all available observations from the period 1998-2001 in 2x1 degree boxes from the simulations with the fine-scale model with the original (TP0) and final set of parameters (TP1)

Referee comment: In the discussion section, the main items are discussed, but I would suggest authors some changes in order to make the section more clear: The introductory paragraph is redundant, as it simply summarizes the entire workflow and this is already well clear from the previous sections. This section looks more like a conclusion than an opening of discussion.
Author's response: We agree that this paragraph is redundant.
Changes to the manuscript: This paragraph has been removed.

Referee comment: The title of section 4.1 is misleading. In the paper the model is not validated, as this would require to compare the model output with a completely independent dataset from the one used for calibration/tuning. From my understanding of section 2.3 all data have been used for tuning therefore the model has not been validated. I would suggest to title this section "uncertainty connected to observation" that is an appropriate title for the discussion in this section. I would also suggest authors to refer to Stow et al., 2009 (http://dx.doi.org/10.1016/j.jmarsys.2008.03.011) for comprehensive analysis of this topic.
Author's response: What the referee points out is correct; the same dataset has been used both for tuning and comparison of the model results.
Changes to the manuscript: The title has been changed to "Uncertainties connected to observations", we think this more accurately describes this section. We have

also added a sentence about the same dataset being used for both tuning and validation and referred to Stow et al, 2009.

Referee comment: *The first sentence in section 4.1 is arguable. The quality of measures does not depend (only) on their abundance: a broken thermometer will always give the wrong temperature. I suggest authors to reformulate this sentence and in particular to be more clear with the meaning of "quality of measure" for them.*
Author's response: The referee has a good point.
Changes to the manuscript: 'Quality of the measurements' was changed to 'representativity of the measurements'

Referee comment: *Authors state (page 8412) that fluorometer Chl-a may vary with a factor of 3-4 compared to HPLC Chl-a. I may agree with this, but I recommend authors to clarify if they refer to in situ fluorometer Chl-a or Chl-a measured with a fluorometer in the lab from extracted pigments. In the latter case the error is expected to be much lower than the one suggested by author. A reference to back up their estimate would be needed as well.*
Author's response: We did mean fluorometer measurements from the field.
Changes to the manuscript: It has been specified that we mean fluorometer measurements from the field in the text.

Referee comment: *In section 4.2 authors state that changes in mortality of zooplankton produced little effect, contrarily to the expectation but they did not provide any potential reason for this.*
Author's response: Without further analysis, an answer to this will be quite speculative, but given that we may be allowed to speculate: For example an increase in zooplankton mortality would decrease the population of zooplankton and decrease the grazing mortality of phytoplankton. This would again increase the phytoplankton population and in turn increase nutrient consumption and decrease nutrients. Here there are two potential feedback loops: increased phytoplankton will be available as food for the remaining zooplankton, increasing their growth or because a large part of dead zooplankton will sink out of the system as detritus, the decreased rate of remineralization from zooplankton would decrease nutrient concentrations and limit the growth of phytoplankton. The opposite would be the case for a decreased zooplankton mortality. In order to pin down the exact reason we would have to rerun the model with different zooplankton mortality parameters and output all rates of transfer between different variables for these runs.
Changes to the manuscript: We feel that this is speculative and prefer not to write a possible reason into the paper, but rather say that we are not sure about the reason.

Referee comment: *In the same section, authors rightly interpret the lack of effect of the change in N:Chl ratio on the model performance on simulating Chl with a compensatory mechanism. This mechanism should lead to a different distribution of phytoplankton along the water column. I suggest authors to bring this evidence to corroborate their hypotheses and to discuss the potential consequences*
Author's response: Looking closer into these results we realized that this is the result of a mistake in the processing of the model results, and in retrospect we realize that we should have been more suspicious towards these results, while the nutrients are not very sensitive to the change, the change in chlorophyll is actually quite big. Our theory about different vertical distribution of phytoplankton as a result of altering this parameter was still correct. However, the effect was small, changing concentration of phytoplankton (expressed in units of mg N/m^3) only by about 3-5% difference between the runs with ratios 13.7 and 6.3, compared to the effect on chlorophyll concentration (or phytoplankton expressed in units of mg Chl/m^3) in two runs that was about double in the run with ration 6.3 compared to 13.7 (N10 and N08).

Changes to the manuscript: New values have been added in figure 4 and 5 and the text have been modified to take into account the new results. We have not written that there was a mistake in the discussion paper thinking that it would only be confusing to the reader that has not read the discussion paper.

Referee comment: I totally agree on the limitation due to computational constraint highlighted in the last paragraph of section 4.2. Authors could state while they chose to run the sensitivity test on using the entire 3D model instead of running those in faster 1D set-up (maybe in contrasting environment in the domain), particularly since authors do not show spatial pattern of sensitivity (by the way, this information could be really informative and would increase the impact of the paper).
Author's response: We do have a 1-D version with GOTM coupled to NORWECOM, but the GOTM-NORWECOM gives quite different results from the full 3-D model, it does not overestimate the magnitude of the spring bloom and the duration of the bloom is much shorter, it underestimates the chlorophyll concentration during July when the model presented here overestimates it. The GOTM-NORWECOM model could probably have been used for a parameter sensitivity analysis, but for the sake of the tuning we found that the results were too different for it to be useful.

Referee comment: In few occasions (e.g. beginning of page 8415), errors in the simulation of physics have been used to explain errors in the biogeochemistry. The explanation given are perfectly reasonable, but the general performance of the physical model has not been shown, nor adequate reference has been given in support of authors' hypotheses.
Author's response: Our colleagues have compared the model to the hydrography from the Svinøy section (and other regular sections) we see that the model rarely places the fronts in the correct position. In the case of the Svinøy section, which is upstream of station M, the model places Atlantic water – often defined as having salinity greater than 35 - too far to the west (Figure R3), but unfortunately there are no publications where these results are shown.
Changes to the manuscript: Since we do not have any publications showing the (mis)placement of fronts, but we know his is true, we added 'not shown' to the manuscript. With regards to a late development of MLD leading to a late spring bloom, we have used Samuelsen et al. (2009) as a reference.

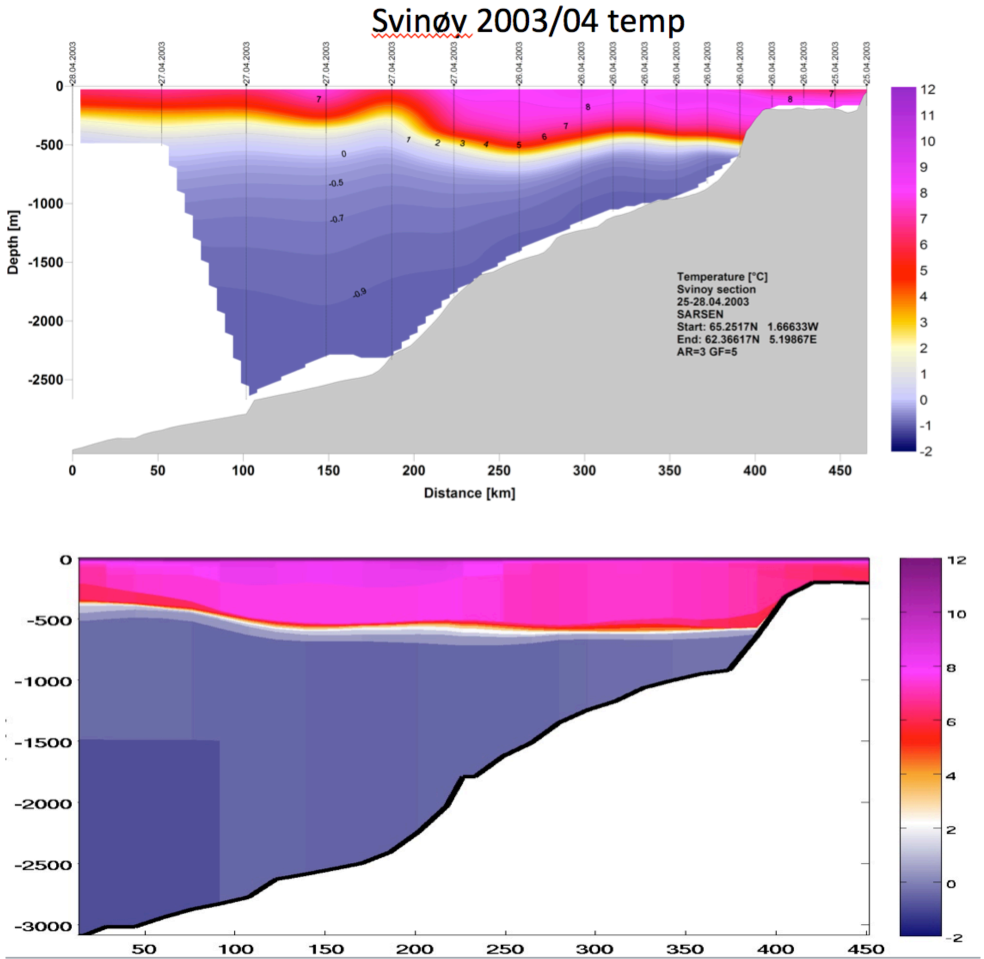


Figure R3. Salinity section from the Svinøy-section from observations (above) and the model referred to as high-resolution in this paper (below).

<u>Referee comment</u>: Similarly, bad simulation of bloom initiation has been suggested as potential error in Chl-a simulation, however comparisons between bloom initiation timing (model vs. data or model vs. model during the sensitivity test) have not been provided. Such a way, these statements remains quite speculative.
<u>Author's response</u>: We have looked at the timing of the bloom in this and previous studies, and none of our efforts to adjust the timing have not been successful in mowing it more than 3-5 days back or forth.
<u>Changes to the manuscript</u>: 'not shown' has been added behind the sentence "The model is consistently late in its initiation time and none of the parameter alterations significantly affected the timing of the spring bloom" to indicate that we have actually looked at this. When the same thing is mentioned earlier in the manuscript, the reference to the paper Samuelsen et al. 2009 has been included. This paper shows the timing issue quite clearly in figure 3.

<u>Referee comment</u> From line 15 of page 8415 authors do not discuss regional differences in performance but they discuss the general performance of the model, therefore this part should go under a different header (either a 4.4 header or a generic Conclusion).
<u>Author's response</u>: This referee is right.
<u>Changes to the manuscript</u>: This part of the manuscript is now under the heading '5. Conclusions'

<u>Referee comment</u> Finally, but I appreciate that this is a personal opinion, I would remove any dubitative form when authors states that model could be improved in closer collaboration with empiricists. I believe that this is the way forward without any doubt if modellers want to build reliable model that describe the main ecological principle and pathway and are up-to-date to the more recent

understanding of marine ecosystems.
Author's response: We agree with the referee.
Changes to the manuscript: The word 'perhaps' has been removed

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Further minor corrections suggested:
Referee comments
1.Page 8401, l 24-26: For clarity I suggest to write: "The HYCOM-NORWECOM model was tested against local in-situ data and derived gridded climatology of nutrients, as well as satellite data, however. . ."
2. Page 8402, l10: add a comma between salinity and temperature
3.Page 8402 l24: I'm not native English, however I believe that "provide" is a better word than "proved" in this context
4.Page 8406, L20: the standard Taylor diagram show standard deviation, correlation coefficient and centered RMS not variance (see Taylor, 2001 figure 2)
Changes to the manuscript: The text has been changed according to the reviewer suggested.

Referee comment: Page 8410, l21: "profiles in the upper 1000m of the water column IN THE NORWEGIAN BOX. . ."
Changes to the manuscript: We added 'in the Norwegian Sea box' in this sentence

Referee comment: Page 8411, l22: I would rewrite the sentence starting with "It is howewver.." like this: "different requirements for geographical coverage, number of stations and frequency are needed depending on the different issues addressed, parameters measured and the area complexity (e.g. Ottersen et al., 1998)"
Changes to the manuscript: The sentence now reads: "Depending on the issues addressed, there will be different requirements for geographical coverage, number of stations, frequency and parameters measured (e.g. Ottersen et al., 1998)."

Referee comment: *Table 2: I believe that there is a typo for case N12: it should be maximum microzooplankton grazing rate, and not grazing preferences for microzooplankton*
Changes to the manuscript: Yes, this was a typo, it has been corrected.

Referee comment: Table 3: this could be moved in the supplementary information
Changes to the manuscript: The other reviewer suggested to move it to an appendix, after reading the journals definition of supplementary material, we found that appendix was more fitting, so it has been moved to an appendix.

Referee comment: *Figures 4,5,6,7: I really like the colour coded system, as it is really communicative and easy to understand. However, at the same time it can be also misleading: e.g., in figure 4 a big improvement from 0.2 to 0.49 will not be highlighted at all, whilst a small improvement from 0.49 to 0.51 will stand out. I would suggest authors to write also the value of the different metrics inside the coloured box.*
Author's response: We like this suggestion.
Changes to the manuscript: We have added the numbers in figure 4 and 5. After the reviewers suggestion above to look at the spatial pattern, we have changed figure 6 and 7 (now 7 and 8) to show this, the boxes on those figures are too small to contain numbers, so we did not include them there. A typo on the label of the model efficiency figures has also been corrected.

Referee comment: *Figure 8: is the Taylor diagram showing relative SD (i.e. SDmodel/SDdata) or the absolute value? In any case I would plot the dotted circumference passing through the DATA point, to highlight when model and data have the same standard deviation.*
Author's response: The Taylor diagram shows relative SD.
Changes to the manuscript: A dotted line for SD=1 has been added to the Taylor diagram and the information that it is showing the relative SD is added to the figure label.

Reply to Referee #2

Referee comment*: Throughout the paper, please be careful with the usage of the word "data". Both model output and observations are data and sometimes it is rather confusing if "data" is used without further specification, particularly if the application of the word switches between modelled and observational data. I recommend for most cases to replace the word data with the word "observations" (where applicable) and use model data or model output at others.*
Author's response: we see that this can be a problem.
Changes to the manuscript: We have checked the manuscript throughout and changed from 'data' to observations' or 'observational data' where we thought it may have been unclear if the data are from the model or the observations.
Where observations are described as 'in-situ', 'observed' or 'satellite' we consider that it is clear that these are observational data and we have not changed these.

Referee comment: I would recommend using names for the model versions discussed rather than the use of: the current version, this version, the original version, the version from 1998 . . ..
Changes to the manuscript: We have followed the reviewer's suggestion where applicable and referred to the specific versions listed in Table 1.

Referee comment*: Revise title to somehow include "Arctic" and "biogeochemical"*
Author's response: Having a more specific title is a good suggestion, but the model covers more than just the Arctic, therefore we wanted to include North Atlantic as well.
Changes to the manuscript: We changed the title to: "Tuning and assessment of the HYCOM-NORWECOM V2.1 biogeochemical modeling system for the North Atlantic and Arctic"

Detailed comments:
Referee comment: p8400
(1) l 5 has -have
(2) l 7 The model revisions
(3) l 13/14 rm sentence "probably as a result...
Changes to the manuscript: We have changed (1) and (2), but for (3) we prefer to keep the sentence about improved circulation in the high-resolution models since we think this is an important point.

(4) l 24 BGC models are less accurate – what does that mean?
Author's response: What we mean by this is that while physical models are based on the well-established 'equations of motion' and the main challenges are in how these equations are represented numerically and how sub-grid processes and forcing are represented, the equations that are used to describe the system correctly are not known in biogeochemical models.
Changes to the manuscript: The new formulation is as follows "Not all biogeochemical processes in the ocean are well understood and therefore biogeochemical models are less accurate than circulation models both with respect to model formulations and parameterizations. Observational data for validation and model evaluation are more scarce than for circulation models."

Referee comment: p8401
l 5/6 this sentence doesn't make sense
Changes to the manuscript: We added 'is': "…for estimating unknown parameters, the assimilation of ocean color data in operational models is underway."

Referee comment: p8402
(1) l 8/9 suggest: ...for forecasting and regularly evaluated using in sutu....and sea ice.

(2) L 21 derived from GlobalNEWS model output
(3) L24 proved ???=> provided?
Changes to the manuscript: (1) This sentence was changes to "HYCOM is routinely used for forecasting and the predictions are regularly evaluated using in-situ and …". (2) and (3) was changed according to the reviewer's suggestion.

Referee comment: p8403
(1) L5 determine => determines
(2) L10 is – are
(3) L11 and silicate => and nitrate?
(4) L16/17 rephrase
(5) L23 the same as - derived from (or add "in")
Changes to the manuscript:
(1) and (3) has been corrected
(2) is kept as is, since it refers to 'the main distinction, which is singular.
(4) has been rephrased to "NORWECOM V2.0 was primarily applied to the North Sea, while HYCOM-NORWECOM, focused the open ocean regions of the North Atlantic, therefore the extinction coefficient due to water and non-chlorophyll substances was reduced from 0.07 to 0.04 (Hansen and Samuelsen, 2009)."
(5) we added 'in'

Referee comment: p8404
L20 runs, to limit the computational cots, as the 15km . . .
Changes to the manuscript: This was changed according to the reviewer's suggestion.

Referee comment: p8405
(1) suggest putting table 3 in an appendix
(2) L 5-7 confusing,
(3) rephrase L19 In the case that....=> In case of several . . .
(4) L20 Rm sentence One caveat...modelled chlorophyll superfluous
(5) 2.3 what data???
Changes to the manuscript:
(1) Table three has been moved an appendix
(2) The sentence has been changed to "In order to assess the effect of the revised parameter set on the 15-km model, two simulations were performed; one with the with the higher resolved grid (simulation names starting with TP); the original set of parameters (TP0) and one with revised set of parameters (TP1)."
(3) This was changed according to the reviewer's suggestion.
(4) This sentence was removed from that section, however we think this is an important piece of information, so we added the sentence "The model assumes constant N/Chl-ratio (11 g N/g Chl in the control run)." to the model description.
(5) New heading is "Description of observations"

Referee comment: p8406
*(1) L9 -11 shorten: A combination of metrics ** and ** was used.. ...are defined as:*
(2) Eq 6 what is n
(3) 2.5 put in appendix with table 3
Changes to the manuscript:
(1) The sentence now reads: "A combination of model efficiency (ME) and percentage model bias (Pbias) was used for the comparison between the model simulations and observations. These statistical quantities are defined as:"
(2)We have changed the sentence below eq 6 to "where D_n is observation from station n, M_n is the corresponding model estimate, $\overline{D}$ is the mean of the observations, and N is the total number of stations." Hopefully it is now clear what is the meaning of n and N.
(3) We would like to keep this in the main text, since this is a model description paper, we think this is essential information.

Referee comment: p8407

(1) L21 .. no skill => is this shown somewhere?

(2)L23 both runs????? there are 16 runs, do you mean both resolutions?

(3) L24 (Fig.5). - what about the few showing a positive bias?

Author's response:

(1) The sentence was meant to say 'lower skill', not 'no skill'

(3) In line 24 we are still talking about the runs with the original parameters, hopefully this is clear after the rephrasing of the sentence below.

Changes to the manuscript:

(1) The first paragraph in section 3.1 has ben rewritten for better clarity and the last sentence has been removed.

(2) and (3) The sentence has been changed to : "Hereby the runs with the original parameter set for both resolutions show no skill for the ME (figure 4) and large negative percentage biases (figure 5), meaning that the model consistently overestimates the chlorophyll."

Referee comment: p8408

(1) L1 ..is overestimated => Is this shown?

(2) L 2 We have also observed => found (keep the word observed for the observations)

(3) L3-5 In addition ... - this has already been stated (do not repeat)

(4) 3.2 Parameter alterations ???? better title?

(5) L 8 Many of the parameter ...

(6) L9 as seen in Figs 4 and 5 – Can't see the improvement in those figures, pls clarify

Author's response:

(1) This can be seen in the Taylor diagram (fig. 8 in the original paper) – we now refer to this figure and have renumbered it to figure 6.

(6) With the inclusion of numbers on figures 4 and 5 (as suggested by the first reviewer) it should be easier to see where there are improvements (or deterioration) now.

Changes to the manuscript:

(1) We have added a reference to figure 6 (former figure 8) in the sentence

(2) We now start the sentence with "Analysis have shown"

(3) We have removed this sentence

(4) We changed the title to "Parameter modifications"

(5) We added "the"

(6) The actual values are now added to figure 4 and 5.

Referee comment: p8410

(1) revised run – revised model/ or revised parameterisation

(2) L7 regions. In the Norwegian Sea observations are available throughout...

(3)L16 show – shows

(4) Watch the use of data, data, data....

(5) L25 has -have

Changes to the manuscript:

(1) 'revised run' has been changed to 'revised model run'

(2),(3) and (5) We followed the reviewers suggestion

(4) as said above, we have amended this.

Referee comment: p8411

(1) last paragraph of 3.3 What about the influence of ice algae? Make note

(2) Discussion: Try to minimize repetition, use concise sentences, please review for grammar

Author's response:

(1) We are not sure what the question is about the ice-algae, since we talk about a delay in the spring bloom in that paragraph; perhaps the question is if ice-algae can help influence the timing of the spring bloom. We are not sure if this is the case, but this would anyway only influence a very small part of the model domain and

not the large open ocean regions. We mention the lack of ice-algae in the model as a source of error in the discussion.
(2) We have carefully gone over the discussion section and checked for repetitions and to improve the language as was also asked for in the general comments to the paper.

Referee comment: p8412
(1) 8412 L 2 claims to the accuracy – what does that mean? ...accuracy can be relaxed ???
(2) L 7 research vessels paragraph on the quality of the observational data can be shortened
(3) L13 here the – here, are the outspell HPLC
(4) L 5 to 24 shorten, this has limited relevance to the paper
(5) L24-28 this is a known issue, does not need that much detail (does not more or less depend on the resolution, it does depend on the resolution)
Author's response:
(1) Note that we are talking about detecting changes, not detecting absolute values.
(2) We prefer to keep all of this information in the manuscript because we think it is important to have an understanding about the observations as well.
Changes to the manuscript:
(1) In order to clarify this, we rewrote the two sentences: "For example, for observing changes in the deep ocean, taking measurements one or a few times a year is enough, however changes in the deep ocean are so small that detecting changes require large accuracy. In comparison, the coastal areas and surface waters needs to be measured substantially more often in order to capture the variability, but since these waters have large variability the requirements to accuracy can often be relaxed."
(2) We deleted "to the spatial and temporal limitation of the observations" in the last sentence.
(3) We have written out HPLC: High-performance liquid chromatography and changed 'here the' to 'here, are the'
(4) For the same reason as the response to (2) we have kept the information, but rephrased the text.
(5) We removed " more or less"

Referee comment: 4.2 restructure and shorten: suggest: parameter changes with little impact are: with high impact ... not analyzed ..
E.g. sentence
Changes in the zooplankton mortality also had little effect on the results, this is the closure term in the model and it is a bit surprising that this term only had a small effect on the model results.
Changes to the manuscript: The sentence was changed to "The zooplankton mortality is the closure term in the model, but contrary to other studies (e.g (Steele and Henderson, 1992) perturbations of this parameter had little effect on the results." As said before, we have carefully gone through all of the discussion section.

Referee comment: p8415
(1) L 7 Ice front => ice edge ?
(2) L 9 large error => error of what?
(3) L7-14 rephrase, shorten
(4) L 15 severe – clear
(5) L18 showed – shown
(6) L 20 The model is late ??? The spring bloom is simulated late
(7) L 23 What does phyto convection mean
Author's response:
(7) Phyto-convection is the early seeding of the spring bloom by phytoplankton that was mixed down during winter.
Changes to the manuscript:
(1), (4) and (5)Was changes as the reviewer suggested.

(2) added “errors in chlorophyll or nutrient”
(3) The paragraph has been rephrased, it may not be shorter, some unnecessary information has been omitted.
(6) We changed the sentence before to include the information about the late spring bloom and deleted the first part of that sentence, including the formulation in question.
(7) We chose to keep this as is as it is quite well known and interested readers can read the Backhouse paper, but we now write ‘phyto-convection process’

Referee comment: p8416
(1) The meaning of the first paragraph is not clear, rephrase also rephrase
(2) L 9-11 Last sentence is unnecessary and can be removed.
(3) Table 2 This table is somewhat confusing Do the ratios need to be given in mg/mg and mmol/mmol ?? Maybe one conversion info as a table footnote is sufficient > For several runs two representations are given for pi21, should one be pi23?
(4) For N14 => diatomer – diatoms
(5) Fig 3 fall and autumn refer to the same season :-) I think the first should be spring and summer
(6)Fig 4 If not defined in caption refer to text: Model efficiency (ME, see text)
(7) Fig 3-7 dataset => observations Fig.8 what does “Data” mean ?
Changes to the manuscript:
(1) This paragraph has been rephrased.
(2) This part has been removed, but a shorter version of the same information is included in the first paragraph of what I now termed ‘Conclusion’
(3) Yes, we agree it is unnecessary to give both units, we have chosen to keep the numbers in units of mg/mg since the model operates in units of mg.
(4), (5) and (6) This has been corrected according the reviewers suggestion
(7) We have gone through the manuscript and checked out uses of data, it has been changed in the figure labels as well.

Other changes to the manuscript

Here we list some additional changes to the manuscript not mentioned in the answer to reviewers, in addition a pdf-file including the word-manuscript with 'track-changes' has been included in the reply (we have removed track-changes for formatting and corrections of obvious typos). Most of these changes were done to shorten the manuscript and improve the language as suggested by the reviewers.

- 1. Introduction
    - 'more scarce' -> 'scarcer'
    - removed: 'which is the area'
    - The long sentence next to last was split in two.
- 2.1 Model description
    - removed: ' on a regular basis'
    - We have added the reference to Eppley (1972) when describing the temperature-dependent growth in the model description.
    - The description of the river nutrient forcing was moved to '2.2 Experiment setup' where the other forcings are described.
- 3. Results
    - 'not apparent in figure' changed to ' not shown'
    - First paragraph: The text has been change to adapt to the updated figures.
    - Section 3.3 – has been rewritten, and has hopefully been improved.
- 4. Discussion
    - We have split the discussion into a discussion and a conclusion.
    - The first paragraph of the discussion was removed, but a shorter version of this paragraph is used as the first paragraph of the conclusion. The last two paragraphs of the original discussion have been reorganized and are now also in the conclusion.
    - The discussion has been edited so that it is shorter and the language has been checked.

Tuning and assessment of the HYCOM-NORWECOM V2.1 biogeochemical modeling system for the north Atlantic and Arctic Ocean

A. Samuelsen[1], **C. Hansen**[2] **and H. Wehde**[2]

[1] Nansen Environmental and Remote Sensing Centre and Hjort Centre for Marine Ecosystem Dynamics, Thormøhlensgate 47, 5006 Bergen, Norway

[2] Institute of Marine Research and Hjort Centre for Marine Ecosystem Dynamics, Nordnesgaten 33, 5005 Bergen, Norway

Correspondence to: A. Samuelsen (annette.samuelsen@nersc.no)

Abstract

The HYCOM-NORWECOM modeling system is used both for basic research and as a part of the forecasting system for the Arctic Marine Forecasting Centre through the MyOcean project. Here we present a revised version of this model. The present model, as well as the sensitivity simulations leading up to this version, have been compared to a dataset of in-situ measurements of nutrient and chlorophyll from the Norwegian Sea and the Atlantic sector of the Arctic Ocean. The model revisions having most impact included adding diatoms to the diet of micro-zooplankton, increasing micro-zooplankton grazing rate and decreased silicate-to-nitrate ratio in diatoms. Model runs are performed both with a coarse- (~50 km) and higher-resolution (~15km) model configuration, both covering the North Atlantic and Arctic Ocean. While the new model formulation improves the results in both the coarse- and high-resolution model, the nutrient bias is smaller in the high-resolution model, probably as a result of the better resolution of the main processes and improved circulation. The final revised version delivers satisfactory results for all three nutrients as well as improved result for chlorophyll in terms of the annual cycle amplitude. However, for chlorophyll the correlation with in-situ data remains relatively low. Besides the large uncertainties associated with observational data this is possibly caused by the fact that constant C/N- and CHL/N ratios are implemented in the model.

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1 Introduction

Physical ocean forecasting systems are now operational in many ocean regions (Le Traon, 2013) and in several forecasting systems biogeochemical models have been included (Edwards et al., 2012; Wan et al., 2012). Not all biogeochemical processes in the ocean are well understood and therefore biogeochemical models are less accurate than circulation models both with respect to model formulations and parameterizations. Observational data for validation and model evaluation are scarcer than for circulation models. At the same time, operational systems including biogeochemical variables can supply valuable information on environmental indicators such as oxygen concentration, N/P-ratios, and algae concentrations. Over time, they may give information on accumulated quantities, such as annual primary production and inter-annual variability in phytoplankton production. Data assimilation is also being used for improving the model predictions (Sakov et al., 2012) and for estimating unknown parameters, the assimilation of ocean color data in operational models is underway.

HYCOM-NORWECOM is used as a part of the operational system for the Arctic (the Arctic Marine Forecasting Centre) implemented through the EU-FP7 supported MyOcean project. The biogeochemical forecast has been operational since the fall of 2011. In connection to the setup of the biogeochemical part of the forecasting system, a series of sensitivity runs testing alternative model formulations were performed and a subsequent update of the HYCOM-NORWECOM system was implemented. The final model formulation chosen was uploaded to the forecasting system in October 2012 and is now the operational model used. Daily values of nutrient, phytoplankton, oxygen etc. can be browsed at http://www.myocean.eu/web/24-catalogue.php and downloaded after registration. Focal areas for this study are the Nordic Seas and the Arctic. These areas contribute to a large fraction of the world ocean carbon sink (Takahashi et al., 2009). Aside from assessing the whole model area (Fig. 1) we focus the comparison on two smaller regions, one in the Norwegian Sea, important area for the heat transport into the Nordic Seas and one in the Barents Sea where one of the branches of Atlantic Water enters the Arctic Ocean.

Here we present HYCOM-NORWECOM V2.0 and V2.1 together with the sensitivity simulations leading up to the V2.1 (Table 1). The model results are evaluated against an in-situ dataset for the Norwegian Sea and the statistical results are presented. The HYCOM-NORWECOM model was tested against local in-situ observations and derived gridded

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climatology of nutrients, as well as satellite data. However, we found that the in-situ data was the most instructive and the tuning relied most heavily on this dataset when making the upgrade. Statistical measures of the models performance for each of the parameter sets were calculated in sub-regions as well for the entire area.

2 Methods

2.1 Model description

HYCOM-NORWECOM is a coupled physical biological modeling system. HYCOM (v2.2.12), the HYbrid Coordinate Ocean Model (Bleck, 2002), is an ocean model using hybrid coordinates; isopycnal coordinates in the deep stratified waters, and z-level coordinates in the upper mixed layer. A description of this setup of HYCOM can be found in Sakov et al. (2012) and user guides for the different versions of HYCOM are available online at http://hycom.org/hycom/documentation. HYCOM is routinely used for forecasting and the predictions are regularly evaluated using in-situ and remote-sensing observations of salinity, temperature and sea ice (http://myocean.met.no/ARC-MFC/V2Validation/index.html). Comparisons between observations, free-runs (used in this study) and assimilative runs can be found in Sakov et al. (2012) and Samuelsen et al. (Samuelsen et al., 2009a). NORWECOM (Aksnes et al., 1995; Skogen and Søiland, 1998) is currently run with 11 variables: nitrate, phosphate, silicate, diatoms, flagellates, micro- and meso-zooplankton, nitrogen detritus, phosphorous detritus, biogenic silica and oxygen (Fig. 2). The micro- and meso-zooplankton were recently added and use the formulations and parameters defined in ECOHAM (Pätsch et al., 2009; Stegert et al., 2009). The coupling of NORWECOM towards HYCOM was first done in 2005 and has been used for several studies in the Norwegian Sea and North Atlantic (Hansen et al., 2010; Samuelsen et al., 2009b). An overview of the different version can be found in Table 1.

The complete description of the NORWECOM V2.0 can be found in the user guide (Skogen and Søiland, 1998), below we provide a description of the differences in the biogeochemical formulations in HYCOM-NORWECOM here compared to that version. With regards to nutrient limitation the NORWECOM V2.0 applied a multiplicative relationship for the total growth (μ_{phy}) of phytoplankton:

$$\mu_{phy} = \mu_{\max} \times \mathrm{Rad\_lim} \times \prod_{i=1}^{n} \mathrm{Nut\_lim}_i \qquad (1)$$

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Where μ_{max} is the maximum growth rate, Rad_lim is the growth limitation due to light and Nut_lim$_i$ is the growth limitation for nutrient i. In HYCOM-NORWECOM it is the minimum of the limitation factors that determines the growth:

$$\mu_{phy} = \mu_{\max} \times \min\left(\text{Rad\_lim}, \text{Nut\_lim}_{i,i=1,n}\right) \qquad (2)$$

Except for when growth is not limited, formulation (1) will give a smaller growth rate than formulation (2) since the value of the limitation of light and nutrients are always between 0 and 1.

As in NORWECOM V2.0 (Skogen and Søiland, 1998), the main distinction between diatoms and flagellates in NORWECOM is that diatoms consume and is limited by silicate in addition to phosphate and nitrate. Diatoms have higher maximum growth rate than flagellates (Table 2), but the temperature-dependence for growth is the same, following Eppley (1972). The half saturation constants for nitrate and phosphate are smaller for flagellates (K_N=1.5 mmol/m^3 and K_P=0.094 mmol/m^3) than for diatoms (K_N=2.0 mmol/m^3 and K_P=0.125 mmol/m^3). The model assumes constant N/Chl-ratio (11 g N/g Chl in the control run).

NORWECOM V2.0 was primarily applied to the North Sea, while HYCOM-NORWECOM, focused the open ocean regions of the North Atlantic, therefore the extinction coefficient due to water and non-chlorophyll substances was reduced from 0.07 to 0.04 (Hansen and Samuelsen, 2009).

NORWECOM V2.0 (Skogen and Søiland, 1998) did not include zooplankton, but now there is an option of running the model with two zooplankton components, microzooplankton and mesozooplankton. The formulations for zooplankton are the same as in ECOHAM v4 (Pätsch et al., 2009), but modified to adjust for differences in the food-web structure. In HYCOM-NORWECOM, the mortality rate for phytoplankton independent of grazing is 0.035. When zooplankton is excluded, a quadratic relationship representing both grazing and other causes of mortality is used. Zooplankton grazing (G) by a size-class of zooplankton (Z) on a specific food source (fs) is described by:

$$G_{fs,Z} = \frac{T_{fac}\, g}{k + \sum P_{fs,Z}\, fs}\, fs \cdot Z \qquad (3)$$

Here, T_{fac} is the temperature dependence $T_{fac} = 1.5^{\frac{T-T0}{T0}}$, where T is the local temperature and T0 is set to 10°C, g is the maximum grazing rate (0.4 day^{-1} for mesozooplankton and 0.5 day^{-1}

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for microzooplankton) and *k* is the half saturation constant for zooplankton grazing which is set to 1 mmolN/m^3 for both size classes of zooplankton.

$$P_{fs,Z} = \frac{pi_{fs,Z} fs}{\sum pi_{fs_i,Z} fs_i} \qquad (4)$$

where pi_{fs} are the grazing preferences for the different food sources, the grazing preferences for microzooplankton can be found in Table 2, while the preferences for mesozooplankton are 0.45 for diatoms and 0.275 for both microzooplankton and detritus.

The assimilation efficiency for both size-classes of zooplankton is set to 0.75 (Pätsch et al., 2009) and the mortality (M_Z) is also formulated as a half saturation relationship:

$$M_Z = m_Z \frac{Z}{k_m + Z} \qquad (5)$$

where m_Z is the maximum mortality rate (0.2 day^{-1}) and the half saturation constant k_m is 0.2 mmolN/m^3 for both size classes of zooplankton. For the loss terms of zooplankton 90% of the material goes into the detritus pool and 10% is returned to nitrate.

2.2 Experiment setup

The tuning was done on a coarser grid (30-50 km) than the 15-km grid (Fig. 1) used in the operational runs to limit the computational cost, as the 15-km model takes about 5 times as long to run. The model was forced by the ERA-Interim (Simmons et al., 2007) from 1989 and ERA40 (Uppala et al., 2005) for the period prior to 1989 (only spinup). The physical model was initialized from rest with climatological temperatures and salinity from the GDEM (Carnes, 2009). The biogeochemical model was initialized from climatological nutrients and oxygen values from the Worlds Ocean Atlas (WOA2001: Conkright et al., 2002) and constant low values for the other variables in 1993. Throughout the run relaxation back to climatological temperature, salinity, nutrients and oxygen was applied at the lateral boundaries. A weak relaxation of salinity (relaxation timescale of 200 days) was also applied at the surface. River nutrients were derived from GlobalNEWS model output (Seitzinger et al., 2005). In all, 16 sensitivity simulations were performed with the coarse model (simulation names starting with N) and the parameter changes in each run are summarized in Table 2 and the location of the relevant code is given in Table A1. In order to assess the effect of the revised parameter set on the 15-km model, two simulations were performed; one

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with the with the higher resolved grid (simulation names starting with TP); the original set of parameters (TP0) and one with revised set of parameters (TP1). The model was started from climatological nutrient values and constant low values for the other variables in 1993. In order to spin up the model, it was then run with the original parameters from 1993-1995. Three years spin-up has been shown to be sufficient for the system (Hansen, 2008). The sensitivity simulations were initiated in 1996 and run for a 6-year period. The impact of a single parameter or model formulation change was investigated in 11 sensitivity simulations. Subsequently the impact of five different combinations of these alterations was studied. Model-observation comparisons were performed in the period 1998 to 2001 because of relatively good in-situ data coverage combined with availability of ocean color data in this period.

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The model data to be compared to in-situ data was extracted from the model from files containing daily averages. The modeled values from the grid box and model layer containing the observation point on the day of the observation were selected. The model data was not interpolated temporally or spatially. In the case of several observations within the same grid cell and layer, the mean of the observed values was used.

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2.3 Description of observations

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An observational dataset collected as a part of the Norwegian Institute of Marine Research monitoring activities was used. In addition to comparing the simulations to the entire dataset, we also focused the comparison on two sub-regions; one in the Norwegian Sea and one the Barents Sea (Fig. 3). The available in-situ data relevant to the NORWECOM model are nutrients (silicate, nitrate, nitrite and phosphate) and chlorophyll, obtained by analysis of discrete water samples. Because we only have one type of nitrogen nutrient source in the model, the modeled nitrate was compared to the sum of observed nitrate and nitrite. The Norwegian Sea sub-region includes Station M and thus observational data are available throughout the year for all of the variables, while in the Barents Sea observations are collected primarily during August and September (Fig. 3).

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2.4 Statistical method for model evaluation

In the paper by Allen et al. (2007), several metrics for evaluation of biogeochemical models were presented. A combination of model efficiency (ME) and percentage model bias (Pbias)

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was used for the comparison between the model simulations and observations. These statistical quantities are defined as:

$$ME = 1 - \frac{\sum_{n=1}^{N}\left(D_n - M_n\right)^2}{\sum_{n=1}^{N}\left(D_n - \overline{D}\right)^2} \tag{6}$$

where D_n is observation from station n, M_n is the corresponding model estimate, $\overline{D}$ is the mean of the observations, and N is the total number of stations. The model efficiency is a measure of the model-observation misfit in relation to the variability of the observational data.

$$Pbias = \frac{\sum_{n=1}^{N}\left(D_n - M_n\right)}{\sum_{n=1}^{N} D_n} \times 100 \tag{7}$$

Pbias gives an indication on whether the model results are consistently under- or overestimated compared to the observations.

In addition, standard deviation, correlation coefficient and the centered root mean square error of chlorophyll and nutrients were evaluated in Taylor diagrams (Taylor, 2001) that show the overall quality of the runs.

2.5 Code availability

The full model code is available at https://svn.nersc.no/hycom/browser/HYCOM_2.2.12/CodeOnly/src_2.2.12/. The code is continually under development and version control is used when updating the code, so the HYCOM-NORWECOM V2.0 used for in the reference run, which were performed in October 2011 is revision number 186, while HYCOM-NORWECOM V2.1 corresponds revision number 224.

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3 Results

3.1 Performance of control runs

The model efficiency showed that the results from the control runs with the original parameters (N00 and TP0) were in general good with respect to nutrients (Fig. 4). The model performance was better for nitrate and phosphate than for silicate. In terms of ME for the nutrients there is little difference between the coarse and the fine model, but the results from the high-resolution model is slightly better. The percentage bias is also similar in the two control runs and again the estimates of nitrate and phosphate have higher skill compared to silicate (Fig. 5). The bias is positive, meaning that the modeled nutrients are consistently lower than the observed nutrients (eq. 7). The nutrient bias is slightly better in the high-resolution model than the coarse model. Below 500 meters (not shown), nitrate and phosphate are generally excellent in terms of bias, while silicate varies from excellent to good, except for a region in the central Norwegian Sea where it is poor. However, since the observed nutrients have low variability below 500 meters the ME shows no skill in most regions. Below 500 meters the model is probably quite influenced by both initial condition and the relaxation towards climatological nutrients at the boundary, as the residence time for the deep waters is estimated to be 2-10 years (Aagaard et al., 1985). Above 500 meters, the biases are generally poorer, while the model shows some skill in terms of predicting the observed nutrients. For the upper waters masses the residence time in this region it is about 3 month (Poulain et al., 1996), hence the initial and boundary condition have limited influence there.

The prediction of the chlorophyll content is even more challenging than for the nutrients. Hereby the runs with the original parameter set for both resolutions show no skill for the ME (Fig. 4) and large negative percentage biases (Fig. 5), meaning that the model consistently overestimates the chlorophyll. For chlorophyll there is no consistent improvement with resolution. Correlation between the observed and modeled chlorophyll is poor and the amplitude of the annual cycle is overestimated (Fig. 6). Analysis have shown that the model runs are consistently late in the spring bloom, a persistent feature in this model system (Samuelsen et al., 2009b).

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3.2 Parameter modifications

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As seen in section 3.1, the main challenge of the model lies in the overestimation of chlorophyll during the summer months. Many of the parameter changes were thus aimed at reducing the error in the phytoplankton fields, but as seen in figures 4 and 5 many of the changes had a positive influence on the simulated nutrient values as well. The original and new model formulations and parameter values of all the sensitivity simulations are listed in Table 2.

The first run, N01, had quadratic rather than linear mortality rate of phytoplankton, this change was aimed at increasing the phytoplankton losses during periods with high phytoplankton biomass. This alteration had little effect on the results, nevertheless it was also tried in combination with other parameter changes, N07 and N13, but no improvement was observed, therefore this alteration was not included in the final model formulation.

In nature, a wide range of Si:N ratios are observed in diatoms (Sarthou et al., 2005), therefore the second and third run, N02 and N03, altered the fixed uptake ratio of Si:N for diatoms, by decreasing and increasing this value by 25% respectively. In the control runs the model tended to consume all the silicate before nitrate in the spring, while this was not the case in the observations. A reduction in this ratio improved the modeled silicate in terms of model efficiency, while estimates of nitrate and phosphate gets reduced skill. This change however, reduced the summer chlorophyll concentrations, most likely because the spring diatom bloom consumed more nitrate, which is the limiting nutrient during the summer bloom. Increasing the ratio had the opposite effect. Because large flagellate summer concentration has been a recurring challenge in the model the reduced Si:N ratio was retained in some of the subsequent runs.

The next three sensitivity simulations explored alterations to the zooplankton mortality term; quadratic mortality (for both zooplankton size classes) – N04, increased and decreased mesozooplankton mortality – N05 and N06. These alterations had little effect on the error statistics and were not considered in any of the subsequent runs.

Three runs where the sensitivity to the choice of nitrate to chlorophyll ratio was investigated. The first (N08) was a simple increase by 25%, while the values of 12.5 (N09) and 6.3 (N10) were found in the literature (Fouilland et al., 2007; Yentsch and Vaccaro, 1958). In the North Atlantic values varying from 1 to 12.5 was found in the literature (Fouilland et al., 2007; Yentsch and Vaccaro, 1958). The alteration had little effect on the overall results for nutrient, but a rather large effect on chlorophyll. In general an increase of this ratio lead to an improvement in the chlorophyll comparison and a decrease to deterioration of the model results. We did not alter this value during the tuning, but think that a mechanistic model allowing for variable N:Chl ratio should be included in the model.

Motivated by the observation that diatoms can be consumed by microzooplanton (Sarthou et al., 2005) we made an experiment where diatoms were included in the diet of microzooplankton (N11). The microzooplankton grazing rate was also increased (N12). These runs, especially N12, had a negative effect on the silicate results, but a positive effect on the nitrate and phosphate. These changes also contributed to better results for the chlorophyll. The increased microzooplankton grazing rate resulted in improved performance of the model and it was the first simulation where the biases in both 1998 and 1999 were better than 'Poor' for chlorophyll.

From the above simulations we learned that reduction of the Si:N-ratio and microzooplankton grazing were the changes having the most positive impact on the model performance. Since these changes to zooplankton grazing negatively affected the silicate results, this alteration was combined with the reduction of the Si:N ratio in simulations N14 and N15. The run including diatoms in the microzooplankton diet was combined with reduced Si:N ratio in run N14, this only improved the silicate results. When these changes were also combined with increased microzooplankton grazing (N15) the results for all nutrients improved. In the last experiment, N16, a reduction of the maximum growth rate for both types of phytoplankton were added to N15, this had an additional positive effect on the chlorophyll errors. The parameter set in N16 was decided upon and studied in the high-resolution model.

3.3 Assessment of revised model simulation

The observations in some regions such as Station M and in the repeated sections (visible in the winter panel of Fig. 3) are collected more systematically and are more numerous than in the other regions. In the Norwegian Sea at Station M observations are available throughout the year, in the repeated sections each season is sampled, and an extensive survey in of the Barents Sea is done annually in August/September (Fig. 3). This should be kept in mind when comparing the performance of the run with original and revised parameters in different regions (Figs. 7 and 8). Overall the regional estimates were worse than the one including all observational data, but there are also areas where there are significant improvements. The

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results show that in terms of Pbias, nitrate and phosphate were improved in the central Norwegian Sea and Eastern part of the Barents Sea (Fig. 7). In the northwest of the Norwegian Sea eastern part of the Barents Sea there is little improvement, but the two latter regions only have data in specific seasons (Fig. 3). For silicate the regions where there is improvement is more intermittent, but the bias in the original run was 'poor' over most of the region, this is no longer the case. The bias for chlorophyll changes sign, but not show any regional improvement. The model efficiency shows improvement in the estimates of all three nutrients, in particular in the central Norwegian Sea where the results were initially not so good (Fig. 8). Chlorophyll remains below 'no skill' in the most of the domain, except for a few places in east and north part of the domain, where it is 'good' (Fig. 8). Most of the differences between the two runs occur in the upper 100 meters. The difference between the original and revised model run in the Norwegian and Barents Sea (boxes in Fig. 3) in terms of chlorophyll is summarized in a Taylor diagram (Fig. 6). This Taylor diagram shows that overall the new runs are in better agreement with the observations, the improvement is mostly in terms of reduced standard error (green dashed curves). The amplitude is improved in the Norwegian Sea, but for the comparison to all observations it is now too low. There are only small differences in the correlation coefficients, but they are overall slightly lower in the run with revised parameterizations.

To assess the revised run at different depths, profiles in the upper 1000 meters of the water column in the Norwegian Sea box have been compared to in-situ data for nutrient and chlorophyll (Figs 9 and 10). Below 200 meters the differences from observations are similar for the two parameter sets. The same is the case for the upper 200 meters, during January and April when the water column is well mixed and the surface concentrations reflect the deep concentrations. During July the run with revised parameters is closer to the observation for nitrate, but further from the observations for silicate, during October both of these nutrients are closer to the observation with the revised parameters. For phosphate it is difficult to judge from figure 9 which profile is closer to the observations. However, we have seen before that there is an overall improvement in the surface nutrients for the run with the revised model (Figs. 7 and 8). For chlorophyll (Fig. 10), it is clear that the overestimation of values that occurs with the original parameterization has now been reduced to give reasonable values. In April there is a clear indication in the observations that nutrients are being consumed in the upper layers, this is not the case in either of the model runs, and consistent with the modeled surface chlorophyll values that are lower than observed in this period (not shown). The late

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onset of the spring bloom has been a persistent challenge in the model for several years and seems to be related to delayed onset of stratification in the physical model fields, rather than the biological formulations (Samuelsen et al., 2009b).

4 Discussion

4.1 Uncertainties connected to observations

In general, the representativety of the measurements depends on how often it is measured – i.e. the uncertainty decreases with increasing number of observations. Depending on the issues addressed, there will be different requirements for geographical coverage, number of stations, frequency and parameters measured (e.g. Ottersen et al., 1998).

Programs on *in situ* monitoring of the biogeochemical environment are mainly carried out by discrete sampling and subsequent analysis along with regularly monitoring cruises or by stationary measuring systems like buoys. Monitoring cruises are restricted in spatial and temporal coverage, hence limiting the availability of high quality observational data. In addition the measurement methodologies are, especially for the biogeochemical parameters, an issue in terms of uncertainty of the specific measurement (i.e. Proctor and Roesler, 2010).

Exemplary for the variety of biogeochemical measurements are the challenges connected to the measurements of Chl *a* concentration, which are performed by analysing filtered water samples with spectrophotometric or high-performance liquid chromatography (HPLC) methodologies which are cost intensive. In order to lower the costs, a range of autonomous sensors has been developed to overcome these limitations. These sensors measure the Chl *a* fluorescence, which is used to provide an estimate of the Chl *a* concentration. The ratio between automated Chl a fluorescence measurements from the field and HPLC Chl *a (w:w)*, may vary with a factor 3-4 depending on the light regime, shading effects and the species composition of the samples (e.g. Jaccard et al., 2014).

In addition, when comparing to model results there is an added uncertainty in what the observations represent. One measurement may represent the value in a few litres of water, while the model value represents the value in ~10^9 m^3 of water, depending on the model resolution. Here, the same dataset was used for evaluation of the effect of the tuning, as was used to study the needs for tuning. To be fully validated, the model should be compared to

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independent observed data (Stow et al., 2009). However, due to scarce availability of observed data, it was decided to use all data for both activities.

4.2 Parameter changes

Most of the parameter changes were included to reduce the systematic overestimation of phytoplankton biomass during summer. Some parameter alterations were conducted to study the sensitivity of the model to the variety of ecosystem properties reported in the literature, this included different Si:N ratios and the inclusion of diatoms in the diet of microzooplankton. Several of the parameter alterations investigated had little impact on the results of the model. Quadratic, rather than linear, mortality in the phytoplankton was one of the changes that had little effect while a change in the grazing rates had a large effect indicating that the phytoplankton in this model system is largely controlled by zooplankton grazing rather than other sources of mortality.

The zooplankton mortality is the closure term in the model, but contrary to other studies (e.g (Steele and Henderson, 1992) perturbations of this parameter had little effect on the results. The reason for the lack of sensitivity to the closure term is not clear. Changes in the grazing term have large impact on the model results, this probably means that zooplankton is more controlled by food availability than other mortality sources. The sensitivity of this model to the diet compositions of zooplankton has also been shown in a more theoretical study on parameter estimation by data assimilation by Simon et al. (2012)

Increasing the N:Chl ratio would on one hand decrease the amount of chlorophyll per phytoplankton biomass, but also how quickly light is attenuated with depth. This alters the vertical distribution of phytoplankton, but it changes the concentrations only by a few percent, hence this effect is small compared to the effect on the chlorophyll concentration from altering the N:Chl ratio. The change of N:Chl (which is proportional to the C:Chl ratio in this model) with light availability is now well established (Geider, 1987) and implementing a variable N:Chl ratio is one of the future developments planned for this model.

The changes in the uptake ratio of silicate to nitrate had a large influence on the progress of both the diatom bloom and the flagellate bloom. Silicate is the limiting nutrient for diatoms, and when lowering this ratio more nitrate can be consumed leaving less nitrate for the flagellates and limiting the size of the bloom. Observed uptake ratios of Si:N vary widely and

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probably also varies between species, regions and seasons. Ideally a flexible uptake ratio could be included, for example as in the ERSEM model (i.e. Blackford et al., 2004), but including variable stoichiometry also increases the number of variables that has to be advected in the model and hence the computations cost considerably.

Because of computational limitations, only a small subset of the parameters was tested in this tuning exercise, the parameters were picked based upon past experience with the model. As grazing seems to be an important control mechanism in the model, the zooplankton assimilation efficiency may be an important parameter to test in the future. The temperature dependence of growth and respiration for both zooplankton and phytoplankton would probably influence the progress of the blooms across regions, but past experience with the model has shown that this model has little sensitivity to parameters related to phytoplankton growth, hence these parameters have been mostly left unchanged in this study. Additionally the sinking rates for detritus influence the amount of regenerated nutrients during summer.

4.3 Regional differences in performance

Evaluating the final run (TP1) compared to all observational data (Figs. 4 and 5) and to observations in different regions (Figs. 7 and 8), it is clear that the model performed better overall than on a region-by-region basis. The explanation for this may lie partly in the placement of water masses in the model combined with the locations of the measurements. In the Norwegian Sea the majority of measurements are taken at a single location (Station M). For the model to perform well there, it needs to simulate the correct water masses at this exact point. Station M is located close to a front between two water masses, and the model is not always simulating the location of this front well (not shown). In the Barents Sea most of the observations are collected in sections or over the whole area during early fall, therefore some of the dependency on simulating the correct location of fronts falls away in this region. In shallow areas, such as along the coast and in the Barents Sea, better representation of benthic processes as well as the lack of tides are probably sources of errors.

The location of the ice edge affect the results of the biogeochemical model (Samuelsen et al., 2009a). The observations used here are primarily from open-ocean regions, so we have limited knowledge of the model performance close to the ice edge. The comparison of the physical model simulation (free-run) to satellite observations shows that the ice-edge follows the observed pattern (Sakov et al. 2012), but of course it is not 100% accurate. In the model

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light does not propagate through ice, and the ice edges also influences mixing, therefore errors are expected in both chlorophyll and nutrients if the model places the ice edge incorrectly. In addition, the fact that we don't include ice-algae in the model also introduces sources of errors.

5 Conclusions

In total 18 sensitivity runs were performed on the higher- and coarser resolution model grid. First, the effect of tuning of single parameters was studied. Subsequently, the tuning of combinations of parameters were tested in the coarse model. The conclusion was that the best overall results were obtained when a combination of grazing preference for microzooplankton, Si:N ratio in diatoms and reduced growth rate for phytoplankton was used. This combination of parameters was then changed in the higher-resolution model and the differences in performance between the two sets of parameters were investigated in that configuration.

The revised run shows a clear improvement compared to the original run, particularly for nutrients but also for chlorophyll, but while the previous run tended to overestimate the annual cycle of chlorophyll, the revised run tends to underestimate the amplitude (Fig. 6). Based on these results, the revised parameter set presented here were also implemented as part of an operational system for the Arctic. A major difference between the model runs presented here and the operational system is that the operational system includes data assimilation in the physical model (Sakov et al., 2012), which may alter the physical model and in turn alter the performance of NORWECOM. A study of the impact of data assimilation on this model (Samuelsen et al., 2009a) showed that there were typically a difference of 5-10% for the nutrients and chlorophyll between the free run and the run with assimilation, but with difference up to 20% in the Arctic. Data assimilation can also be applied to the biogeochemical model, both as a mean of improving the forecast fields and as a method for optimizing model parameters (Simon et al., 2012).

We have shown that the model reproduces a reasonable annual cycle, but one persistent challenge the initiation time of the spring bloom is later than the observations. None of the parameter alterations significantly affected the timing of the spring bloom (not shown), this indicates that the error in timing is an effect either of the physical model or a missing process, such as for example phyto-convection process (Backhaus et al., 2003). Another challenge is to show that the model also produces realistic interannual variability. The model shows less

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variability than the observed data, but this is also expected as the observations include a spatial and temporal variability that cannot be resolved of a model of this resolution.

During the tuning process the parameter sensitivity of the module was explored and the changes that were motivated by observation-based findings, for example that Si:N is highly variable and that microzooplankton are grazing on diatoms, had a positive influence on the model. This suggests that greater refinement of the models in general should be done in closer collaboration with ecologist and field oceanographers.

Acknowledgements

This work was done with the support of the EU FP7 Project MyOcean2 (project number 283367) and the NFR funded SEASERA project SEAMAN (project number 227779/E40). A grant for CPU time was given by the Norwegian Supercomputing Project (NOTUR2).

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Table 1. Model versions and references.

HYCOM	NORWECOM	HYCOM-NORWECOM	References
V2.2.12	V2.0	V1.0	Description:(Skogen and Søiland, 1998); Examples of application: (Hansen and Samuelsen, 2009; Hansen et al., 2010)
V2.2.12	V2.0+zooplankton	V2.0	Application: Samuelsen and Bertino, 2011
V2.2.12	V2.0+zooplankton+ parameter tuning	V2.1	This paper

Table 2. Overview of runs performed with the associated parameter values.

	Parameter for tuning	Original value	New value
N00	Reference run		
TP0	Reference run with high resolution		
N01	Quadratic mortality for phytoplankton	cc(3), cc(3)=4.0e-7	cc(3)/15.0+cc(3)*P/15.0
N02	Si:N-ratio in diatoms	1.75 mgSi/mgN=0.875 mmolSi/mmolN	0.575mmolSi/mmolN=1.15 mgSi/mgN
N03	Si:N-ratio in diatoms	1.75 mgSi/mgN=0.875 mmolSi/mmolN	1.175mmolSi/mmolN=2.35 mgSi/mgN
N04	Quadratic mortality in zooplankton	m_z*(z/(z+cnit*k6)), m_z=0.2, z=zooplankton-conc [mgN/m^3]., cnit=14.01mgN/mmolN, k6=0.2	m_z/5.0+m_z*z/25.0
N05	Mesozooplanton mortality (+25%)	$m_{z\text{-meso}}$=0.2	$m_{z\text{-meso}}$=0.25
N06	Mesozooplanton mortality (-25%)	$m_{z\text{-meso}}$=0.2	$m_{z\text{-meso}}$=0.15
N07	Combination of N01 and N02	cc(3), cc(3)=4.0e-7, 1.75 mgSi/mgN	cc(3)/15.0+cc(3)*P/15.0, 1.15 mgSi/mgN
N08	N:Chl-ratio	11	13.75
N09	N:Chl-ratio	11	12.5
N10	N:Chl-ratio	11	6.3
N11	Grazing preferences for microzooplanton	pi21=0.633-flagellates, pi24=0.367-detritus	pi21=0.333-flagellates, pi23=0.333-diatoms, pi24=0.333-detritus

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N12	Maximum microzooplankton grazing rate	g=0.5	g=1.0
N13	Combination of N11 and N1	pi21=0.633-flagellates, pi24=0.367-detritus cc(3), cc(3)=4.0e-7	pi21=0.334-flagellates, pi23=0.333-diatoms, pi24=0.333-detritus, cc(3)/15.0+cc(3)*P/15.0
N14	Combination of N11 and N2	pi21=0.633-flagellates, pi24=0.367-detritus, 1.75 mgSi/mgN	pi21=0.334-flagellates, pi23=0.333-diatomes, pi24=0.333-detritus, 1.15 mgSi/mgN
N15	Combination of N14 and N12	pi21=0.633-flagellates, pi24=0.367-detritus, 1.75 mgSi/mgN, g(micro)=0.5	pi21=0.334-flagellates, pi23=0.333-diatoms, pi24=0.333-detritus, 1.15 mgSi/mgN, g(micro)=1.0
N16	Combination of N14 and reduced growth rate for phytoplankton	pi21=0.633-flagellates, pi24=0.367-detritus, 1.75 mgSi/mgN, Vmax(dia)=1.53E-5, Vmax(fla)=1.02E-5	pi21=0.334-flagellates, pi23=0.333-diatoms, pi24=0.333-detritus, 1.15 mgSi/mgN, Vmax(dia)=1.15E-5, Vmax(fla)=0.76E-5
TP1	High-resolution run with the parameter values of N16	pi21=0.633-flagellates, pi24=0.367-detritus, 1.75 mgSi/mgN, Vmax(dia)=1.53E-5, Vmax(fla)=1.02E-5	pi21=0.334-flagellates, pi21=0.333-diatoms, pi24=0.333-detritus, 1.15 mgSi/mgN, Vmax(dia)=1.15E-5, Vmax(fla)=0.76E-5

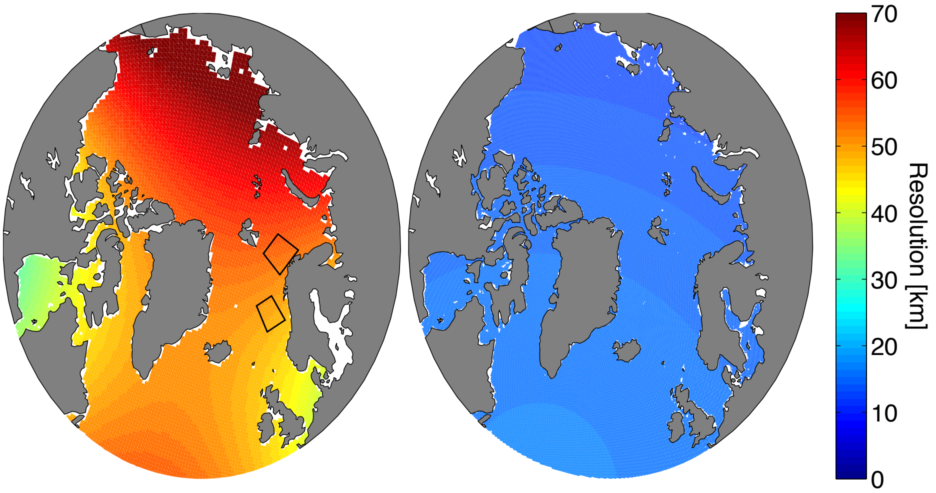

Figure 1. Resolution of the two model grids used in this study. The two areas indicated by black lines in the map to the left are the areas referred to as Norwegian Sea – southern area - and Barents Sea – northern area.

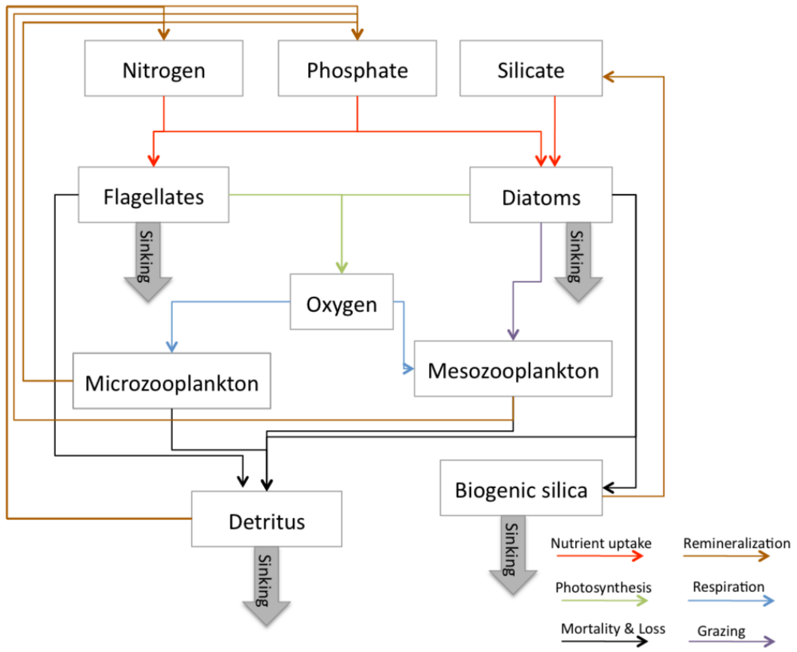

Figure 2. Flow chart of the interaction between the individual model components in NORWECOM.

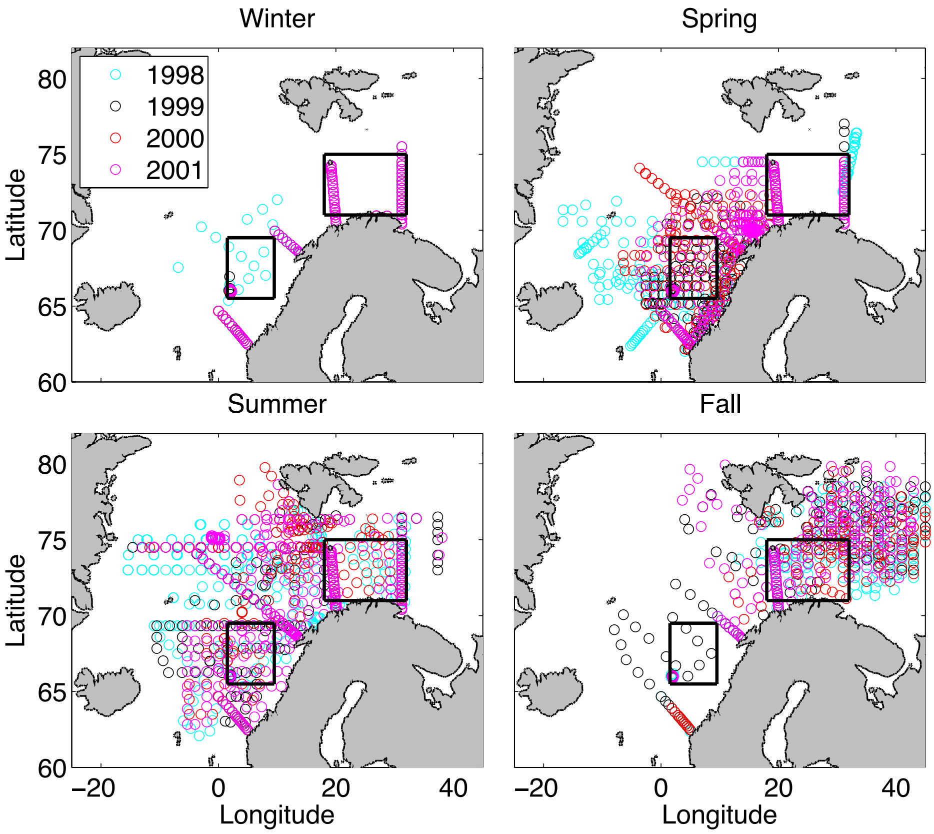

Figure 3. Spatial in-situ data coverage for nitrate in different years and seasons for the dataset used. The coverage for the other variables is similar. The southern areas are mostly sampled in spring and summer, while the Arctic regions are more sampled in summer and fall. There are very few open-ocean measurements during winter, but in the sections visible in the winter-panel (upper, left) there are observations for all years and seasons.

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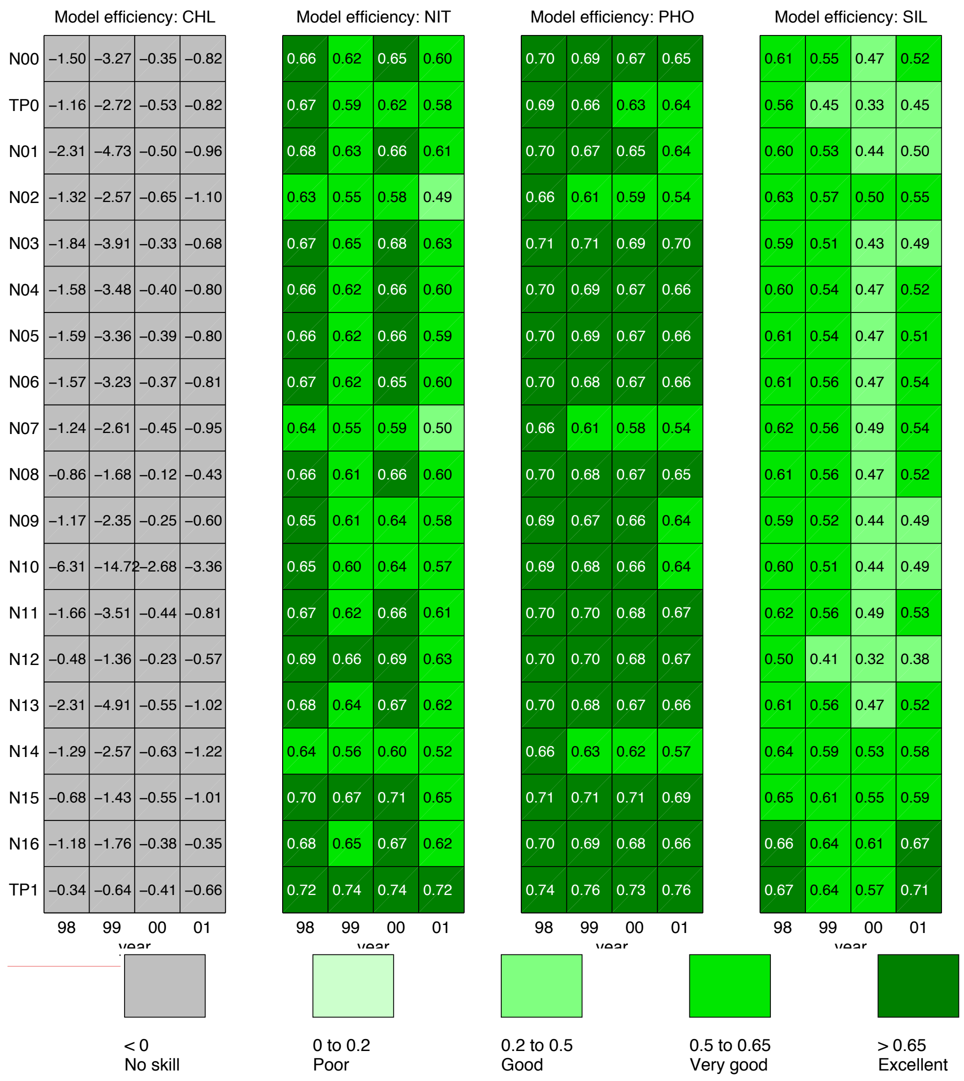

Model efficiency: CHL

	98	99	00	01
N00	−1.50	−3.27	−0.35	−0.82
TP0	−1.16	−2.72	−0.53	−0.82
N01	−2.31	−4.73	−0.50	−0.96
N02	−1.32	−2.57	−0.65	−1.10
N03	−1.84	−3.91	−0.33	−0.68
N04	−1.58	−3.48	−0.40	−0.80
N05	−1.59	−3.36	−0.39	−0.80
N06	−1.57	−3.23	−0.37	−0.81
N07	−1.24	−2.61	−0.45	−0.95
N08	−0.86	−1.68	−0.12	−0.43
N09	−1.17	−2.35	−0.25	−0.60
N10	−6.31	−14.72	−2.68	−3.36
N11	−1.66	−3.51	−0.44	−0.81
N12	−0.48	−1.36	−0.23	−0.57
N13	−2.31	−4.91	−0.55	−1.02
N14	−1.29	−2.57	−0.63	−1.22
N15	−0.68	−1.43	−0.55	−1.01
N16	−1.18	−1.76	−0.38	−0.35
TP1	−0.34	−0.64	−0.41	−0.66

Model efficiency: NIT

	98	99	00	01
N00	0.66	0.62	0.65	0.60
TP0	0.67	0.59	0.62	0.58
N01	0.68	0.63	0.66	0.61
N02	0.63	0.55	0.58	0.49
N03	0.67	0.65	0.68	0.63
N04	0.66	0.62	0.66	0.60
N05	0.66	0.62	0.66	0.59
N06	0.67	0.62	0.65	0.60
N07	0.64	0.55	0.59	0.50
N08	0.66	0.61	0.66	0.60
N09	0.65	0.61	0.64	0.58
N10	0.65	0.60	0.64	0.57
N11	0.67	0.62	0.66	0.61
N12	0.69	0.66	0.69	0.63
N13	0.68	0.64	0.67	0.62
N14	0.64	0.56	0.60	0.52
N15	0.70	0.67	0.71	0.65
N16	0.68	0.65	0.67	0.62
TP1	0.72	0.74	0.74	0.72

Model efficiency: PHO

	98	99	00	01
N00	0.70	0.69	0.67	0.65
TP0	0.69	0.66	0.63	0.64
N01	0.70	0.67	0.65	0.64
N02	0.66	0.61	0.59	0.54
N03	0.71	0.71	0.69	0.70
N04	0.70	0.69	0.67	0.66
N05	0.70	0.69	0.67	0.66
N06	0.70	0.68	0.67	0.66
N07	0.66	0.61	0.58	0.54
N08	0.70	0.68	0.67	0.65
N09	0.69	0.67	0.66	0.64
N10	0.69	0.68	0.66	0.64
N11	0.70	0.70	0.68	0.67
N12	0.70	0.70	0.68	0.67
N13	0.70	0.68	0.67	0.66
N14	0.66	0.63	0.62	0.57
N15	0.71	0.71	0.71	0.69
N16	0.70	0.69	0.68	0.66
TP1	0.74	0.76	0.73	0.76

Model efficiency: SIL

	98	99	00	01
N00	0.61	0.55	0.47	0.52
TP0	0.56	0.45	0.33	0.45
N01	0.60	0.53	0.44	0.50
N02	0.63	0.57	0.50	0.55
N03	0.59	0.51	0.43	0.49
N04	0.60	0.54	0.47	0.52
N05	0.61	0.54	0.47	0.51
N06	0.61	0.56	0.47	0.54
N07	0.62	0.56	0.49	0.54
N08	0.61	0.56	0.47	0.52
N09	0.59	0.52	0.44	0.49
N10	0.60	0.51	0.44	0.49
N11	0.62	0.56	0.49	0.53
N12	0.50	0.41	0.32	0.38
N13	0.61	0.56	0.47	0.52
N14	0.64	0.59	0.53	0.58
N15	0.65	0.61	0.55	0.59
N16	0.66	0.64	0.61	0.67
TP1	0.67	0.64	0.57	0.71

Figure 4. Model efficiency (ME, see text) for the model simulations compared to all available observations from the period 1998-2001.

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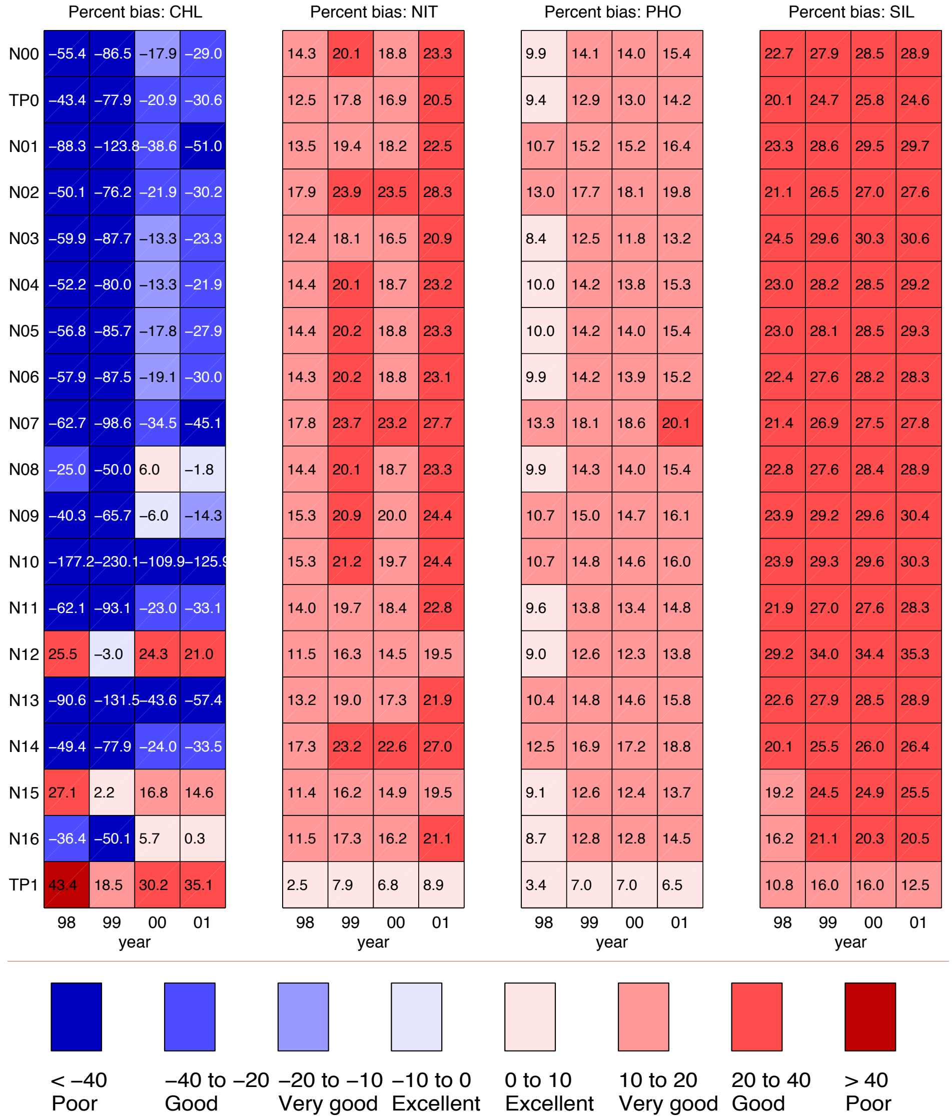

Percent bias: CHL

	98	99	00	01
N00	−55.4	−86.5	−17.9	−29.0
TP0	−43.4	−77.9	−20.9	−30.6
N01	−88.3	−123.8	−38.6	−51.0
N02	−50.1	−76.2	−21.9	−30.2
N03	−59.9	−87.7	−13.3	−23.3
N04	−52.2	−80.0	−13.3	−21.9
N05	−56.8	−85.7	−17.8	−27.9
N06	−57.9	−87.5	−19.1	−30.0
N07	−62.7	−98.6	−34.5	−45.1
N08	−25.0	−50.0	6.0	−1.8
N09	−40.3	−65.7	−6.0	−14.3
N10	−177.2	−230.1	−109.9	−125.
N11	−62.1	−93.1	−23.0	−33.1
N12	25.5	−3.0	24.3	21.0
N13	−90.6	−131.5	−43.6	−57.4
N14	−49.4	−77.9	−24.0	−33.5
N15	27.1	2.2	16.8	14.6
N16	−36.4	−50.1	5.7	0.3
TP1	43.4	18.5	30.2	35.1

year

Percent bias: NIT

	98	99	00	01
N00	14.3	20.1	18.8	23.3
TP0	12.5	17.8	16.9	20.5
N01	13.5	19.4	18.2	22.5
N02	17.9	23.9	23.5	28.3
N03	12.4	18.1	16.5	20.9
N04	14.4	20.1	18.7	23.2
N05	14.4	20.2	18.8	23.3
N06	14.3	20.2	18.8	23.1
N07	17.8	23.7	23.2	27.7
N08	14.4	20.1	18.7	23.3
N09	15.3	20.9	20.0	24.4
N10	15.3	21.2	19.7	24.4
N11	14.0	19.7	18.4	22.8
N12	11.5	16.3	14.5	19.5
N13	13.2	19.0	17.3	21.9
N14	17.3	23.2	22.6	27.0
N15	11.4	16.2	14.9	19.5
N16	11.5	17.3	16.2	21.1
TP1	2.5	7.9	6.8	8.9

year

Percent bias: PHO

	98	99	00	01
N00	9.9	14.1	14.0	15.4
TP0	9.4	12.9	13.0	14.2
N01	10.7	15.2	15.2	16.4
N02	13.0	17.7	18.1	19.8
N03	8.4	12.5	11.8	13.2
N04	10.0	14.2	13.8	15.3
N05	10.0	14.2	14.0	15.4
N06	9.9	14.2	13.9	15.2
N07	13.3	18.1	18.6	20.1
N08	9.9	14.3	14.0	15.4
N09	10.7	15.0	14.7	16.1
N10	10.7	14.8	14.6	16.0
N11	9.6	13.8	13.4	14.8
N12	9.0	12.6	12.3	13.8
N13	10.4	14.8	14.6	15.8
N14	12.5	16.9	17.2	18.8
N15	9.1	12.6	12.4	13.7
N16	8.7	12.8	12.8	14.5
TP1	3.4	7.0	7.0	6.5

year

Percent bias: SIL

	98	99	00	01
N00	22.7	27.9	28.5	28.9
TP0	20.1	24.7	25.8	24.6
N01	23.3	28.6	29.5	29.7
N02	21.1	26.5	27.0	27.6
N03	24.5	29.6	30.3	30.6
N04	23.0	28.2	28.5	29.2
N05	23.0	28.1	28.5	29.3
N06	22.4	27.6	28.2	28.3
N07	21.4	26.9	27.5	27.8
N08	22.8	27.6	28.4	28.9
N09	23.9	29.2	29.6	30.4
N10	23.9	29.3	29.6	30.3
N11	21.9	27.0	27.6	28.3
N12	29.2	34.0	34.4	35.3
N13	22.6	27.9	28.5	28.9
N14	20.1	25.5	26.0	26.4
N15	19.2	24.5	24.9	25.5
N16	16.2	21.1	20.3	20.5
TP1	10.8	16.0	16.0	12.5

year

< −40	−40 to −20	−20 to −10	−10 to 0	0 to 10	10 to 20	20 to 40	> 40
Poor	Good	Very good	Excellent	Excellent	Very good	Good	Poor

Figure 5. Percentage bias (Pbias, see text) for the model model simulations compared to all available observations from the period 1998-2001.

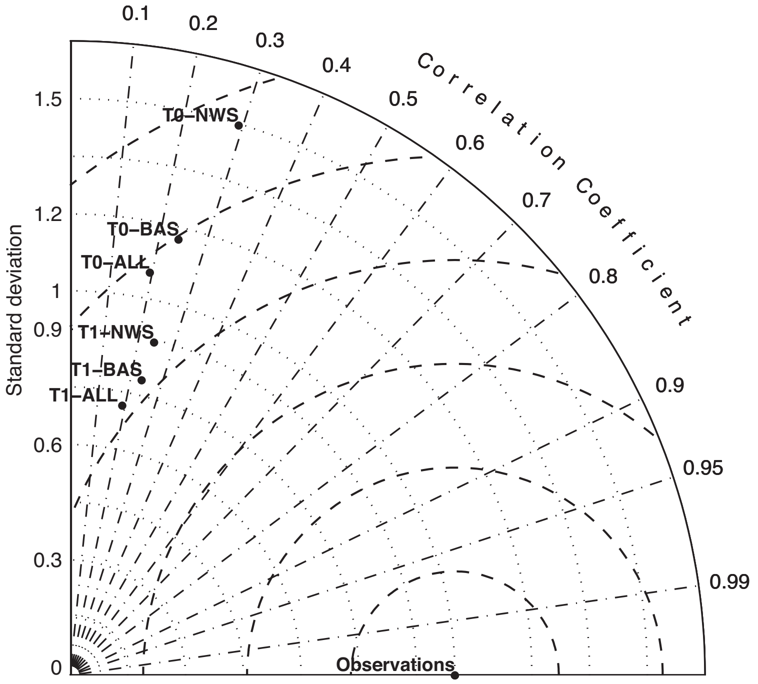

Figure 6. Taylor-diagram for comparison with in-situ chlorophyll for the entire area (ALL), the Barents Sea (BAS) and the Norwegian Sea including station M (NWS). The curved dotted lines show the standard deviation relative to the observations.

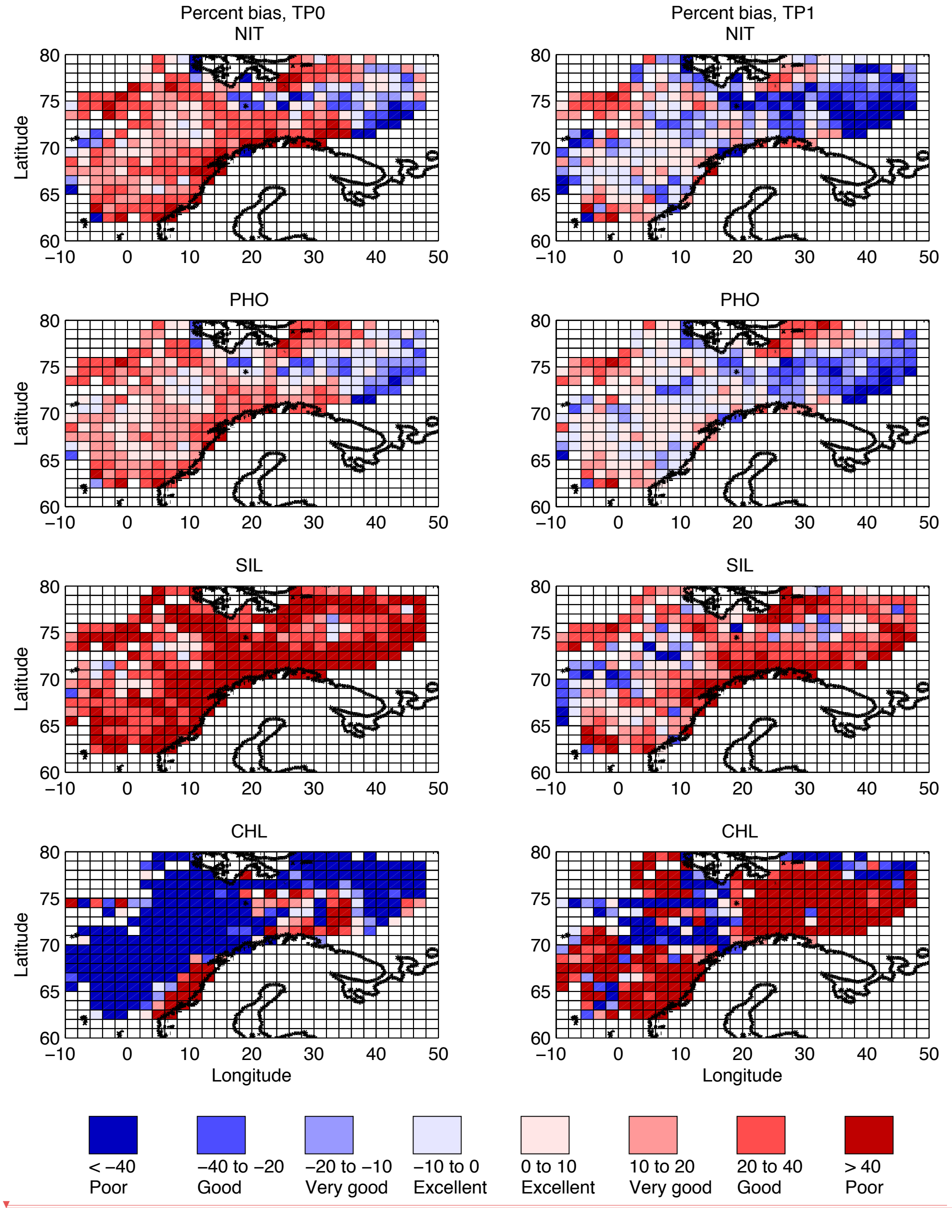

Figure 7. Percentage bias (Pbias, see text) in the upper 100 meters for the model simulations compared to all available observations from the period 1998-2001 in 2x1 degree boxes from the simulations with the fine-scale model with the original (TP0) and final set of parameters (TP1).

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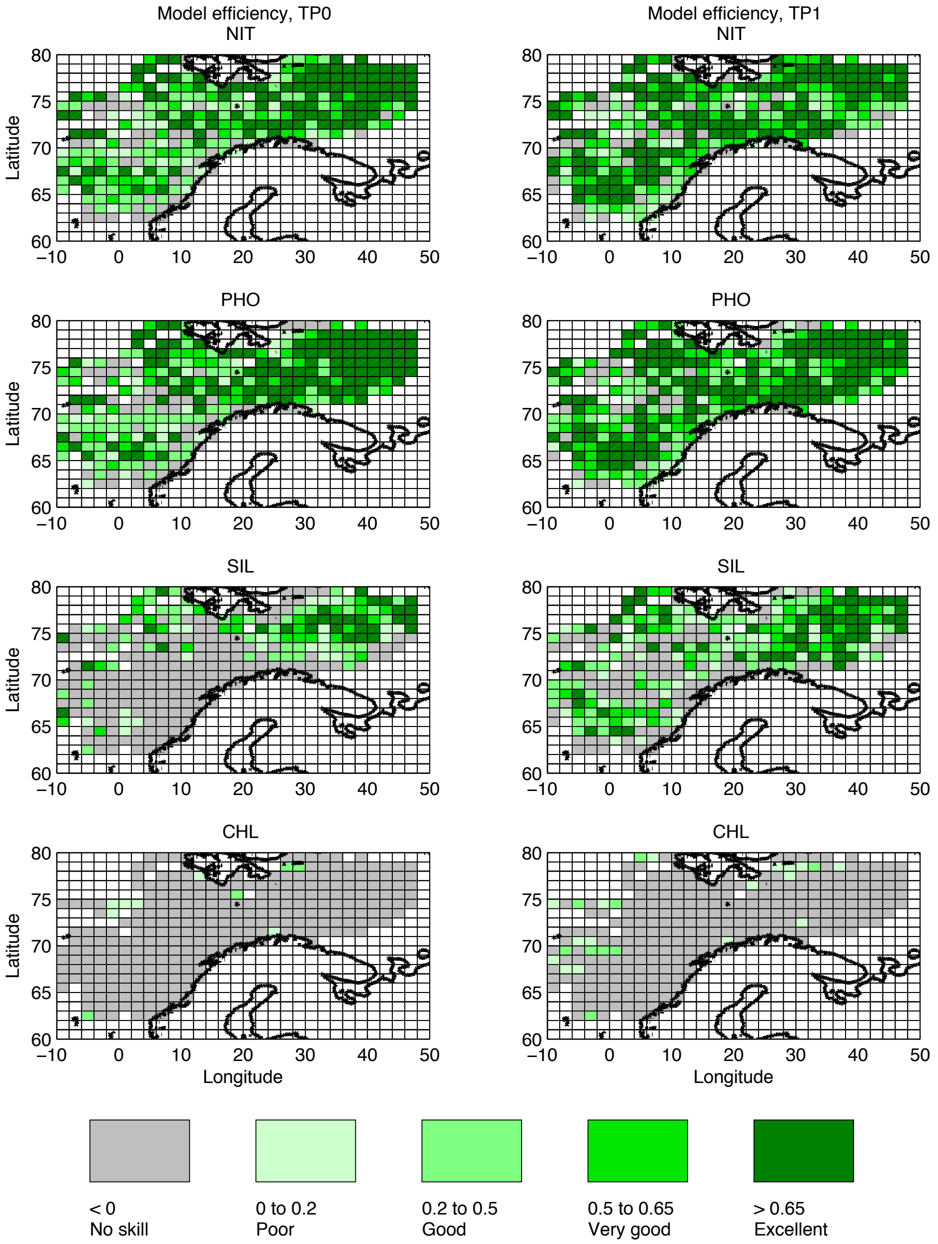

Figure 8. Model efficiency (ME, see text) in the upper 100 meters for the model simulations compared to all available observations from the period 1998-2001 in 2x1 degree boxes from the simulations with the fine-scale model with the original (TP0) and final set of parameters (TP1).

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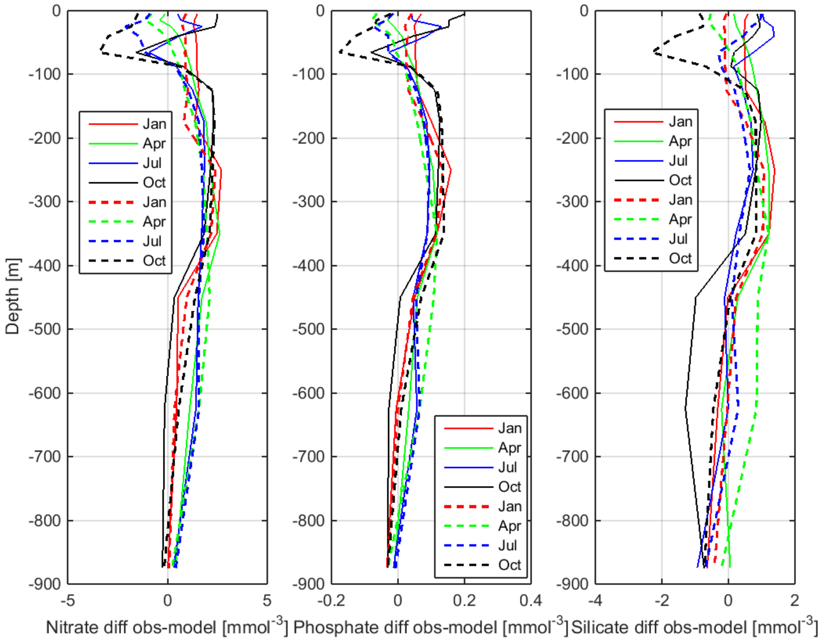

Figure 9. Profiles of difference between model and observations in different months in the Norwegian Sea box – solid lines are the revised simulation and dashed lines the control run. All observations in the Norwegian Sea box between 1998 and 2001 have been used.

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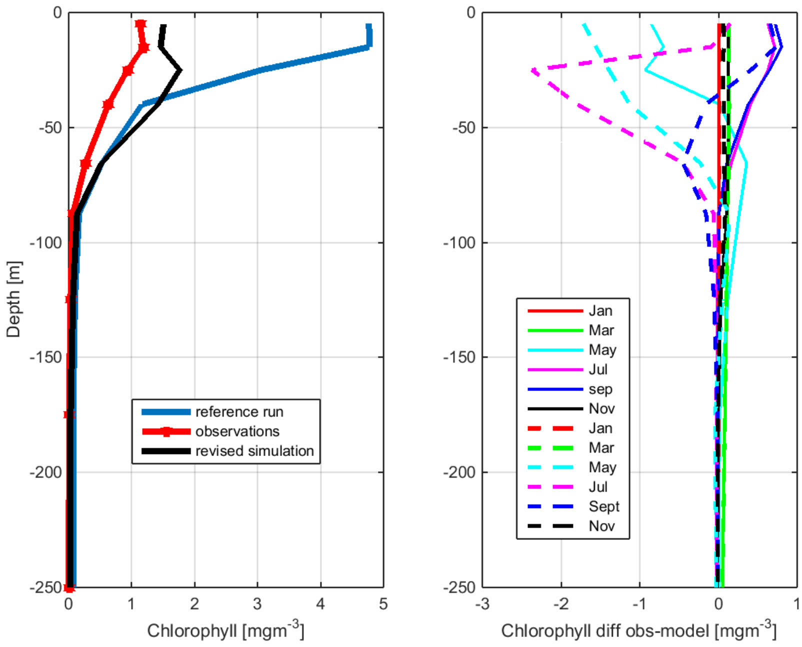

Figure 10. Chlorophyll profiles from the control and reference run using the higher resolution model in June (a) in the Norwegian Sea box as well the difference between observations and model in the other months (b) – solid lines are the revised simulation and dashed lines the control run. All observations in the Norwegian Sea box between 1998 and 2001 have been used.

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Appendix

Table A1. Location of changes in the model code, all files are located in https://svn.nersc.no/hycom/browser/HYCOM_2.2.12/CodeOnly/src_2.2.12/nersc/NORWECOM/

	Parameter for tuning	Relevant files	Remarks
N01	Quadratic mortality for phytoplankton	m_NOR05_detritus.F: line 77-89 mod_necessary_ecovars.F90: line 45-54	ZOOPL is 'defined' in all runs in this paper
N02/NO3	Si:N-ratio in diatoms	mod_necessary_ecovars.F90: line 45-54	
N04/NO5/NO6	Meso zooplankton mortality	m_NOR05_zoo_growth.F: line 53	For quadratic mortality, the mortality was set inside the loop calculating mesozooplankton (this code was never submitted to the subversion control system).
N07	Combination of N01 and N02	See above for N01 and NO2	
N08/N09/N10	N:Chl-ratio	biocom.h: line 107-108	
N11	Grazing preferences for microzooplanton	m_NOR05_zoo_growth.F: line 26, 100-132	

N12	Grazing preferences for microzooplankton	m_NOR05_zoo_growth.F: line 26, 101	
N13	Combination of N11 and N01	See above for N11 and N01	
N14	Combination of N11 and N2	See above for N11 and N02	
N15	Combination of N14 and N12	See above for N14 and N12	
N16	Combination of N14 and reduced growth rate for phytoplankton	See above for N14 and m_NOR05_affin.F: line 64 and 66	

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A total of 18 sensitivity runs including control runs were performed, on the higher-resolution and coarser model grid. First, the effect of tuning of single parameters, such as mortality for phytoplankton and zooplankton, Si:N ratio, N:Chl ratio and grazing preference for zooplankton was studied. Second, the tuning of combinations of parameters, for instance grazing preference and mortality rate, were tested in the coarse model. The conclusion was that the best results were obtained when a combination of grazing preference for microzooplankton, Si:N ratio in diatoms and reduced growth rate for phytoplankton was used. This combination of parameters was then changed in the higher-resolution model and the effects of changing parameters were investigated there as well. Also in the higher-resolution model grid the simulations with revised parameters show improvements for nutrients and chlorophyll.

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For example, for observing changes in the deep ocean, taking measurements one or a few times a year is enough, there are however changes in the deep ocean are so small that detecting changes require large claims to the accuracy of these observations. In comparison, the coastal areas and surface waters needs to be measured substantially more often in order to capture the variability, but since these waters have large variability the requirements to accuracy can often be relaxed.

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On top of the uncertainties connected to the observed data themselves,

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On top of the uncertainties connected to the observed data themselves,

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On top of the uncertainties connected to the observed data themselves,

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to reproduce the correct initiation time of the spring bloom.

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The model is consistently late in its initiation time and none

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The model is part of an operational system for the Arctic and based on the sensitivity runs and the comparisons of these to available in situ observations a new set of parameters were decided on and implemented in the operational model.

A major difference between the model runs presented here and the operational system is that the operational system includes data assimilation in the physical model (Sakov et al., 2012), which may alter the physical model and in turn alter the performance of NORWECOM. A study of the impact of data assimilation on this model (Samuelsen et al., 2009a) showed that there were typically a difference of 5-10% for the nutrients and chlorophyll between the free run and the run with assimilation, but with difference up to 20% in the Arctic. As newer data becomes available more improvements can be included also taking into account the effect of assimilation on the system.

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Figure 8. Taylor-diagram for comparison with in-situ chlorophyll for the entire area (ALL), the Barent Sea (BAS) and the Norwegian Sea including station M (NWS).