Interactive comment on "On the influence of sea-ice physics in multi-decadal ocean-ice hindcasts"by Petteri Uotila et al.

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Received and published: 22 August 2016

Dear authors,

In my role as Executive editor of GMD, I would like to bring to your attention our Editorial version 1.1: http://www.geosci-model-dev.net/8/3487/2015/gmd-8-3487-2015.html. This highlights some requirements of papers published in GMD. In particular, please note that for your paper, the following requirements have not been met in the Discussions paper:

- "The main paper must give the model name and version number (or other unique identifier) in the title."
- "If the model development relates to a single model then the model name and the version number must be included in the title of the paper. If the main intention of an article is to make a general (i.e. model independent) statement about the usefulness of a new development, but the usefulness is shown with the help of one specific model, the model name and version number must be stated in the title. The title could have a form such as, "Title outlining amazing generic advance: a case study with Model XXX (version Y)"."

Therefore I recommend to change the title of your article to something like: "On the influence of sea-ice physics in multi-decadal ocean-ice hindcasts: a NEMO 3.6 case study using the sea-ice schemes LIM2 and LIM3"in your revised submission to GMD.
Yours, Astrid Kerkweg

Authors' response:

Thank you very much for pointing these journal guidelines out. Following them and Reviewer #1 suggestions we have changed the title of our article to: "Comparing some aspects of the ocean hydrography, circulation and sea ice between NEMO3.6 LIM3 and LIM2". We think this new title well describes the manuscript content and matches the GMD journal requirements.

Interactive comment on “On the influence of sea-ice physics in multi-decadal ocean-ice hindcasts” by Petteri Uotila et al.
Referee #1.

This article analyzes the effect of the new LIM3 sea ice model compared to the old LIM2 sea ice model in ocean stand-alone simulations with the new NEMO3.6 model. The results show an improvement of the sea ice representation but little effect on the rest of the ocean. Since the NEMO-ocean model is widely used in the climate modelling community and will also be the ocean component of a number of CMIP6 models, I find this comparison useful and worth to publish. The article is generally well written and organized. However, at a number of places, some more clarifications are needed and I find a few of the explanations for the differences between the model versions not entirely convincing.

Author response: We thank the reviewer for carefully reading the manuscript and for her/his constructive suggestions that significantly improved the manuscript. Please find below our responses to the reviewer’s general comments and specific points.

Main points:

1. Several times, the authors state that the main objective of this study is to evaluate ocean hydrography and circulation. The manuscript in its present form does not reflect this. While the comparison of sea ice representation between LIM2 and LIM3 is done in detail, the evaluation of the ocean circulation part is rather superficial, partly because differences between NEMO-LIM2 and NEMO-LIM3 are small in the ocean away from the ice. If the ambition of the authors really is to focus mainly on the evaluation of the ocean circulation and if this article should be the major reference for the performance of the new NEMO3.6 model, much more detailed analyses are needed. However, if the main idea is to specifically focus on the effect of LIM3 and LIM2 in NEMO3.6, I would suggest to state that this article should be on: “Sea ice representation and some aspects of the ocean hydrography and circulation”. In this case not much additional analysis is needed.

Author response: Thank you very much for this suggestion. Yes, our main idea is to focus on the effect of LIM3 and LIM2 in NEMO3.6. Hence, we decided to follow your suggestion and changed the title of our article to: "Comparing some aspects of the ocean hydrography, circulation and sea ice between NEMO3.6 LIM3 and LIM2". We think this new title well describes the manuscript content and matches the GMD journal requirements, as pointed out by the Editor.

We would also like to make a point that the majority of oceanic diagnostics we carried out, such as hydrography and transports, were excluded from the manuscript because they showed very small differences between LIM2 and LIM3, or the differences had similar characteristics than what the oceanic diagnostics included in the manuscript reveal. We think this is due to the fact that the largest impacts of the sea-ice model are concentrated to the upper ocean. Therefore we think that is fair to say that the oceanic analysis has had a large focus, in addition to sea-ice, although only a small part of it ended up in the present version of the manuscript due to the reasons mentioned.

2. It would help to add also subfigures of “LIM2-Obs” in the figures. It is often very difficult to really judge from LIM3-Obs and LIM3-LIM2, how much LIM3 really improved the result, especially if the colour scales for LIM3-OBS and LIM3-LIM2 are different.

Author response: A good point. We added "LIM2-Obs"panels to the figures.

3. Differences between NEMO3.6-LIM2 and NEMO3.6-LIM3 are often rather small and taken over a relatively short period (10-years). Thus, significances of the differences should be calculated and shown in the figures.

Author response: We agree. We used the t-test to estimate the 5% significances levels for average LIM3-LIM2 differences and hatched the areas of statistically significant differences in the figures.

4. The impact of the ice model on mixing, deep water formation and ocean circulation will take place through salinity changes. However, the restoring in the model (+ the prescribed atmosphere that cannot feed back onto the ocean) might hide much of this effect. Thus, the experiments without freshwater adjustments are very important in order to analyze the impact of the ice-model on the ocean and results from these experiments should be discussed more in detail.

Author response: This is true and we concur. We have added panels to the figures and expanded the discussion on the experiments without freshwater adjustments. Our main finding is that the LIM3–LIM2 differences are smaller than LIM3FW–LIM2FW differences, in particular in the upper ocean. However, the difference patterns are remarkably similar.

5. It should be considered to reformulate the abstract. It is not very clear, includes some, for the abstract, unnecessary information and could instead mention some more of the major results from this study.

Author response: The abstract has been reformulated. We hope it is now more clear with necessary information and major results.

Specific comments:

Abstract: 1. p1, l6: “Results of such analysis . . ..”: I do not think this justification is needed in the abstract

Author response: You are right. We have removed the sentence.

2. p1, l8: Delete “while NEMO-LIM2 deviates more”

Author response: Deleted.

3. p1, l11: “skill sufficient for ocean-ice hindcasts that target oceanographic studies”: unclear, make clearer or delete

Author response: We clarified this sentence and state now that "... produced sea ice with a realism comparable to that of LIM2."

4. P1, l17-20: Since coupling to the atmosphere is mentioned, the potential effect of ice variations/ trends on atmospheric circulation should be shortly discussed as well (e.g. Barnes 2013; Francis et al. 2009; Francis and Vavrus 2012; Garcia Serrano and Frankignoul 2014; Hopsch et al. 2012; Koenigk et al. 2016; Liptak and Strong 2014; Overland and Wang 2010; Petoukhov and Semenov 2010; Screen 2014; Yang and Christensen 2012, ...). One motivation to improve sea ice models is that this might have large consequences on atmospheric climate conditions as well.

Author response: Yes, this is definitely an aspect that deserves to be mentioned. We added such a discussion to Introduction.

5. P2, l2-3: See main point 1: The main focus of this study seems to be the effect on sea ice and not on ocean circulation, which is by far less intensive analyzed in this study.

Author response: We agree, please see our answer to your Main point 1.

6. P3, l12: I thought the minimum horizontal length is a bit smaller than 50km in the Arctic near the poles, e.g. around Greenland. Please check.

Author response: You are correct. After checking the ORCA1 grid file, we found that the smallest grid cell lengths in the Arctic Ocean are between 40-50 km. We reworded the sentence to begin with "A typical horizontal..."from "The minimum horizontal..."as we want to tell the reader what the typical ORCA1 grid resolution is in the polar regions.

7. P4, l17: Please explain what is meant with a salinity restoring rate of -100mm/day. If this is a freshwater flux (global average?), this sounds very large.

Author response: The salinity restoring rate is a global negative feedback coefficient which is provided as a `namelist` parameter. The SSS restoring term should be viewed as a flux correction on freshwater fluxes to reduce the uncertainties we have on the observed freshwater budget. We added this additional information to the text. We admit that -100 mm/day is a large value. However, it is a smaller one than the default NEMO value which is -166.67 mm/day. We decided to to use the smaller value after discussions with the NEMO users of the COST EOS Ocean Synthesis action. Based on the community discussion it is likely that many NEMO users are using this, or even a higher, salinity restoring rate with ORCA1.

8. P4, l30-P5, l2: I am confused about what tuning has been done for each of the versions? Here, it is stated that a specific and optimized tuning has been done for each of the versions. In the conclusions you state; "no specific tuning has been done". I agree that two optimized model versions should be compared. In this context, I wonder if really the same effort has been done to optimize NEMO3.6LIM2 as for optimizing NEMO3.6LIM3? My worry is that the LIM2-ice-parameters have been taken from an older NEMO-LIM2 version and that the NEMO3.6-ocean parameters have been tuned with LIM3 and not with LIM2. Please describe in more detail how these two versions have been tuned and optimized.

Author response: This is a good comment and we think that the reviewer's concern regarding the LIM2–LIM3 comparison are justified. It is a very difficult one to address, because, in practice, there has been no systematic tuning procedure. As a result, the default parameter values of both sea-ice models are probably not the most optimal ones. They are, however, the default values obtained with the code and the ones that an average NEMO-LIM user is likely to end up using. Moreover, the systematic optimisation of both sea-ice models would have been a too daunting and complex task for this paper. Instead, we selected a more pragmatic approach and used the default parameter values. We think that this approach produces valuable results to the NEMO user community.

Regarding the detailed history of the LIM parameter values, we note that LIM2 has been used with the DFS forcing for about 10 years by the DRAKKAR community, mostly at 1/4° (ORCA025) resolution. The default LIM2 parameter values are a result of this exercise. Only the horizontal diffusivity (for scalability) and the EVP rheology (for numerical stability) were adjusted to the ORCA1 resolution.

The LIM3.6 default parameter values mostly come from the initial model version (Vancoppenolle et al. 2009), with some corrections on ice strength P^* and albedo following Rousset et al. (2015). Both studies used a NCEP based atmospheric forcing, so it is quite comforting, and even a bit surprising, that no specific tuning of LIM3 to DFS forcing was required.

By contrast, the LIM3SC virtual sea-ice thickness parameters were specifically tuned to match two key relationships of the multi-category version: 1) the growth rate–thickness dependence, and 2) the rate of concentration decrease versus sea-ice thickness dependence.

9. P5, l4-10: I am not sure I really understand this: Are you saying that LIM2 with P from LIM3 simulates much less ice volume but the same ice area than LIM2 with its standard P*? Why is this indicating "insignificant oceanic impacts"? Please clarify.*

Author response: We have reworded the text and decided not to mention the unclear "insignificant oceanic impacts". Instead we note that the LIM2 with its standard P^* results in a more realistic sea-ice volume which is why we decided to use it instead of the LIM2 simulation using the higher LIM3 P^*.

10. Experiments: A table listing the different simulations would be helpful

Author response: This is a good suggestion. We have added such a list as Table 1.

11. P5, l15: If LIM3 with 1 ice category is much better than LIM2 but physically closer to LIM2 than LIM3, what is the reason that LIM3-1IC is better? This feature is then obviously more important for an ice model than e.g. multiple ice thickness categories.

Author response: Suggested reasons for different performances between LIM2 and LIM3SC clearly point to differences between the thermodynamics parameterisations, including the latent heat reservoir. It is really hard to deduce the differences beyond this, because the thermodynamics code of the models are quite incompatible.

Regarding the second point, the sea-ice differences between LIM3 and LIM2, and LIM3 and LIM3SC are comparable and have the same sign. This indicates that the impact of multiple ice categories versus a single ice category is clear and systematic although when comparing LIM3 and LIM2 this is partially masked by additional LIM3–LIM2 differences due to other differences in model configurations. The corresponding differences between LIM3SC and LIM2 are on the average smaller which signifies the primary importance of ice categories rather than the sea-ice thermodynamics parameterisations.

12. P6, l 24: Again, I do not have the impression that this study only shortly focuses on the sea ice and merely on sensitivity experiments and oceanographic analysis. Section 3 is the longest of all sections.

Author response: This is true, please see our answer to your Main point 1.

13. P6, l29, Figure1 b: I do not see 50% reduction in the East-Siberian Sea. Largest reduction seems to be between North Pole and northern Kara Sea. Please check.

Author response: Well spotted, we changed the text accordingly.

14. Figure 1: It would be good to show the spatial distribution of LIM3MC as well.

Author response: We added LIM3MC (now LIM3SC) spatial distributions to Figure 1.

15. Figure2: It is not really self-explanatory to call LIM3 with 1 single ice category "LIM3MC". This sounds like LIM3 with multi-ice categories. Maybe better LIM3SC.

Author response: True. LIM3MC stands for LIM3 mono-category, but since it may be confused with multi-category we follow your suggestion and use the LIM3SC abbreviation instead.

16. P 7, l34: I do not think you can explain the LIM3 low summer ice extent by the ice-albedo-feedback. The ice-albedo feedback exists in reality. Maybe you can explain the low summer ice extent by too low ice albedo in LIM3 or a too strong effect due to unrealistic distribution of ice thicknesses (e.g too much thin ice). On the other hand, the annual cycle in LIM2 is even larger than in LIM3 (which is opposite to the NH). Does not this speak against an effect of the ice categories?

Author response: Our thinking was too simplistic here. What we concluded for the spring NH sea-ice extent evolution in terms of the enhanced ice-albedo feedback due to LIM2 sub-grid-scale ice thickness distribution seem not to directly hold for the SH spring sea-ice extent evolution. We reformulated the text to explain this better:

The time series of annual mean sea-ice extent of LIM3 is rather well reproduced and closely follows observations (Figure 2d), but the sea-ice spring retreat is systematically too strong and summer extent too low. The LIM3 winter sea ice is on the average thicker than the LIM2 sea ice, while in summer their thicknesses are close to each other (not shown here). On the other hand, the average LIM3 sea-ice concentration is systematically about 1–10% smaller than the LIM2 one, even in the central ice pack. As a result, the LIM3 sea-ice extent is smaller, particularly in summer.

The processes explaining the low LIM3 summer sea-ice extent are related to (1) the steeper decline of LIM3 mean sea-ice thickness and (2) to its systematically lower sea-ice concentration. Arguably the most important process is the positive ice-albedo feedback, which is governed by the fast melting of thin ice enabling an effective penetration of solar energy into the upper ocean. Negative sea-ice–related feedbacks are the ice thickness–ice strength relationship and the ice thickness–ice growth rate relationship which is important during the growth period. Models with sub-grid-scale ice thickness distribution have a less resistant ice pack to convergence resulting in thicker ice than a single-category model under similar conditions (Holland et al. 2006) In LIM3, this feedback exposes more open water during the melt period. In summary, the primary reason for the LIM3 low summer sea-ice extent seems to be its systematically low sea-ice concentration, and large open water fraction, which reduces the grid cell mean albedo and enhances the ice-albedo feedback. The LIM3 sub-grid-scale ice thickness distribution further enhances this feedback process, while simultaneously reducing the ice thickness–ice strength feedback.

17. P8, l21: I think your numbers are wrong. PIOMAS shows values of about 4-8x103 km3 in September and 20-25x103 km3 in early spring in the last decade. Please check your values.

Author response: Yes, the numbers were incorrect, thank you for pointing this out.

18. P8, l26: LIM2 shows a stronger negative trend as LIM3? This is thus opposite to the ice *area trends?*

Author response: This is the case. LIM2 has on the average thicker ice and a too small negative sea-ice extent trend. However, LIM2 has a more strongly decreasing sea-ice volume than LIM3.

19. P9, l18: Here you state that the sea ice albedo feedback is less important in the SH. I agree but this is in contradiction to the argumentation before that the stronger sea ice albedo feedback in LIM3 explains the LIM3-low summer ice extents (see point 16).

Author response: This contradiction does not exist any more, please see our response in point 16. Sea-ice albedo feedback occurs in NH and in SH, while it is more directly enhancing the spring sea-ice melt of LIM3 compared to LIM2 in the NH than in the SH.

20. Figure 3: The displacement of the Beaufort Gyre in LIM3 seems to agree with the positive ice bias and the general tendency of LIM to have the thickest ice displaced/ extended towards the Northern American coast.

Author response: This is a good observation. We have added it to the text.

21. P10, l12/13: I do not understand: ". . .at regions." Sentence uncomplete?

Author response: Yes, this sentence was incomplete. We changed it to: "LIM3 has a smaller ice extent and a lower ice concentration close to the ice edge (not shown here)."

22. P 10, L25: Yes, but on the other hand LIM3MC with constant salinity does perform quite well. Without simulations that separately analyze the impact of the different new features in LIM3, it is very speculative to argue that the prognostic sea ice salinity improved ice volume and area. The results from section 4.1 do not support the conclusion that prognostic salinity is strongly improving the ice volume/ extent. Please rethink this statement here.

Author response: We understand this and we wanted to be very careful with our wording. After rethinking we note that the impacts of the sea-ice salinity scheme appear rather small as no clear signal showing the improvements due to the prognostic sea-ice scheme emerges from our simulations. Therefore, we decided to remove the first sentence of this paragraph.

23. P12, l 22ff: 54 years are rather short from an ocean circulation point of view. A systematic decrease by 1-2 Sv in the AMOC might lead to larger effects on the ice after longer periods. Furthermore, I think the statement that "if problems appear, they are related to the coupling .." might be misinterpreted. In the uncoupled ocean-ice model, the atmosphere cannot feedback to the ocean. Thus, the effect of salinity/ freshwater changes on the ice is probably not very large. However, in a coupled system, small changes in the freshwater balance or related changes in AMOC and SST-pattern could lead to strong effects in the atmosphere, which in turn might strongly affect the ocean currents, ocean heat transports and ocean-ice coupling as well. Thus, changing the freshwater balance in the ocean could create important issues in a coupled model and could be the reason for performance issues in the coupled model. Please reformulate to avoid misunderstanding.

Author response: We agree, it is likely that the differences between the simulations continue to increase if the simulations are run further. Also, it is true that in a coupled system oceanic changes modify the atmosphere which then modifies the upper ocean characteristics. We reformulated the text and do not discuss about the coupled modelling environment any more.

24. From Fig. 5 it seems that more freshwater is transported in the East Greenland Current to the south and then further into the Labrador Sea. This might be related to the fact that there is more ice in the Greenland Sea in LIM2, which leads to a more constraint freshwater transport in the EGC in LIM2 than in LIM3. However, you relate the lower salinity in LIM2 in the Labrador Sea to more local melting. To decrease salinity this would also need a net transport of sea ice into the Labrador Sea because stronger local ice growth and ice melt would not decrease the SSS. Did you analyze net ice-growth rates in LIM3 and LIM2?

Author response: This is a good point again. We agree that it is reasonable to assume that the fresher LIM2 surface in the Labrador Sea is primarily related to the higher net transport of sea ice from the EGC, and not to the local freezing/melting of ice. We have reworded the text accordingly.

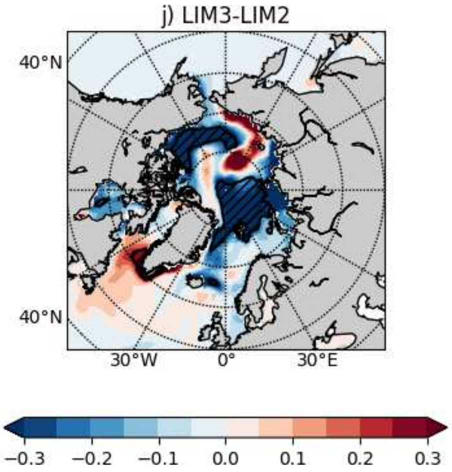
25. Figure 5 g: I am a bit surprised over the cold bias in NEMO3.6-LIM3 in the Fram Strait-Svalbard area. Is this related to too high ice velocities and too much ice in this area? For September, Figure1 b does not seem to indicate too much ice but maybe in the rest of the year. Please add a sentence on this.

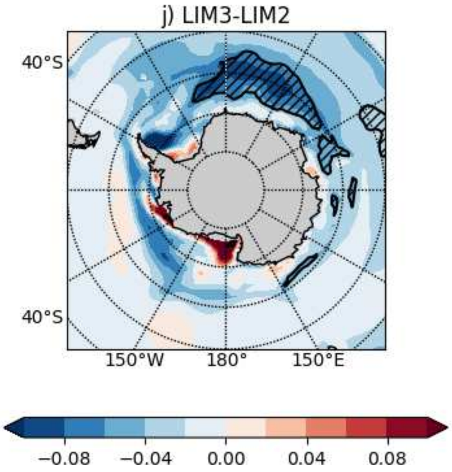
Author response: A sentence was added. Both NEMO3.6-LIM3 and NEMO3.6-LIM2 show this cold bias (see new Figure 5i and l). We think that this is related to the DRAKKAR forcing, namely to its ERA-Interim based near-surface air temperature. Notz et al. (2013) have shown that the ERA-Interim forcing is too cold here and produces too much ice.

Notz, D., F. A. Haumann, H. Haak, J. H. Jungclaus, and J. Marotzke (2013), Arctic sea-ice evolution as modeled by Max Planck Institute for Meteorology's Earth system model, J. Adv. Model. Earth Syst., 5, doi:10.1002/jame.20016.

26. Figures 5/6 and salinity discussion: Given the fact that SSS is quite strongly restored in NEMO-LIM2 and NEMO-LIM3, can we really conclude from the small differences in SSS that the sea ice model has a small impact on the salinity distribution? Are the SSS-differences between LIM2 and LIM3 as small in the experiments without freshwater adjustments?

Author response: To check this we plotted SSS for the experiments without freshwater adjustments and show them below and are comparable to new Figure 5d and 6d (simulations with freshwater adjustments).





It is evident that the experiments without freshwater adjustments have larger SSS differences, and the regions of significant statistical difference are larger and may have changed. For example a region north of Greenland in the Arctic Ocean is not significantly saltier in LIM3FW than in LIM2FW although that was the case when comparing LIM3 and LIM2. We have added these notes to the salinity discussion and changed the conclusion that the sea-ice model has a small impact on the surface salinity, as this is not the case in the absence of freshwater adjustments.

27. P15, l1,2: Why is a larger Atlantic warm water inflow associated with a smaller AMOC? There is some discussion in the community how strong the AMOC is linked to the ocean heat transport into the Arctic but most studies suggest that an increased AMOC leads to increased transports of Atlantic water masses into the Arctic.

Author response: Our statement on the link between the Atlantic warm water inflow and AMOC is a speculative one. After reading your comment it sounds counterintutive. We decided to delete this speculative statement.

28. Fig. 9: Are you sure that the 15% ice edge is at the right place and really the observed ice edge? It goes very far to the south and the east in the Greenland Sea and also in the Labrador Sea. Please check.

Author response: Well spotted, thanks. The 15% ice edge is from LIM3 and not the observed one as incorrectly stated in the caption. As we want to illustrate that the mixed layer depth is shallow under sea ice, we still show the LIM3 ice edge but state it correctly in the figure caption.

29. LIM3-Ref also indicates deep convection in the Greenland Sea far inside the ice area. Further NEMO does not show any deep convection in the Labrador Sea but the climatology does not either. Results from ARGO-floats, which cover the time period 2000-2015 (Holte et al. 2010; http://mixedlayer.ucsd.edu/) show deep convection in the Labrador Sea and might be more reliable than the climatology used in this study.

Author response: Thank you for pointing this out and mentioning the ARGO-float based MLD estimates. We added them to Figure 9. They seem to generally agree well with the deBoyer MLDs, although differences exists. As you say, the ARGO-float based estimates show deeper MLDs in the Labrador Sea than deBoyer ones, which is now mentioned in the text.

30. P16 AMOC: The observational based estimates should be mentioned: e.g. RAPID: 16.9 Sv (at 26.5N), Ganachaud (2003) and Lumpkin and Speer (2007): 18.5 Sv (at 24N) and 16.5 Sv at 48N (Ganachaud). There are many things well simulated in NEMO, but unfortunately not the AMOC . . ..

Author response: We agree. We added these observational estimates to the text.

31. P17, l1-3: Again, the SSS-restoring might hide differences between LIM3 and LIM2: Is the AMOC-difference between LIM3 and LIM2 the same in the experiments without freshwater adjustments?

Author response: To see this we added the AMOC time series of experiments without freshwater adjustments in Figure 10. For both LIM2 and LIM3, experiments without freshwater adjustments, LIM2FW and LIM3FW, have statistically significantly lower AMOCs at the 5% level than the ones with the freshwater adjustments. As the LIM3 AMOC is on the average smaller than the

LIM2 AMOC, also LIM3FW AMOC is on the average smaller (0.7 Sv for 2003–2012) than the LIM2FW AMOC. The difference here is that LIM3–LIM2 AMOC difference in 2003–2012 is not statistically significant, while the LIM3FW–LIM2FW AMOC difference is (at the 5% level). It is reasonable to assume that the freshwater adjustments bring LIM3 and LIM2 AMOC closer. We mention this now in the text.

32. P 17, l20: I would delete "briefly". As stated before: this comparison is - if not the main - but an important part of this study.

Author response: Deleted.

33. P17, l22 and l29-30: The conclusions on the sea ice albedo puzzle me: First you argue that the better representation of the sea ice albedo feedback is the main improvement and then you argue that the model is stable to changes in summer albedo. The first is also related to the different thickness classes but is it really a sign for realism if the model is insensitive to the change of summer albedo? How much is the summer albedo changing with the new sea ice albedo scheme? Maybe, the difference is small?

Author response: The other reviewer was also puzzled. Our wording is misleading and provides a view that overestimates the effect of the new sea-ice albedo scheme. The LIM3 sea-ice thickness categories enhances the ice-albedo feedback than the single-category LIM2 which has been shown by Holland et al. (2006), for example, and discussed earlier. The new albedo scheme provides better transitions between the different ice types, slightly modifies the surface albedo compared to the old scheme and affects the model behaviour to a limited extent only. Therefore, the impact of the new sea-ice albedo scheme is secondary compared to the sea-ice thickness categories. We now mention this in Conclusions.

34. P 18, l3: I think it is a bit overstated to say that you evaluated the oceanic transports across major transects of the world ocean. You only looked at the AMOC and the Drake Passage. You do not show any results from ocean heat transports in the different oceans or transports into the Arctic or overflows (Denmark Strait, IcelandFaroe-Scotland).

Author response: In the manuscript, we only show the AMOC at 50–53°N and the Drake Passage volume transports, but we have calculated and compared other transports (volume, heat and salinity) as well. We decided not to include plots of these other transports in the manuscript due to their similarities between LIM2 and LIM3 or because they did not provide any important additional information, and for not to increase the number of figures too high and not to extend the manuscript too long. Specifically, we calculated the oceanic transports for AMOC across 20–23°N, 30–33°N, 40–43°N, 45–48°N and 50–53°N. Moreover, we calculated time series across the Australia–Antarctica transect, the Bering Strait, the Denmark Strait, the Drake Passage, the Florida Strait, the Gibraltar Strait, and the Greenland–Norway transect at 60°N. This has now been mentioned in the text.

Typings, etc.

P1, l7"while NEMO-LIM2 deviates more". Could be deleted, if LIM3 agrees better than it is clear that LIM2 deviates more.

Author response: Deleted.

P13, l6/ l7: “melted freshwater” sounds weird. Better: “freshwater from melted sea ice”

Author response: Changed to "freshwater melted from excessive sea ice."

P 14, l10: delete one “be”

Author response: Deleted.

P17, l13: A set . . . “was” performed.

Author response: Corrected.

P 17, l13: “. . . in the global ORCA1 grid”: Add a “configuration” or “using the global ORCA1 grid.

Author response: Added.

Interactive comment on “On the influence of sea-ice physics in multi-decadal ocean-ice hindcasts” by Petteri Uotila et al.
Referee #2

General comments

The paper presents an evaluation of the updates to the LIM sea ice model, within the NEMO ocean model, version 3.6. A comparison is made between the previous configuration, LIM2, and the new one, LIM3. Some sensitivity runs are performed, to allow differences between LIM2 and LIM3 to be attributed to particular configuration changes. The model output is also evaluated against appropriate observational datasets. Only the sea ice configuration, and not that of the ocean, has changed between the two model versions, but the authors carry out a detailed study of the impact on the ocean as well as the sea ice. The paper is well-structured and methodical. It is generally scientifically robust, although I have some specific concerns which I will outline below. The paper is well-written, and the standard of English is generally good. I recommend publication after the issues outlined below have been addressed.

Author response: We thank the reviewer for her/his supportive comments and excellent suggestions that significantly improve the manuscript. We followed all the points she/he rose. Please find our detailed responses below.

Specific comments

- *Five model configurations are analysed in the paper – LIM2, LIM3, LIM3MC, and the two simulations to test sensitivity to the freshwater adjustments. The configurations are described in detail in Sections 2.4, 4.1 and 4.2. However, I think that a useful complement to this would be a table summarising the settings in each configuration. That way, the reader could refer back easily to the table while studying the results.* Author response: A good suggestion, thanks. We added Table 1 which lists the simulations used for the study and their main characteristics.
- *In several figures, the authors use both green and red. This should be avoided if possible, as readers who are colour-blind will have difficulty in distinguishing between these colours. The “rainbow” colour scheme used in Figure 3 should be avoided for the same reason if possible.* Author response: We followed your advice and use now different line colours. Furthermore, we do not use the "rainbow"colour scheme in Figure 3 any more.
- *The atmospheric forcing dataset used by the authors is based on ERA-40 before 2001, and ERA-Interim thereafter. Several authors have cast doubt on the reliability of ERA-40 in the polar regions, due to the sparsity of observations there. For example, Screen Simmonds (2011) noted a discontinuity in Arctic temperature in 1997, leading to a significantly exaggerated warming in the mid-to-lower troposphere. While the main period considered by the authors, 2003-2012, is wholly covered by the ERA-Interim-based forcing, the period immediately before could be affected by the inaccuracies in ERA-40, and there could be some residual impact in 2003-2012 due to the “memory” of the ocean. In addition, the authors do sometimes make use of the model output from before 2003 (for example, when discussing the trends in ice extent since 1979 as presented in Figure 2b). They should therefore reflect in the paper on the possible impact on the results of any inaccuracies in the ERA-40 forcing data.* Author response: This is a mistake from our side which has now been corrected in the text. After double checking

the description of DFS 5.2 forcing data, see Dussin and Barnier (2014, https://www.drakkar-ocean.eu/forcing-the-ocean/the-making-of-the-drakkar-forcing-set-dfs5), we realise that the DRAKKAR 5.2 data are based on ERA-Intering since 1979, not since 2001, which is the case of earlier versions of DRAKKAR data. Before 1979, the DRAKKAR 5.2 data are based on a combination of ERA-40 and ERA-Interim climatology. Hence, the inaccuracies of ERA-40 have a minor impact on the main study periods. We thank the reviewer for leading us to find our mistake.

- *In Section 3.1, where the authors refer to the trends in SH ice extent as "statistically significantly increasing", they should specify the level of significance and the method used to assess it. In a number of other places in the sea ice sections, the authors refer to results as "significant". For example, in Section 3.2, the interannual variations in annual mean NH ice volume are "significant". In the same section, the LIM3 SH ice volume is said to have a "significant positive trend", the trend in GIOMAS ice volume is "significantly negative", and LIM2 has "no significant trend". There are further examples in the discussion of the sensitivity runs in Section 4. Do the authors mean "statistically significant"? And if so, how was this assessed and what is the level of significance? This should be specified in the paper.* Author response: When referring to the sea-ice trends and differences we mean the statistical significance at the 5% level. We reformulated the text and now explicitly specify the level of statistical significance and the methods to assess it. In other occasions, where we used the word 'significant', or its derivatives, in a descriptive sense and did not mean 'statistically significant', we replaced 'significant' with other words, such as 'remarkable', 'clear' or 'apparent'. These expressions refer to differences or findings which appear physically unambiguous.

- *In the discussion of the impacts on the ocean (Section 5), there is no discussion of statistical significance of the results. In a number of cases, I wondered if the inter-model differences, and the differences with respect to observations, were significant with respect to the interannual variability, especially where the differences were small. For example, in Section 5.6, the authors refer to "small temperature and salinity differences" between the LIM simulations. And in Section 5.8, they refer to the fact that the AMOC in LIM2 is up to 0.4 Sv stronger than that in LIM3. Are these differences statistically significant above the interannual variability?* Author response: This is a good point, thanks. We calculated significance levels between LIM3 and LIM2 variables and between LIM simulations and observational data whenever possible. Following these calculations we now indicate significant differences at the 5% level in figures representing geographical climatological distributions. Related discussion has been added to the text.

- *In most cases, the authors restrict their analysis to the last decade of the 54-year simulations. Given that the model starts from rest and will take some time to spin up, this is the correct approach. However, restricting the period of study to 10 years means that multidecadal variability will not be picked up in the analysis. To what extent are the differences between LIM2 and LIM3, or the differences between the LIM configurations and observations, dependent on factors that may be subject to multidecadal variability? I appreciate it may be difficult to answer this question with the results available, but I think the authors should at least mention it in the discussion of their results.* Author response: This is a good discussion point which we added to Conclusions section. Judging from Figure 1 multi-decadal sea-ice extent time series, it seems sensible to assume that LIM2–LIM3 differences are not very sensitive to interdecadal variability during the last few decades of simulations. This is because the mutual annual minimum, mean and maximum sea-ice extent differences remain systematic between the simulations. We can assume that upper ocean differences behave like the sea-ice ones, while deeper in the ocean the differences remain quite small.

- *In Section 3.2 (page 10, lines 12-13), the authors state “Close to the ice edge, LIM3 has a smaller ice extent and a lower ice concentration at regions”. I’m not sure what is meant by “at regions”. Does it mean “in certain locations”? If so, then please change it.* Author response: Yes, this sentence has a bad wording. We changed it to: "LIM3 has a smaller ice extent and a lower ice concentration close to the ice edge (not shown here).

- *In the conclusions, the authors refer to the new sea ice albedo scheme implemented in LIM3 in April 2016. They state “Our preliminary tests on this new scheme demonstrate the robustness of LIM3, as its sea-ice distribution appears almost insensitive to changes in summer albedo”. I find this statement surprising, as several studies have shown that sea ice simulations are indeed extremely sensitive to albedo in summer (see, e.g., Kim et al., 2006, and Rae et al., 2014). While use of a reliable atmospheric forcing dataset should reduce the need for tuning via albedo adjustments (see, e.g., Hunke, 2010), I would still expect the sea ice simulation to be sensitive to albedo changes. Perhaps I have misunderstood what the authors mean by this statement, but I would appreciate some clarification.* Author response: Here, our wording appears wrong, as this is not what we meant. Thank you for pointing this out. We rewrote the sentence to be: "This new sea-ice albedo scheme, with better transitions between the different ice types, slightly modifies the surface albedo compared to the old scheme and affects the model behaviour to a limited extent only."

- *In the figures, the results are generally presented as LIM3-LIM2, or LIM3-obs. This makes sense, as the authors are presenting the first study of a simulation with the new LIM3 configuration, and comparing it with the previous configuration (LIM2) and observations. However, in the text the authors often discuss the results in reverse. For example, on page 16, line 3, when referring to Figure 9e: “In the Southern Ocean, the observed mixed layer is shallower than the LIM3 mixed layer...”. This wording seems a bit strange and “back-to-front” to me, as the results in the figure are presented as LIM3 minus obs (and anyway the purpose of the paper is to assess LIM3 against observations, not the other way round). I would prefer to see the wording in the text reflect the way the results are presented in the figures (“In the Southern Ocean, the LIM3 mixed layer is deeper than observed”), unless there is a good reason to do otherwise. There are several other examples of this type of “back-to-front” wording throughout the paper to which similar remarks apply.* Author response: A good point, thanks. The "back-to-front"wording carries from the stage when we plotted obs-LIM3 and we did not realise to change the wording. This has now been done and we do not spot "back-to-front"wording any more.

Technical corrections

- *Where the authors mention results without including figures (e.g. in Section 3.2, although there are other places where this occurs), it would be useful for the reader if they stated “not shown here”.* Author response: A good point, we now state "not shown here"where we mention results without figures.

- *Page 7, line 5: “Figures 2a and b” should be “Figures 2a and c”.* Author response: Well spotted. We changed the text accordingly.

- *Page 7, line 14: “minimum extends” should be “minimum extents”.* Author response: Corrected.

- *Page 9, line 15: “a lesser significance as in the...” should be “a lesser significance than in the...”.* Author response: Amended as suggested.

- *Page 14, line 4: "smaller between LIM3 and WOA13 than between PHC3" should be "smaller between LIM3 and WOA13 than between LIM3 and PHC3"* Author response: This is right. We modified the sentence accordingly.

- *Page 14, line 21: "around the East Antarctica" should be "around the East Antarctic" or "around East Antarctica" (without "the").* Author response: Changed to "around the East Antarctic".

- *Page 14, line 30: "loose heat to the water masses" should be "lose heat to the water masses".* Author response: Corrected.

- *Page 15, line 2: "might be associated to" should be "might be associated with".* Author response: Changed "associated to"to "associated with".

- *Page 15, line 33: "This is at least partly due to cold, non-responsive and prescribed winter atmosphere..." should be "This is at least partly due to the cold, non-responsive prescribed winter atmosphere..." (add "the", delete "and").* Author response: deleted.

- *Page 16, line 10: "and one where denser LIM2 surface entrain deeper" should be "and one where the denser LIM2 surface entrains more deeply".* Author response: Modified as suggested.

- *Page 16, line 11: "with most distinct ones visible" should be "with the most distinct ones visible".* Author response: Done.

- *Page 16, line 18: "Danabasoglu et al. (2014) assessed the mean AMOC of eighteen ocean-ice models forced by prescribed atmospheric forcing from 1948– 2007 and run five repetitive forcing cycles...": Inconsistent tenses (past/present). "run" should be "ran".* Author response: Corrected.

- *Page 16, line 20: "Here, results of..." should be "Here, the results of...".* Author response: Changed.

~~On the influence~~ Comparing some aspects of ~~sea-ice physics in multi-decadal ocean-ice hindcasts~~the ocean hydrography, circulation and sea ice between NEMO3.6 LIM3 and LIM2

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Abstract. A set of hindcast simulations with the new NEMO3.6 ocean-ice model in the ORCA1 grid and forced by the DFS5.2 atmospheric data was performed from 1958–2012. ~~We focussed on simulations that differ only~~ Simulations differed in their sea-ice component: the old standard version LIM2 and its successor LIM3. Main differences between these sea-ice models are the parameterisations of sub-grid-scale sea-ice thickness distribution, ice deformation, thermodynamic processes, and sea-ice salinity. Our main objective was to diagnose the ocean-ice sensitivity to the updated ~~NEMO-LIM~~ NEMO-LIM3 sea-ice physics. ~~Results of such analysis have not been published for this new NEMO version~~Additional sensitivity simulations were carried out for the attribution of observed differences between the two main simulations.

In the ~~polar regions~~Arctic, NEMO-LIM3 compares better with observations ~~, while~~ by realistically reproducing the sea-ice extent decline during the last few decades due to its multi-category sea-ice thickness. In the Antarctic, NEMO-LIM3 more realistically simulates the seasonal evolution of sea-ice extent than NEMO-LIM2~~deviates more , producing too much ice in the Arctic, for example. Differences between NEMO-LIM2 and ~~. In terms of oceanic properties, improvements are not as evident, although NEMO-LIM3 ~~do not change in simulations even when the freshwater adjustments are turned off~~reproduces a more realistic hydrography in the Labrador Sea and in the Arctic Ocean, including a reduced cold temperature bias of the Arctic intermediate water at 250 m. In the extra-polar regions, the oceanographic conditions of the two NEMO-LIM versions remain relatively similar, although they slowly drift apart over decades. ~~A simplified NEMO-LIM3 configuration, having a virtual, single-category sea-ice thickness distribution, produced sea ice with a skill sufficient for ocean-ice hindcasts that target oceanographic studies. We conclude that NEMO3.6 is ready to be used as a stand-alone ocean-ice model and as a component of coupled atmosphere-ocean models~~This drift is probably associated with a more effective in deep water formation at the coastal waters of Antarctica manifested as deeper mixed layers.

1 Introduction

Sea ice is an important part of Earth's climate system because it effectively regulates the amount of energy being transferred between the atmosphere and oceans (Vaughan et al., 2013). Our current understanding on sea-ice related climate dynamics is incorporated in complex yet realistic climate models consisting of a sea-ice model component which is coupled to atmospheric and oceanic components (Griffies, 2004). In these models, sea ice can affect the ocean circulation and hydrography through ocean-ice interactions (see for example, Goosse and Fichefet, 1999; Kjellsson, 2015). To understand the effect of sea ice on the ocean, coupled global ocean-ice models, where the coupled atmospheric component is replaced with prescribed atmospheric forcing, can be used (Griffies et al., 2009).

Additionally, the sea-ice cover and its variability may affect the large-scale atmospheric circulation, also outside the high latitudes. For example, some studies suggest that the Arctic sea-ice loss has increased the frequency of atmospheric blocking events which then has changed the snowfall over America and Eurasia (Francis and Vavrus, 2012; Barnes, 2013). However, the impacts of the Arctic warming on lower latitudes are masked by the large internal climatic variability and the detection of robust signals is very difficult due to relatively short time series of reliable observational data (Koenigk and Brodeau, 2016). These observational shortcomings can partly be overcome by analysing long climate model experiments which optimally should incorporate the most realistic sea-ice models to minimise the model uncertainty.

Recently, the version 3.6 of the Nucleus for European Modelling of the Ocean (NEMO) was released, along with its new sea-ice component, Louvain-la-Neuve Sea Ice Model (LIM) version 3.6 (Madec et al., 2015; Rousset et al., 2015). The new LIM3 code implements many sea-ice physics improvements compared to the previous LIM2 code, as has already been documented (Vancoppenolle et al., 2009b; Massonnet et al., 2011; Vancoppenolle et al., 2015). However, the effect of LIM3 on the ocean circulation and hydrography remain to be systematically investigated. Accordingly, our aim is to analyse NEMO-LIM2 and NEMO-LIM3 simulations, ~~particularly their ocean circulation and hydrography~~ including the most distinct ocean hydrography and circulation differences. As these differences may emerge over multi-decadal time scales due to slow oceanic processes, we carry out multi-decadal hindcast simulations with prescribed atmospheric forcing. This analysis assists us to comprehensively understand the oceanic response to the state-of-the-science sea-ice physics in multi-decadal ocean-ice hindcasts.

To support our task, a significant body of literature presenting ocean-ice model assessments provide us an important reference when carrying out our NEMO-LIM assessments. For example, papers of the CORE-II virtual special issue of the Ocean Modelling Journal, such as Danabasoglu et al. (2014, 2016); Downes et al. (2015); Farneti et al. (2015); Griffies et al. (2014); Wang et al. (2016a, b), and of the ORA-IP special issue of the Climate Dynamics Journal, such as Chevallier et al. (2015), are particularly relevant for this study. As the majority of CORE-II and ORA-IP ocean model configurations, our grid configuration (ORCA1) does not resolve ocean eddies. In this coarse-resolution ocean-ice model category, the eddy transport of momentum and heat are parameterised, for instance. Our simulations also share the use of CORE bulk formulae with the CORE-II experiments (Large and Yeager, 2004).

In the polar context, which is the regional focus of our study, the most important CORE-II papers include Downes et al. (2015), where the Antarctic sea ice and Southern Ocean water masses are analysed, and Wang et al. (2016a, b) who investigated the Arctic sea ice and the Arctic Ocean freshwater. Recently, Chevallier et al. (2015) analysed the Arctic sea ice in a set of ocean reanalyses to assess how the assimilation of observations affects the sea-ice characteristics. In addition to observational data, we use these ocean-ice model assessments as a benchmark when analysing our simulation performance.

The paper is divided into six sections. Section 2 describes the two versions of the ocean-ice models, NEMO-LIM2 and NEMO-LIM3, their initial and boundary conditions, model input data and observational reference data. In Section 3, we present sea-ice related results of the reference LIM3 hindcast simulation in comparison with observations and the reference LIM2 hindcast. Section 4 presents results of the NEMO-LIM sensitivity simulations to test the robustness of LIM3 and LIM2 differences for surface freshwater adjustments. In section 4 we also assess how realistic sea ice a simplified LIM3 single-category ice thickness parameterisation reproduces. In section 5 differences of the ocean characteristics between NEMO-LIM2 and NEMO-LIM3 are discussed. Finally, the most important findings are highlighted in the conclusion section.

2 Models and Methods

All simulations presented here are based on the version 3.6_STABLE (revision 5918, released on 26 November 2015) of the NEMO-LIM ocean-ice modelling system (Madec et al., 2015), in the ORCA1 configuration. In NEMO, the OPA ocean component is coupled with the LIM sea-ice model. For almost a decade, LIM2 has been the reference NEMO sea-ice model (Fichefet and Morales Maqueda, 1997), but in June 2015, a new and more sophisticated version, LIM3.6, became available as the reference sea-ice model for NEMO3.6 (Rousset et al., 2015).

2.1 NEMO ocean component OPA

OPA is a finite difference, hydrostatic, primitive equation ocean general circulation model. Its vertical coordinate system is based on z^* levels with partial cell thicknesses allowed at the sea floor. The vertical mixing of tracers and momentum uses the turbulent kinetic energy scheme (Gaspar et al., 1990; Blanke and Delcluse, 1993). A quadratic bottom friction boundary condition is applied together with an advective and diffusive bottom boundary layer for temperature and salinity tracers (Beckmann and Haidvogel, 1993). The model uses a non-linear variable volume scheme for the free surface, and an energy-enstrophy conserving scheme for momentum advection. A no-slip boundary condition is applied on the momentum equations with the horizontal Laplacian momentum diffusion. The tracer equations in OPA use the TVD advection scheme by Zalesak (1979) with the Laplacian diffusion along isoneutral surfaces.

The simulations are performed on an ORCA-like global tripolar grid with 1° nominal horizontal resolution and 75 vertical levels. Additional refinement of the meridional grid down to 1/3° is present near the Equator. ~~The minimum~~ A typical horizontal grid cell length is about ~~50~~ 40–50 km in the Arctic Ocean and 40 km in the Antarctic region, while the vertical level thickness ranges from 1 m near the surface increasing to 200 m at the bottom.

2.2 NEMO sea-ice components LIM2 and LIM3

Our ocean-ice configurations only differ in their sea-ice component, all other experimental conditions being identical. We use the levitating sea-ice framework, following the convention of Campin et al. (2008): the growth and melt of ice impact the ocean mass and the salinity, but do not affect the pressure experienced by the ocean surface.

LIM2 (Fichefet and Morales Maqueda, 1997; Timmermann et al., 2005) is a sea-ice model in the line of the two-level model of Hibler (1979). It features: a single sea-ice category and open water represented using ice concentration; the Semtner (1976) 3-layer thermodynamics with a virtual reservoir of shortwave radiation heat which parameterizes brine inclusions; the revisited C-grid elastic-viscous-plastic rheology of Bouillon et al. (2013); the second-order moment-conserving advection scheme of Prather (1986), plus a few extra parameterisations. LIM2 implements the snow-ice formation by infiltration and freezing of seawater into snow when deep enough. The effect of sub-grid-scale snow and ice thickness distributions is implicitly parameterised by enhancing the conduction of heat through the ice and by melting the ice laterally to account for thin ice melting. The surface albedo depends on the state of the surface (frozen or melting), snow depth, and ice thickness following Shine and Henderson-Sellers (1985).

LIM3.6 (Vancoppenolle et al., 2009a; Rousset et al., 2015) is a sea-ice model in the line of the AIDJEX model, with multiple sea-ice categories (Coon et al., 1974; Thorndike et al., 1975). Multiple categories allow to resolve the intense growth and melt of thin ice, as well as the redistribution of thinner ice onto thicker ice due to ridging and rafting. LIM3 dynamics (advection and rheology) are the same as in LIM2. Thermodynamics are multi-layer and include an explicit description of the effect of brine on the storage and conduction of heat (Bitz and Lipscomb, 1999), and a parameterization of brine drainage (Vancoppenolle et al., 2009a) that affects ocean-ice salt exchanges. The default NEMO3.6 configuration uses five ice thickness categories and two vertical layers for thermodynamics. Alternatively, LIM3.6 (Rousset et al., 2015) can be run with a single sea-ice category, using two virtual ice thickness distribution parameterisations (enhanced conduction and thin ice melting).

2.3 Model input data

The NEMO model bathymetry is a combination of ETOPO1 Amante et al. (2009) in the open ocean, and GEBCO (IOC, 2003) in coastal regions. All the simulations were extended over the period 1958–2012 and forced by the DFS5.2 atmospheric data set, developed through the DRAKKAR consortium (Brodeau et al., 2010). This data set is based on satellite observations (monthly precipitations and daily radiative heat fluxes) and combined ERA-40 (before ~~31 December 2001~~1979) and ERA-Interim (from ~~2002~~ 1979 onward) meteorological reanalyses~~, and provides 6-hourly~~ . DFS5.2 provides 3-hourly air temperature and humidity at the 2 m level, and wind velocity at the 10 m level (Uppala et al., 2005; Dee et al., 2011). Prescribed surface boundary conditions were calculated by using the CORE bulk formulae proposed by Large and Yeager (2004). As in Brodeau et al. (2010), simulations were forced with the monthly river run-off climatology based on Timmermann et al. (2009). The ocean and sea-ice models had a time step of 3600 s, which was also the interval when surface boundary conditions were updated.

As a standard practice in forced ocean-ice simulations, the mean sea level controls were used to prevent the unrealistic drift of the sea surface height due to freshwater boundary forcing distorted by errors in precipitation, evaporation and river runoff (Griffies et al., 2014). Specifically, this was done by setting values `nn_fwb=2` and `nn_ssr=.true.` in the NEMO namelist. The `nn_fwb` parameter is used to reset the freshwater budget, evaporation minus precipitation minus river runoff, and `nn_ssr` enables the restoring of sea-surface salinity (SSS). The SSS restoring rate is a negative feedback coefficient which is provided as a namelist parameter `rn_deds`. This parameter should be viewed as a flux correction on freshwater fluxes to reduce the uncertainties of the observed freshwater budget. Following the default ORCA1 NEMO3.6 configuration and discussions with

NEMO users, the SSS restoring rate was set to -100 $\mathrm{mm/day}$ towards the SSS of Polar Hydrographic Climatology version 3 (PHC3) created by Steele et al. (2001). Notably this is a lower value than the NEMO default of -166.67 $\mathrm{mm/day}$.

2.4 Experiments

NEMO-LIM simulations started from the state of no motion in January 1958, with initial conditions for ocean temperature and salinity derived from PHC3 (Steele et al., 2001), and ended in December 2012. We completed two reference simulations, one using NEMO-LIM3 and another one using NEMO-LIM2, with recommended settings. In both LIM configurations, the initial sea-ice thickness was set to 3.0 m where the sea surface temperature was below 0 °C. The initial snow thickness was set to 0.3 m in LIM3 for both hemispheres, while in LIM2 it was 0.5 m in the Northern Hemisphere (NH) and 0.1 m in the Southern Hemisphere (SH). For both simulations, the initial sea-ice concentration was set to 90%, except for LIM2 in the NH, where the initial sea-ice concentration was 95%. The ice strength parameter P^* was set to 2×10^4 (1×10^4) Nm^{-1} in LIM3 (LIM2), while the ocean-ice drag coefficient was 5.0×10^{-3} and the atmosphere-ice drag coefficient follows Large and Yeager (2009) in both models.

Differences between LIM2 and LIM3 initial sea-ice and ice dynamics parameter values originate from the fact that they are recommended values according to the default NEMO3.6 configuration. Instead of setting the LIM2 initial values and ice dynamics identical to LIM3, for example, we took the point of view that we compare two different sea-ice models, each with its own specific and optimised tuning, and with no specific focus on ice dynamics. This is the point of view that was adopted by Massonnet et al. (2011) as well.

Even though the sea-ice initialisation differs slightly in terms of hemispheric snow thickness, it does not impact our results which focus on the last decade 45 years after the initialisation. The lower LIM2 ice strength P^*, however, has an impact and results in weaker ice that deforms easier producing a larger sea-ice volume than would have obtained with the P^* value identical to LIM3. ~~Importantly~~To quantify this effect, a LIM2 ~~model experiment~~ simulation with the LIM3 P^* value ~~, produces a less realistically evolving~~ produces a too small winter Arctic sea-ice volume, ~~with too thin winter sea ice in particular, than with the recommended value. Furthermore, the LIM2 model experiment with the LIM3 P^* value produced almost similar~~ while its sea-ice ~~extent and area than the~~ extent remains almost unchanged (not shown here). Moreover, as found by Holland (2006), multiple sub-grid-scale ice thickness categories, as in LIM3, reduces the effective ice strength compared to a single category model, as LIM2~~experiment with the default~~. Therefore, it is justified to use a higher P^* ~~value, indicating insignificant oceanic impacts. These findings further motivated us to carry out our~~ in LIM3 to offset the reduces ice thickness–ice strength effect. According to these findings, LIM2 ~~simulations with the recommended default ice dynamics parameter values~~with the lower P^* is more realistic and we decided to use it this study.

In addition to the two reference simulations, we carried out sensitivity simulations to determine how significant and systematic differences between LIM3 and LIM2 are. In these sensitivity simulations, processes related to ocean-ice interactions were regulated and adjusted. In this way, we were able to isolate the impacts of individual processes and quantify their significance. First, we switched NEMO-LIM3 into its single-category mode which employs a virtual ice thickness distribution parameterisation, which make the model simpler and computationally cheaper than with multiple categories. Then, instead of using a prognostic salinity profile, we set the LIM3 sea-ice salinity to a constant value of 4 ppm, similarly to LIM2. As a result of the single-category and constant sea-ice salinity, LIM3 is physically to a greater extent closer to LIM2, is computationally fast, but more realistic than LIM2, particularly in the Arctic, as we will show. Table 1 summarises these simulation characteristics.

The second set of sensitivity experiments were performed to examine the impact of ocean surface boundary conditions on ocean-ice properties, and therefore to see how robust our LIM3–LIM2 comparison results are. For this, we carried out NEMO-LIM2 and NEMO-LIM3 simulations where the mean sea level controls were switched off by setting `nn_fwb=0` and `nn_ssr=.false.` in the NEMO configuration namelist. After completing these NEMO-LIM2 and NEMO-LIM3 simulations without freshwater adjustments, we calculated and compared their differences to the corresponding ones based on the reference simulations where the freshwater controls were kept on.

2.5 Reference data

When quantitatively assessing the modelled sea-ice and upper ocean realism, we included comparisons with satellite-based and reanalysis products of sea-ice concentration, thickness and velocity. Since 1979, space-borne passive microwave sensors have produced a nearly continuous and consistent record of ice concentration which provides a good basis for model validation. For sea-ice concentration we used the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 2 (Meier et al., 2013), which covers both polar regions at a 25 km grid cell size. The observed sea-ice extent data, which were based on satellite observed sea-ice concentrations, are the NSIDC Sea Ice Index (Fetterer et al., 2002). For sea-ice velocity analysis, the OSI-SAF product by Lavergne et al. (2010) was used. Sea-ice thickness and volume were compared with reanalyses from the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) for the NH, and from the Global Ice-Ocean Modeling and Assimilation System (GIOMAS) for the SH (Schweiger et al., 2011). It is worth noting that these ice thickness data are model products, not entirely based on observations and have significant uncertainties.

For hydrographic comparisons, we decided to use two observational data sets. First, we selected aforementioned PHC3, which is a global climatology with a combination of NODC's 1998 world climatology, the EWG Arctic Ocean Atlas, and selected Canadian data provided by the Bedford Institute of Oceanography (Steele et al., 2001). PHC3 was updated with the Arctic Ocean temperature and salinity observations in 2005. Additionally, we used the most recent World Ocean Atlas 2013 (WOA13) (Boyer et al., 2013) averaged over the years 2005–2012. WOA13 lacks the Arctic observations included in PHC3, but has more recent observations elsewhere. Therefore, at least outside the Arctic Ocean, the WOA13 data temporally matches better with our NEMO-LIM comparison period of 2003–2012. As we will show in Section 5, WOA13 and PHC3 mainly differ in terms of Arctic SSS, while otherwise climatological differences are relatively small from the NEMO-LIM assessment perspective. Notably, Wang et al. (2016b) used PHC3 in their ocean-ice model Arctic intercomparison study, and using PHC3 here as well makes qualitative comparisons of our results with theirs straightforward. Finally, PHC3 was used to determine the initial hydrographic conditions of our model simulations, and comparisons between 2003–2012 LIM3 climatology and PHC3 show how much our simulations diverged from their initial state in 45 years.

Modelled mixed layer depths (MLD) were compared with the observational ~~climatology by de Boyer Montégut et al. (2004)~~ climatologie by de Boyer Montégut et al. (2004) and Holte et al. (2016). It should be noted that observational uncertainties in the Arctic

Ocean and in polar regions south of 55°S are particularly large due to a limited number of measurements. Hence, we concentrated in the North Atlantic and the Southern Ocean outside the regions of high uncertainty in our MLD comparisons.

3 Sea-ice results

In this section, we analyse how well LIM reproduces large-scale climatological sea-ice properties (ice areal coverage, volume and drift). In order to evaluate the new sea-ice model, we compare LIM3 results to satellite observations, reanalysis data and as well as to the equivalent LIM2 simulation. All mean fields are computed over the last decade of integration, from 2003 to 2012. As the LIM3 sea-ice properties have already been analysed by (Vancoppenolle et al., 2009b; Massonnet et al., 2011; Vancoppenolle et al., 2015) and our results agree rather well with theirs, we ~~only~~ rather shortly present our sea-ice findings and merely focus on novel findings from the sensitivity simulations and oceanographic analysis in the sections following this one.

3.1 Sea-ice concentration and extent

In the NH in September, the geographical distribution of LIM3 sea-ice concentration presents high values in the Canadian Arctic Archipelago with a realistic latitudinal decrease toward the Eurasian Arctic (Figure 1a). LIM3 tends to generally underestimate the ice concentration, by $\sim$20% in the central Arctic to $\sim$50% in the ~~East Siberian~~ northern Kara Sea (Figure 1b), while the Laptev and southern Kara Seas are almost ice-free (Figure 1a). This negative summer sea-ice concentration bias is linked to an underestimation of sea-ice thickness in those areas both in winter and summer (not shown here). By contrast, too-large ice concentration is found in the Beaufort Sea (Figure 1b). Clearly the representation of ice concentration in the two models significantly differs in summer: LIM2 produces higher sea-ice concentration compared to LIM3 everywhere in the Arctic Ocean and their difference increases radially from the Canadian Arctic Archipelago toward the Eurasian Arctic (Figure ~~1c~~1e). LIM2 cannot reproduce the seasonal cycle of ice area in the Beaufort and East Siberian Seas toward the Bering Strait, where its sea ice, unrealistically, is rather uniform spatially with a too small open water fraction until a sharp transition to the ice edge (Figure 1c).

Mean seasonal cycles of the modelled sea-ice extents are shown in Figures 2a and ~~b~~ c together with the NSIDC observations, all averaged over the years 2003–2012. In the NH, the LIM3 sea-ice extent closely follows the observed data and represents a clear improvement compared to LIM2, particularly in summer (Figure 2a). The respective LIM2 values are too high. LIM2 does not manage to melt enough ice and systematically overestimates the NH sea-ice extent. On the contrary, the LIM3 multi-category sea-ice thickness distribution allows for larger rates of melting due to its thin ice categories compared to the single-category LIM2, and enhances the seasonal cycle of sea-ice extent bringing it closer to observations.

Associated with the better mean seasonal cycle, the inter-annual time series of sea-ice extent is improved in LIM3 compared to LIM2 (Figure 2b). Both the maximum and minimum sea-ice extent are well reproduced by LIM3, as shown by the time series in Figure 2b that closely follow the NSIDC data in 1979–2012. Moreover, LIM3 realistically captures most of the summer minimum ~~extends~~extents, including the 2007 record minimum. In contrast, LIM2 systematically overestimates yearly minimum, maximum and mean sea-ice extents during the whole period of integration. For example the 2007 minimum is overestimated by 50%. The two LIM models show comparable negative sea-ice extent trends in March, which are less negative than satellite observed trends. In September, the LIM3 trend is close to the observed one, while the LIM2 negative trend is too small. As concluded by Wang et al. (2016a), models which overestimate the Arctic sea-ice thickness, as does LIM2, have a too low September trend, while LIM3, which has a thinner ice, produces a realistic September trend.

In the SH, the LIM3 sea-ice edge is generally well located in the austral summer and the geographical distribution is correctly represented (Figure ~~1d, e~~1g, h). LIM3 sea ice is mostly confined to the western Weddell Sea, the southern Bellingshausen and Amundsen Seas and the southeast Ross Sea. Some differences with satellite observations are present. Notably, LIM3 underestimates the narrow fringe of sea ice around the East Antarctic coast and its sea ice also disappears excessively in the western Weddell Sea, where the model has a lower sea-ice concentration than observed, also indicating that its sea ice is too thin regionally. The LIM2 sea-ice concentration is everywhere larger than the LIM3 one and the observed one across most of the Southern Ocean, with the largest differences in the Ross Sea and the eastern Weddell Sea (Figure ~~1f~~1i, k).

Both LIM models have a seasonal cycle of sea-ice extent with too large amplitudes (Figure 2c). Periods of sea-ice growth are shorter, and sea-ice growth/melt rates are faster than observed. In LIM3, the monthly minimum sea-ice extent in February is less than the observed, while the maximum sea-ice extent in September is overestimated with a seasonal amplitude of 19.2×10^6 km^2 (observed 16.0×10^6 km^2). The LIM2 minimum extent appears to be in better agreement with the NSIDC data, but the ice growth is even faster than in LIM3, and therefore clearly unrealistic. As a result, the LIM2 seasonal cycle amplitude is 19.9×10^6 km^2.

The time series of annual mean sea-ice extent of LIM3 is rather well reproduced and closely follows observations (Figure 2d), but the sea-ice summer retreat is systematically too strong and summer extent too low. The LIM3 ~~low~~ winter sea ice is on the average thicker than the LIM2 sea ice, while in summer their average thicknesses are close to each other (not shown here). On the other hand, the average LIM3 sea-ice concentration is systematically about 1–10% smaller than the LIM2 one, even in the central ice pack. As a result, the LIM3 sea-ice extent is smaller, particularly in summer.

The processes explaining the low LIM3 summer sea-ice extent ~~can be explained by the~~ compared to LIM2 are related to (1) the steeper decline of LIM3 mean sea-ice thickness and (2) to its systematically lower sea-ice concentration. Arguably the most important process is the positive ice-albedo feedback, which is governed by the fast melting of thin ice enabling an effective penetration of solar energy into the upper ocean. ~~This occurs particularly in the marginal~~ Negative sea-ice–related feedbacks are the ice thickness–ice strength relationship and the ice thickness–ice growth rate relationship, which is important during the growth period. These processes affect the ice evolution in both models. However, models with sub-grid-scale ice thickness distribution, as LIM3, have a less resistant ice pack to convergence resulting in thicker ice than a single-category modeli, as LIM2, under similar conditions (Holland, 2006). In LIM3, this feedback exposes more open water during the melt period. It is reasonable to assume that the primary reason for the LIM3 low summer sea-ice ~~zone, where the~~ extent seems to be its lower sea-ice ~~concentration is low and ice thin. The effective~~ concentration to begin with, and consequently its large open water fraction, which reduces its grid cell mean albedo and enhances its ice-albedo ~~feedback also promotes a higher bottom melt leading to thinner ice . Due to its multi-category sea-ice thickness distribution, these processes significantly reduce~~

~~the~~ feedback. The LIM3 ~~sea-ice concentration in summer compared to LIM2~~sub-grid-scale ice thickness distribution further enhances the ice-albedo feedback, while simultaneously reducing the ice thickness–ice strength feedback.

In the SH in September, both LIM models present statistically significantly increasing sea-ice extent anomaly trends, estimated with the linear least-squares fit at the 5% significance level, consistent with observations. However, these modelled September trends are larger than the observed trend (not shown here). The increase of the Antarctic sea-ice extent has been explained by a range of mechanisms. Many studies attribute the increase of sea-ice extent to changes in the atmospheric dynamics, mainly by the increasing trend of the Southern Annular Mode, which in turn has strengthened westerly winds around the Antarctic continent and deepened the Amundsen Sea Low. Stronger westerlies effectively spread sea ice to north and a deeper Amundsen Sea Low increases the sea-ice production in the Ross Sea (see for example, Lefebvre and Goosse, 2008; Holland and Kwok, 2012; Massonnet et al., 2013; Turner et al., 2015). Another potential, simultaneously affecting mechanism increasing the sea-ice extent is the freshening of the Southern Ocean surface, which stabilises the surface layer, reduces the oceanic heat from below and therefore the associated ice melt (see for example Hellmer, 2004; Bintanja et al., 2013). Our model configurations do not implement the inter-annually increasing freshwater forcing, but despite that are able to reproduce the increase of winter Antarctic sea-ice extent. This implies that changes in windiness are likely to be a major mechanism driving the SH sea-ice extent increase. Notably, the LIM modelled trends are larger than the observed ones, which may indicate a too sensitive ice drift response to increasing windiness, a too fast moving model sea ice and a too far northern winter sea-ice edge, as also supported by earlier studies (Uotila et al., 2014; Lecomte et al., 2016).

3.2 Sea-ice volume

In the NH, the monthly mean LIM3 sea-ice volume, which is the domain integral of the sea-ice thickness multiplied by sea-ice area per grid cell, varies from the minimum of ~~2.9~~8.8$\times10^3$ km^3 in September to the maximum of ~~8.8~~29.4$\times10^3$ km^3 in April. Both values are approximately 20% larger than the PIOMAS output. LIM2 and LIM3 maxima agree, but their September minima do not, with the LIM2 ice volume minimum being almost 30% larger. The evolution of the annual mean sea-ice volume in the 1958–2012 period is comparable in both models and, as in the case of sea-ice extent, ~~shows significant~~ has large inter-annual variations (not shown here). As with the sea-ice extent, NEMO-LIM simulations capture the large decrease of sea-ice volume during their last decade, 2003–2012, at a rate of -3.4 (-6.6)$\times10^3$ km^3/decade in LIM3 (LIM2), while the PIOMAS rate is smaller, -2.0$\times10^3$ km^3/decade.

In the SH, the LIM models' monthly mean sea-ice volume reaches its maximum in October and then decreases to 1,600 km^3 in February. The GIOMAS monthly mean sea-ice volume maximum occurs already in September from which it decreases to 2,800 km^3 in February. In general, the GIOMAS monthly mean sea-ice volume is higher than the LIM ones, with a distinctly different seasonal evolution. When comparing the LIM SH sea-ice volumes with GIOMAS, one should remember that the LIM3 SH sea-ice extent is smaller and closer to the observed than the one of LIM2. Hence, the LIM3 mean ice thickness, which is the ratio between sea-ice volume and extent, is larger and more realistic than the LIM2 mean ice thickness, because their sea-ice volumes are rather similar. LIM3 sea-ice volume growth rate is $\sim$30% less than the GIOMAS one, but $\sim$10%

higher than the LIM2 one. In both LIM models, the periods of ice growth are typically longer and periods of melt shorter than in GIOMAS.

As with the sea-ice extent in the SH, the annual mean LIM3 sea-ice volume has a statistically significant positive trend of 1.7×10^3 km^3/decade at the 5% significance level over the past decade 2003–2012. In contrast, the GIOMAS sea-ice volume trend for the same period is statistically significantly negative, -1.4×10^3 km^3/decade, while LIM2 has no statistically significant trend. This indicates that, unlike in the NH, three models disagree in terms of the evolution of Antarctic sea-ice volume, at least for this particular time period.

There are important differences between PIOMAS and NEMO-LIM, explaining the systematic deviation of their sea-ice volume from each other. First, PIOMAS uses NCEP based atmospheric forcing compared to the DFS one used in the NEMO-LIM simulations. Second, PIOMAS assimilates sea-ice concentration and SST data, while the NEMO-LIM simulations do not. Finally, PIOMAS ocean and sea-ice models and the computational grid are different from NEMO-LIM ORCA1 configurations along with numerous physical parameterisations implemented in the models.

In general, close similarities between the LIM2 and LIM3 sea-ice distributions in the SH emphasise the importance of the ocean model dictating the evolution of sea ice, while the level of sophistication of sea-ice model has a smaller importance. This is, at least partly, due to the divergent large-scale sea-ice motion where sea-ice deformation remains small (Uotila et al., 2000). Therefore, different sea-ice deformation parameterisations in LIM2 and LIM3 have a lesser significance as in the relatively shallow Arctic Ocean. Another difference between LIM2 and LIM3 is related to the sea-ice thickness distribution parameterisation, which again has a smaller importance in the Southern Ocean than in the Arctic due to a smaller role of the ice-albedo feedback and the lack of surface melt ponds on the Antarctic sea ice compared to oceanic effects.

3.3 Sea-ice drift

The simulated March and September mean (2003–2012) sea-ice velocities are shown in Figure 3, together with the OSI SAF sea-ice drift product (Lavergne et al., 2010). Both LIM models realistically represent observed large-scale ice drift patterns, which are a direct response to the atmospheric circulation.

In the NH, the LIM3 mean drift pattern in March consists of an offshore motion over Siberian shelves (4–6 $\mathrm{cm/s}$), the anti-cyclonic gyre in the Beaufort Sea (2–4 $\mathrm{cm/s}$), the transpolar drift (4–6 $\mathrm{cm/s}$) from the coast of Eastern Siberia to Fram Strait (Figure 3c). The ice drift through Fram Strait and in the East Greenland Current is particularly strong (16–20 $\mathrm{cm/s}$), as well as the southward drift (14–16 $\mathrm{cm/s}$) through Davis Strait. The Arctic sea-ice velocities in both LIM models are generally higher compared to satellite estimates, and the location of the centre of the Beaufort Gyre is displaced westward, toward the Chukchi Sea (Figure 3a, c and e). A similar positive sea-ice velocity bias was reported by (Chevallier et al., 2015) who analysed 14 ocean-ice reanalysis products. This discrepancy might be a result of a too high air-sea momentum flux driving the ice too fast and, on the shelf regions, due to the lack of a fast-ice parameterisation. On the other hand, the OSI SAF satellite derived sea-ice velocities may have high uncertainties over those regions of highly concentrated and slowly moving ice. Furthermore, the displacement of the Beaufort Gyre in LIM3 agrees with the positive sea-ice concentration bias of Figure 1b where relatively thick ice has been accumulated to (not shown here).

The two LIM models perform somewhat differently in terms of sea-ice speed, LIM2 sea ice being generally faster, in particular in the Beaufort Gyre ~~, but then again weaker in the Nansen Basin~~ (Figure 3e). The 10-year mean Arctic sea-ice velocity in March is 4.6 (4.8) $\mathrm{cm/s}$ for LIM3 (LIM2). Time series of area export through Fram Strait present similar variability in both LIM simulations. During the last simulated decade, the annual mean area fluxes through Fram Strait correspond to more than 10% of the winter ice covered area, being 0.86 (0.89) million km^2 in LIM3 (LIM2), both being comparable to estimates based on SAR data (Smedsrud et al., 2011).

In the SH, the LIM models feature similar and realistic looking distribution of the September ice drift (Figure 3). They show realistic patterns of the Weddell and Ross Gyres, the westward coastal and eastward offshore circumpolar currents. The observed OSI SAF drift generally compares well with the modelled ones in terms of their large-scale velocity field patters although the modelled speeds appear faster than observed, particularly along the ice edge. That suggests that LIM models simulate the Antarctic sea-ice drift reasonably well albeit somewhat too fast which seems to be a consistent ocean-ice model bias (Uotila et al., 2014).

As in the Arctic, the two LIM models have similar sea-ice velocity magnitude within the central ice pack, but larger differences appear close to the ice edge, where the LIM3 ice drift is $\sim$2 cm/s faster than LIM2, and in the coastal areas, where LIM2 speed is $\sim$2 cm/s faster than LIM3 (Figure 3f). ~~Close to the ice edge,~~ LIM3 has a smaller ice extent and a lower ice concentration ~~at regions~~close to the ice edge (not shown here). There the LIM3 ice motion is closer to the free drift and therefore faster that LIM2 ice motion. In the coastal areas, differences in ocean currents and ice deformation parameterisations are likely causes for the velocity differences between the LIM models. The horizontal, perpendicular-to-coast salinity gradient is stronger in LIM2 than in LIM3 in a way that LIM2 coastal surface waters are fresher, while off the coast LIM2 surface waters are saltier than in LIM3. This difference in the salinity gradient modifies the density gradient, coastal geostrophic currents and ice drift along the coast.

3.4 Sea-ice salinity

One important new feature in LIM3 is the prognostic sea-ice salinity compared to the constant 4 ppm sea-ice salinity in LIM2 (Vancoppenolle et al., 2009a). LIM3 explicitly includes the salt water entrapment and drainage in sea ice, where it also impacts on the ice thermodynamic variables such as the specific heat, conductivity and enthalpy. Furthermore, when snow-ice is formed by flooding and freezing of a relatively thick snow layer on top of ice, the LIM3 snow-ice becomes saline in contrast to the LIM2 fresh snow-ice. Vancoppenolle et al. (2009b) found that these improvements impacted on the LIM sea-ice volume, and that the LIM3 sea ice compared better with observations than the LIM2 sea ice.

~~This improved realism is existing in our simulations, as shown in previous sections describing the LIM sea-ice extent and volume. It is likely~~

It is reasonable to assume that to some extent the more realistic LIM3 sea ice ~~is~~ might be due to the advanced salinity dependent halo-thermodynamics and a more realistic seasonal cycle of sea-ice salinity, and associated upper ocean freshwater fluxes. In winter, newly formed LIM3 sea ice preserves a higher salinity than in LIM2 (Figure 4). In contrast, in summer, the remaining LIM3 sea ice has a 2–4 ppm lower salinity than LIM2 in the Arctic (not shown here). However, during the

Antarctic summer, the LIM3 sea-ice salinity stays relatively high, except at the ice edge (not shown here). This is due to the fact that even in summer air temperature remains at freezing over the coastal Antarctic seas. As in Vancoppenolle et al. (2009b), our simulations confirm that the LIM3 prognostic sea-ice salinity behaves realistically~~and compares well with the available observations~~.

4 Sensitivity simulations

Based on rather descriptive analysis of differences between the LIM models, presented in the previous section, we have gained a relatively comprehensive understanding of how their global sea-ice distributions compare. In this section, we address what makes LIM3 sea ice different from LIM2 sea ice. Model grid and atmospheric forcing are identical~~;~~ , sea-ice differences can only arise from differences in sea-ice model physics parameterisations and these differences can be further amplified by ocean-ice feedback processes. To find out which parameterisations are of importance in producing LIM model differences, we performed and analysed some additional simulations.

4.1 NEMO-LIM3 single-category simulation

LIM3 differs from LIM2 in two important aspects: LIM3 has a multi-category sub-grid-scale ~~sea- ice~~ sea-ice thickness distribution and multilayer halo-thermodynamics scheme with prognostic non-constant sea-ice salinity profile. We tested the effect of these parameterisations by carrying out a LIM3 simulation with a single-category sea-ice thickness distribution having a virtual ice thickness distribution and a constant 4 ppm sea-ice salinity. Importantly, by setting the LIM3 sea-ice salinity constant, along with its two vertical ice layers and one snow layer, its thermodynamics scheme becomes similar to the LIM2 one. However, the initialisation procedure of LIM3 is different from the one used in LIM2, as explained in Section 2.3. We denote the LIM3 single-category simulation as ~~LIM3MC~~LIM3SC.

In terms of NH sea-ice ~~extent, LIM3MC~~ concentration and extent, LIM3SC is located between LIM3 and LIM2 (Figures 1d, 1f and 2b). In the SH, ~~and in the SHits~~ LIM3SC annual-mean sea-ice extent follows closely to the one of LIM2 (Figure 2b and ~~d~~2d). However, the monthly sea-ice extent climatology of ~~LIM3MC~~ LIM3SC is distinctly closer to LIM3 and does not have the distorted shape of LIM2 monthly sea-ice extent climatology (Figure 2a and c). Furthermore, the summer minimum and winter maximum of ~~LIM3MC~~ LIM3SC sea-ice extents ~~differ significantly~~ clearly differ from LIM2 ones. This result suggests that the use of the single-category and constant salinity parameterisations brings LIM3 sea ice closer to LIM2 output, as expected, but ~~significant~~ apparent differences remain.

The ~~LIM3MC~~ LIM3SC sea-ice volume relative to two other LIM simulations is more different in the SH than in the NH (not shown here). In the Southern Hemisphere, the ~~LIM3MC~~ LIM3SC sea-ice volume immediately diverts from LIM2 and LIM3, although its annual mean sea-ice extent remains rather close to LIM2 with a seasonal variability closer to the LIM3 one. It is possible that strong ocean-ice feedback processes in ~~LIM3MC~~ LIM3SC affect the melting and freezing rates during its first simulation year, and associated fluxes of salt and freshwater. This in turn modifies the upper ocean stratification and oceanic heat, which result in further differences in ~~LIM3MC~~ LIM3SC sea-ice volume that adjusts above the LIM2 level. The

20 cm thicker ~~LIM3MC~~ LIM3SC initial snow might have contributed to the differences in sea-ice thickness between LIM2 and ~~LIM3MC~~ LIM3SC by reducing the spring melt at the end of the first simulation year resulting in a relatively high sea-ice volume minimum in summer that persists through the simulation. After this, the high ~~LIM3MC~~ LIM3SC sea-ice volume seems to be in a balance with the upper ocean adjusted during the first years of the simulation.

In addition to sea-ice thermodynamics, the sea-ice salinity scheme modifies the ocean-ice salt and freshwater exchange, and upper ocean heat fluxes, which influence the evolution of sea ice. Compared to LIM2, the LIM3 multi-category sea-ice is saltier in winter due to its prognostic sea-ice salinity (Figure 4). This implies a smaller ocean-to-ice salt flux during freezing and a more stably stratified ocean surface layer, particularly in the Southern Ocean and in the Barents Sea where LIM3–LIM2 winter salinity differences seem particularly large (Figure 4). If the LIM3 prognostic salinity was of primary importance, we would expect a higher sea-ice volume in the LIM3 prognostic sea-ice salinity simulation than in the ~~LIM3MC~~ LIM3SC constant sea-ice salinity simulation due to smaller salt rejection rates and associated ocean convection in the Southern Ocean. As this is not the case, the importance of the sea-ice salinity scheme, in modifying the sea-ice evolution by affecting upper ocean heat fluxes, appears to be a secondary one compared to the effects of sea-ice salinity scheme on sea-ice thermodynamics and especially to the effects of sub-grid-scale ice thickness parameterisation.

4.2 Effects of freshwater adjustments

Following a common practise when carrying out forced ocean-ice simulations, we applied a fresh water budget adjustment and SSS restoring in our simulations. The freshwater budget, evaporation minus precipitation minus river runoff, was adjusted from the previous year's annual mean budget to zero at the beginning of each simulation year. Additionally, we added a SSS dependent flux correction term on freshwater fluxes. This flux correction term practically damps the model top-level salinity towards the PHC3 top level salinity PHC3 everywhere, also under sea ice, in LIM2, LIM3 and ~~LIM3MC~~ LIM3SC simulations. These treatments prevent an unrealistic drift of the sea surface height due to errors in the prescribed freshwater budget components.

In addition to the common practise, we completed two otherwise identical integrations, one for LIM2 and one for LIM3, where we turned off the two freshwater adjustment mechanisms to see what kind of effect they have on our results. As expected, the ocean salinity drift became ~~significant~~ remarkable in the non-adjusted simulations, being strongest in the top layer, increasing its salinity by 0.4 psu in 54 years. This salinity change resulted in a global sea-level decrease of 8 m and also modified the ocean density structure. Related to this, a shallower mixed layer in the northern North Atlantic, a slightly weaker (1-2 Sv) Atlantic Meridional Overturning Circulation (AMOC), and a somewhat larger temperature drift were detected from the non-adjusted stimulations.

Perhaps interestingly and in contrast to the North Atlantic, the Southern Ocean mixed layers were deeper without freshwater adjustments (LIM3FW and LIM2FW). Importantly, for the scope of this study, the effects of freshwater adjustments on sea-ice evolution were minuscule. LIM models produced almost identical sea ice ~~, and therefore essentially identical ocean-ice differences,~~ independent of whether the freshwater adjustments were turned on or off. ~~This result implies that in coupled atmosphere-ocean NEMO-LIM configurations, where the freshwater adjustments must be turned off, the ocean-ice coupling~~

~~is unlikely to generate issues. In other words, if problems appear, they are related to the coupling and flux exchanges between the oceanic and atmospheric components~~Mutual oceanic differences between the LIM3 and LIM2 simulations and between the LIM3FW and LIM2FW simulations did not change drastically, as we will show. However, as 54-year simulation is rather short from the ocean circulation perspective, it is possible that in longer simulations the differences between the simulations in terms of oceanic circulation increase to the point that they start to modify the sea-ice characteristics remarkably.

5 Ocean hydrography and circulation

5.1 Arctic surface salinity

We now move on to explore differences in ocean properties between the two LIM versions. Figure 5 shows LIM3 Arctic SSS and sea-surface temperature (SST) averaged over the last decade of the simulation, 2003–2012, and ~~its~~ LIM3 and LIM2 departures from PHC3, WOA13 and LIM2. ~~LIM3~~ LIM models SSS is closer to that of PHC3 than WOA13 due to their surface salinity restoring towards PHC3. LIM models' differences from PHC3 and WOA13 are much larger than ~~its differencesfrom LIM2~~their mutual differences, highlighting the fact that the LIM version has a secondary impact on the Northern Hemispheric ocean properties.

LIM3 surface salinity distribution realistically reflects the fact that the Arctic Ocean has a low salinity surface layer in contrast to the much saltier surface layer of the North Atlantic (Figure 5a). Compared to PHC3 and WOA13, both NEMO-LIM versions are too fresh in the North Atlantic, Labrador Sea and Nordic Seas, although the LIM3 Labrador Sea surface ~~is slightly~~ saltier than that of LIM2~~(Figure 5b–d). In the Greenland Sea, the LIM3 fresher surface compared to LIM2 is related to the melted freshwater from excessive sea ice~~, in particular close to the Greenland coast (Figure 5b–f). In some parts of the Eurasian Basin, LIM3 is saltier than PHC3 which is partly associated with its negative sea-ice concentration bias and the lack of fresh melt water (Figure 5b). Compared to WOA13, LIM3 SSS is much higher due to the SSS restoring toward PHC3, which indicates ~~observational~~ disagreements in terms of Arctic SSS due to the lack of observations and that the PHC3 SSS is higher than WOA13 SSS. As PHC3 was carefully constructed for the Arctic, it is plausible that its SSS climatology is closer to the truth. LIM ocean salinity biases mainly arise from the NEMO ocean model configuration, and the applied boundary conditions, such as the atmospheric forcing, river runoff and freshwater adjustments.

LIM3 has a fresher surface than LIM2 in many areas on the Siberian shelf, Barents Sea and Greenland Sea, associated with the smaller ice-ocean salt flux, thicker ice in winter and larger melt rates during spring (Figure 5d). By contrast, in LIM2, fresher ice and reduced spring melt result in an increased ice-to-ocean salt flux and therefore higher SSS in those regions. However, along the East Greenland coast~~and in the Labrador Sea, thicker~~, thicker LIM2 sea ice is associated with higher melt rates and result in a fresher surface also in the Labrador Sea, where the ice and freshwater drifts to. These differences in surface salinity, associated with sea-ice differences, have potential implications for the strength of AMOC~~, as discussed below~~. Hence, although mutual hydrographic differences between the freshwater adjusted LIM simulations are small compared to their observational biases, they may potentially have an impact on the convective processes in the North Atlantic.

The experiments without freshwater adjustments, LIM2FW and LIM3FW, display larger SSS differences with the expanded or changed regions of statistically significant difference (not shown here). For example, the region north of Greenland in the Arctic Ocean, which is significantly saltier in LIM3 than in LIM2 (Figure 5d), is not significantly saltier in LIM3FW than in LIM2FW. However, LIM3FW–LIM2FW SSS differences remain clearly smaller than the corresponding SSS differences with the observational climatologies. In general the geographical patterns of SSS differences remain rather similar, mainly the magnitudes of SSS differences change. In any case, this indicates that the freshwater flux corrections reduce the salinity differences originating from two different sea-ice models.

5.2 Arctic surface temperature

As with SSS, SST differences between the LIM models in the Arctic are small compared to their differences from PHC3 and WOA13 (Figure ~~5f–h~~5h–l). The LIM models have a distinct cold bias in the North Atlantic and in the Greenland Sea. These cold biases are related to the common atmospheric ERA-Interim based forcing which is known to have a cold anomaly over the Fram Strait–Svalbard region (Notz et al., 2013). In the Norwegian and Barents Seas, ~~LIM3 surface is~~ LIM models’ surfaces are warmer than PHC3, while ~~its difference~~ their differences to WOA13 ~~is~~ are relatively small. The WOA13 climatology represents years 2005–2012 and better matches the NEMO-LIM analysis period of 2003–2012 than PHC3, which contains observations before 2005. As PHC3 SST is colder than WOA13 and ~~LIM3~~ LIM SSTs in the Norwegian and Barents Seas, it is evident that these differences are related to the recent warming of these regions.

Related to the ~~larger LIM2~~ smaller LIM3 sea-ice extent, ~~LIM2 SST is colder than LIM3~~ LIM3 SST is warmer than LIM2 SST across most of the Arctic Ocean, along the East Greenland coast, in Baffin Bay and in the Labrador Sea. In contrast, SST in the Norwegian Sea and Barents Sea is lower in LIM3 than LIM2, associated with a lower salinity. In these regions, saltier LIM2 surface waters release less heat to the atmosphere before reaching the critical density and sinking down, which explains the warmer LIM2 SST. Additionally, ~~these regions have a deeper~~ LIM3 and LIM2 mixed layer depths show remarkable differences across the Nordic Seas, as we will soon show. These SSS, SST and MLD differences signify ~~a more~~ the varying locations of effective upper ocean convection in the ~~LIM2 simulation~~LIM simulations.

5.3 Southern Ocean surface salinity

In the SH, ~~LIM~~ LIM3/LIM2 and PHC3/WOA13 SSS differences are smaller than in the NH (Figure 6b, c, e, f). In the regions covered by sea ice, ~~the LIM3 ocean surface is~~ LIM models’ ocean surfaces are fresher than PHC3, except in some areas along the East Antarctic coast. These coastal differences are smaller between ~~LIM3~~ the LIM models and WOA13 than between the LIM models and PHC3 (Figure 6b, c, e, f), which could be related to a larger number of better quality coastal Antarctic observations included in WOA13 and the fact that the simulation analysis period temporally better matches with WOA13 than PHC3. LIM3 SSS differences with LIM2 ~~form to some extent a similar spatial pattern than its differences with PHC3, although LIM3–LIM2 differences~~ have smaller magnitudes than the LIM models’ differences with the observational climatologies (Figure 6d). Now, ~~LIM2~~ LIM3 Antarctic sea ice is ~~more~~ less extensive, but ~~thinner than LIM3~~ thicker than LIM2 sea ice, on the average. Hence, off the Antarctic coast where the ice melts, ~~less~~ more fresh water is released per area in ~~LIM2 than in~~

~~LIM3~~ LIM3 than in LIM2 resulting in a ~~higher LIM2~~ lower LIM3 SSS. Close to the Antarctic coast the ~~LIM2~~ LIM3 ocean surface is ~~fresher than the LIM3~~ saltier than the LIM2 ocean surface. This is likely to be ~~be~~ due to the ~~smaller~~ greater winter ice formation rates in ~~LIM2, associated smaller~~ LIM3, associated larger salt flux from ice to ocean.

Processes related to the LIM3/LIM2 and PHC3/WOA13 SSS discrepancies in the Southern Ocean are likely to be associated with the other freshwater sources rather than the sea ice related fresh water exchange. Again, this is because the LIM and PHC3/WOA13 differences are of larger magnitudes than the differences between two LIM models. Most important external freshwater sources in the Southern Ocean are precipitation and melt water fluxes from the Antarctic continental ice sheet, and both of these sources are known to have large uncertainties. Given these observational freshwater and SSS uncertainties, we can expect significant differences between NEMO-LIM and PHC3/WOA13 ocean surface characteristics. However, as the NEMO-LIM simulations applied the SSS restoring, LIM and PHC3 sea-surface salinities did not evolve very far apart compared to the simulations where the freshwater was not adjusted (not shown here). As for the Arctic, the LIM experiments without freshwater adjustments display larger mutual differences although their geographical patterns do not essentially change (not shown here).

5.4 Southern Ocean surface temperature

~~LIM3 surface is~~ The surfaces of the LIM simulations are colder than PHC3 and WOA13 around the East ~~Antarctica (Figure 6f, g~~Antarctic and in the Ross Sea (Figure 6h, i). As ~~this difference is~~ these differences are associated with fresher surface and lower than observed ice concentration, it is likely that the more stable ~~LIM3~~ LIM surface stratification decreases the upward oceanic heat flux and increases the surface heat loss to the atmosphere due to larger open water areas. Consistent with this explanation, the somewhat higher LIM2 sea-ice concentration and SSS seem to result in a higher SST than the one of LIM3 around the East Antarctic (Figure ~~6h~~6j).

5.5 Arctic intermediate water (AIW)

In the Arctic Ocean, approximately at 250 m depth, lies the relatively warm AIW layer that originates from the Atlantic Ocean (Figures 7 and 8). AIW is below the halocline and therefore saltier than waters above it (~~Figures 7h and~~ Figure 8b). The NEMO-LIM models simulate too fresh and cold waters at 250 m in the Arctic Ocean (Figure 7b-c, ~~f-g~~h-i). During the first decade of NEMO-LIM simulations, their AIW layers cool and possibly due to too vigorous mixing ~~loose~~ lose heat to the water masses above resulting in weaker and broader thermoclines than PHC3 and WOA13 (Figure 8a).

LIM3 AIW remains warmer than LIM2 (Figure 8a), which indicates a somewhat larger Atlantic warm water inflow into the Arctic Ocean ~~and might be associated to a smaller meridional overturning circulation in the North Atlantic in LIM3. Unlike in the Arctic Ocean, in~~ (Figure 7j). In the Nordic Seas and Barents Sea~~PHC3 and WOA13 are colder than LIM3~~ , LIM3 and LIM2 are warmer than PHC3 and WOA13 at 250 m (Figure ~~7f, g~~7h, i). This indicates that not enough oceanic heat enters the Arctic Ocean in the LIM simulations possibly due to their coarse model grid that does not adequately resolve the basin topography and eddy heat transport. The lack of warm Atlantic water inflow to the Arctic and associated biases are consistent with the ones founded in the multi-model study by Wang et al. (2016b).

5.6 Temperature and salinity differences outside the Polar Regions

Outside the polar regions, small temperature and salinity differences emerge as the LIM simulations proceed. For example, LIM3 has a saltier Atlantic Ocean than LIM2 at the layer from the surface to 1000 m depth (not shown here). LIM salinity differences vary in time with maximum values up to 0.05 psu, while their Atlantic basin averaged salinities are approximately 35.35 psu. On the basin scale, salinity differences between the two LIM simulations above 1000 m depth become notable rather soon, during the first decade of simulations. In other basins, salinity and temperature differences above 1000 m depth and outside the polar regions remain much smaller. However, in the Atlantic Ocean in the layer deeper than 1000 m, ~~LIM2~~ LIM3 starts to evolve into a ~~saltier and warmer state than LIM3~~ fresher and colder state than LIM2 from the late 1970s onward. There basin-wide mean salinity differences amount up to 0.001 psu by the end of simulations. At the same time, in the layer deeper than 1000 m of the Pacific Ocean, LIM3 becomes on the average saltier and colder than LIM2. Changes in these deep water characteristics originate from the surface perturbations, which are slowly transported deeper by the meridional overturning circulation and deep water formation. The key regions where atmosphere-ocean conditions permit the deep water formation and consequently drive the meridional overturning circulation are located in the northern North Atlantic and coastal Antarctica. These are also the regions where the sea-ice cover between the two LIM simulations vary and thus modify the atmosphere-ocean energy exchange, which then affects the deep water formation and the World Ocean meridional overturning circulation.

5.7 Mixed layer depth (MLD)

Oceanic convection, vertical heat transport and deep water formation are intimately related to the MLD. We keep in mind that the observational MLD uncertainties are particularly large in ice covered oceans, because of sparse observations, and therefore limit our comparisons to the North Atlantic and the Southern Ocean. In Figure 9, the mean winter MLD is presented for LIM3 along with its difference from the observed ~~climatology of de Boyer Montégut et al. (2004) ,~~ climatologes of de Boyer Montégut et al. (2004) and Holte et al. (2016), LIM2 differences from the observed climatologies and for the LIM3–LIM2 difference. Clearly, the regions of deep MLD are located off the sea-ice edge ~~.~~ (Figure 9a, g).

~~In the Greenland Sea, the observed MLD is deeper than the LIM3 MLD (Figure 9b). This could be due to excessive winter LIM3 sea ice in the East Greenland Current resulting in a shallower LIM3 mixed layer. The presence of sea ice diminishes the heat loss and reduces the MLD. Furthermore, the region south of Greenland in the North Atlantic, characterised by cold and fresh LIM3 biases, also has a shallower than observed mixed layer. This is to be expected due to the more stable LIM3 surface stratification compared to PHC3~~In the Norwegian Sea and the Barents Sea the observational climatologies agree generally rather well, but in the Labrador Sea where Holte et al. (2016) show deeper MLDs than de Boyer Montégut et al. (2004). In the ~~Norwegian Sea and the Barents Sea~~North Atlantic, the LIM3 ~~MLD is much~~ and LIM2 MLDs are larger than the observational MLD estimates indicating stronger oceanic convection (Figure 9b, c, e, f). This is at least partly due to the cold, non-responsive ~~and~~ prescribed winter atmosphere acting as an infinitive heat sink to the relatively warm ocean surface layer and associated with relatively cold LIM3 and LIM2 SSTs (section 5.2).

In the Southern Ocean, the LIM3 and LIM2 mixed layers are again much deeper than the observed mixed ~~layer is much shallower than the LIM3 mixed layer~~ layers outside the regions covered by ice, particularly in the Pacific sector (Figure ~~9e~~9h, i, k and l). This pattern, to some extent, resembles the MLD difference pattern in the ~~Norwegian Sea and the Barents Sea~~North Atlantic. In the Southern Ocean, as in the North Atlantic, the very deep ~~LIM3~~ NEMO-LIM MLD is a likely response to the prescribed atmospheric forcing and possibly to erroneous precipitation and freshwater fluxes originating from the Antarctic ice sheet.

Although the ~~LIM2~~ LIM3 MLD generally appears to be relatively close to the ~~LIM3~~ LIM2 one in the Arctic, it is ~~approximately 10-20% deeper in the Nordic Seas and the Barents Sea (Figure 9c). These are also regions where the LIM2 SSS is higher than the LIM3 one, and where denser LIM2 surface entrain deeper resulting in a deeper mixed layer than in~~ statistically significantly deeper in some Arctic Ocean locations, such as in the Canadian Basin, where the LIM3 ~~, which, as we will show, is associated with a stronger AMOC in LIM2~~ocean surface is somewhat warmer and fresher (Figures 9d, 5d and 5j). In the Southern Ocean, ~~LIM~~ LIM2–LIM3 MLD differences are quite small, with ~~most distinct ones~~ the statistically significantly regions visible in the ~~Antarctic coastal areas (Figure 9f~~marginal ice zone off the coast of east Antarctica and in along the Antarctic coast (Figure 9j). As these ~~are the regions of~~ coastal regions are the Antarctic Bottom Water formation regions, MLD differences indicate differences in the locations and rates of the deep water formation between the two LIM simulations. This variability in the deep water formation changes the deep water properties, which is manifested as slowly emerging differences in abyssal temperature and salinity, decades after the beginning of simulations, as discussed earlier in section 5.6.

5.8 Atlantic Meridional Overturning Circulation (AMOC)

An important characteristic of a global ocean model is the strength and extent of its AMOC. The observational based estimates of its average strength vary between 16.9 Sv at 26.5°N (Smeed et al., 2016) to 18.5 Sv at 24°N (Ganachaud, 2003; Lumpkin and Speer, 200 16.5 Sv at 48°N (Ganachaud, 2003). In terms of modelled AMOC, Danabasoglu et al. (2014) assessed the mean AMOC of eighteen ocean-ice models forced by prescribed atmospheric forcing from 1948–2007 and ~~run~~ ran five repetitive forcing cycles, restarted from the state at the end of the previous cycle. Many of these fifteen ocean models were also used as the ocean-ice components of CMIP5 climate models. Here, the results of Danabasoglu et al. (2014) provide a useful indicative benchmark for our NEMO-LIM simulations, although one needs to keep in mind differences between CORE-II and our experiment setup, which are likely to affect AMOC. In Figure 10, the time evolution of ~~LIM3 AMOC looks~~ NEMO-LIM AMOCs look rather similar to some ocean-ice models assessed by Danabasoglu et al. (2014) during their first simulation cycle (compare Danabasoglu et al. (2014) Figure 1, middle panel and our Figure 10a). As ~~LIM3~~the NEMO-LIM models studied here, these models initially have an AMOC of 16-17 Sv which gradually, during the first three decades, decreases down to 8-12 Sv. These models, labelled as NOCS, CERFACS and CMCC in Danabasoglu et al. (2014), are based on earlier versions of NEMO than NEMO3.6, but importantly share the identical ORCA1 horizontal grid with us. The NOCS model has 75 vertical levels, as our NEMO-LIM configurations, while CERFACS and CMCC have a smaller number of vertical levels.

In addition to AMOC temporal evolution, our mean AMOC transport patterns in depth-latitude space well resemble the NEMO ORCA1 ones of Danabasoglu et al. (2014). This can be seen by comparing our Figure 10c with their Figure 3. In particular, NOCS and CMCC mean patterns resemble our NEMO-LIM3 pattern with high northward transport regions at 1000 m, a surface maximum at 10-20°N, and a rather strong southward transport approximately at 4000-5000 m (not shown). These qualitative inspections with Danabasoglu et al. (2014) indicate that our NEMO- LIM simulations produce a comparable AMOC to earlier NEMO configurations with comparable horizontal and vertical resolutions.

Deviations between the LIM2 and LIM3 simulations in terms of their AMOC are minor. There are, however subtle, statistically non-significant, differences, as seen from Figure 10a, where the LIM2 annual maximum AMOC within the 50-53°N band is up to 0.4 Sv stronger than the LIM3 AMOC within the same latitude band. The stronger LIM2 AMOC is likely to be driven by stronger deep convection ~~in~~ at the varying locations across the Nordic Seas ~~, apparent as a deeper MLD. As explained earlier, differences~~ (Figure 9d). Differences in MLD are related to differences in ocean surface stratification caused by deviations in sea-ice characteristics between the two LIM simulations.

As expected, the AMOC differences between LIM3 and LIM2 become more apparent when comparing simulations without freshwater adjustments, LIM3FW and LIM2FW. Both LIM3FW and LIM2FW have a statistically significantly lower AMOC at the 5% level than the ones with freshwater adjustments, LIM3 and LIM2 (Figure 10a). As the LIM3 AMOC is on the average smaller than the LIM2 AMOC, also the average LIM3FW AMOC is smaller (by 0.7 Sv n 2003–2012) than the average LIM2FW AMOC. However, the average LIM3–LIM2 AMOC difference is not statistically significant, while the average LIM3FW–LIM2FW AMOC difference is (at the 5% level). Accordingly, it is reasonable to assume that the freshwater adjustments, mainly the SSS-restoring, keeps the LIM3 and LIM2 AMOCs closer to each other.

5.9 Other oceanic transports

In addition to AMOC, we calculated time series of volume, heat and salinity transports through a number of oceanic transects: the Australia–Antarctica transect, the Bering Strait, the Denmark Strait, the Drake Passage, the Florida Strait, the Gibraltar Strait, and the Greenland–Norway transect at 60°N. LIM simulations show slightly varying volume transports in ~~other~~ these major transects, such as the Drake Passage which we decided to show here (Figure 10b). There, LIM2 volume transports became approximately 5 Sv larger than in LIM3. These are relatively small deviations, given the fact that total volume transports in the Drake Passage are around 160 Sv. However, it is possible that these deviations further increase during long, multi-centennial simulations, as demonstrated by Danabasoglu et al. (2014) with respect of AMOC.

6 Conclusions

A set of hindcast simulations (1958–2012) ~~were~~ was performed with the newest NEMO3.6 model ~~in~~ using the global ORCA1 grid forced by the DFS5.2 atmospheric data. The primary objective was to diagnose the sensitivity of the NEMO-LIM ocean-ice system to the representation of physics in the sea-ice model. Results of such analysis have not been published for the newest NEMO in the nominal 1° latitudinal resolution, which is used as the ocean-ice component in many climate models participating in the CMIP6 project. We focussed on two simulations that differ only in their sea-ice component: the widely-used LIM2 and its successor, LIM version 3.6. The main differences between the two sea-ice models lie in their parameterisation of sub-grid-scale sea-ice thickness distribution, ice deformation, thermodynamic processes, and sea-ice salinity.

To assess the performance of two LIM versions, we ~~briefly~~ compared their climatological sea-ice distributions mutually and with observational estimates. In terms of global sea ice, LIM3 compares clearly better with available observations, while LIM2 deviates more, producing too much ice in the Arctic, for example. The better representation of the ice-albedo feedback makes LIM3 more capable in simulating the September minimum of extent than LIM2, including the 2007 extremely low Arctic value. These sea-ice findings are consisted with the ones of Vancoppenolle et al. (2009b); Massonnet et al. (2011); Vancoppenolle et al. (2015); Rousset et al. (2015).

We mostly restricted our analysis to the last decade of the 54-year simulations. By analysing a ten-year period means that the effect of multi-decadal variability is not taken into account. However, earlier and longer analysis periods would have been more impacted by the model spin up from its initial state in 1958. Looking at the multi-decadal sea-ice extent and ocean transport time series (Figures 2 and 10), the LIM2 and LIM3 simulations stay systematically apart. Accordingly, it is sensible to assume that the respective LIM3–LIM2 differences are not very sensitive to the multi-decadal variability, at least during the last few decades of the simulations. Furthermore, it is reasonable to assume that the upper ocean LIM3–LIM2 differences behave like the sea-ice and the oceanic transport ones.

It is worth noting that no specific NEMO-LIM tuning was done for our experiments. It is likely that after some adjustments, such as controlled changes in the sea-ice albedo or ice strength, the NEMO-LIM3 and NEMO-LIM2 sea-ice performance will to some extent increase (Uotila et al., 2012). It is also worth noting that NEMO-LIM3 has been developed further and, for example, a new sea-ice albedo scheme was implemented in April 2016. ~~Our preliminary tests on this new scheme demonstrate the robustness of LIM3, as its sea-ice distribution appears almost insensitive to changes in summer albedo . This robustness also signifies that~~ This new scheme provides better transitions between the different ice types, slightly modifies the surface albedo compared to the old scheme and affects the model behaviour to a limited extent only. Hence, the results of this study remain valid even after the implementation of the new albedo scheme. ~~The differences between NEMO-LIM2 and NEMO-LIM3 seem robust, as they do not significantly change even after switching the NEMO ocean surface freshwater adjustments off.~~

Our model evaluation focussed on the upper ocean properties and to some extent oceanic transports across major transects of the World Ocean, such as the Drake Passage, along with its meridional overturning circulation. This has not been systematically done before for NEMO3.6. In general, ocean hydrographic differences, such as temperature and salinity, between the two LIM versions are confined to the upper ocean and near the sea-ice zone. In terms of large-scale ocean circulation, differences between the two LIM versions remained small, but kept increasing over the decades, also in the extra-polar regions.

As a further sensitivity experiment, we repeated the NEMO-LIM3 hindcast simulation after setting its sea-ice distribution to the single-category mode. At large and as expected, this single-category configuration resulted in a shift of LIM3 sea-ice distribution towards the LIM2 one, but encouragingly the LIM3 single-category sea ice remained clearly more realistic than the LIM2 one. This result indicates that one option for modellers who are considering in upgrading from LIM2 to LIM3, is to start using the single-category LIM3 as an intermediate step. Based on these findings, we conclude that NEMO3.6 is ready as a stand-alone ocean-ice model and as a component of coupled atmosphere-ocean models.

7 Code and data availability

The NEMO version 3.6 version incorporates LIM2 and LIM3.6 sea-ice models, and can be downloaded from the NEMO web site (http://www.nemo-ocean.eu/) at this address: http://forge.ipsl.jussieu.fr/nemo/svn/branches/2015/nemo_v3_6_STABLE. The model input data can be obtained following the references described in section 2.5. The output of model simulations and the computer scripts used to produce the results presented in the paper, including the figures, are available from the corresponding author upon request.

Acknowledgements. We acknowledge the creators of low resolution sea-ice drift product of the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF, www.osi-saf.org). We thank Dr Laurent Brodeau for providing us the very useful Barakuda software package to diagnose NEMO simulations. The work of Lensu and Uotila was supported by the Academy of Finland (contracts 264358 and 283034).

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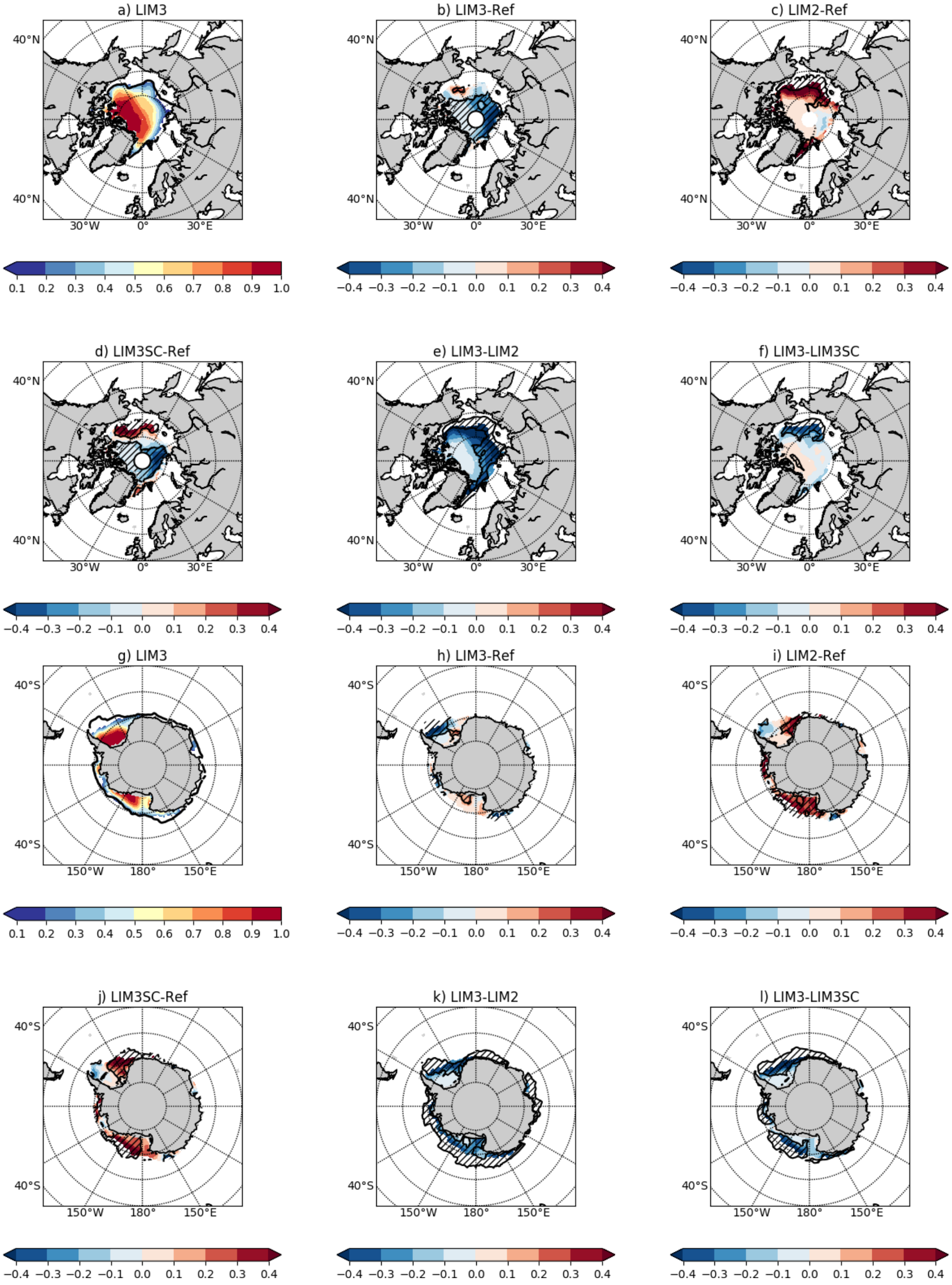

Figure 1. Geographical distribution of Arctic sea-ice concentration averaged for September (~~a–c~~a–f) and Antarctic sea-ice concentration averaged for March 2003–2012 (~~d–e~~g–l). (a, ~~d~~g) show values simulated by LIM3, while (b, ~~e~~h) show LIM3 difference with Meier et al. (2013) passive microwave observations~~and~~ , (c, ~~f~~i) ~~with~~ the corresponding LIM2 difference, (d, j) the LIM3SC difference, while (e, k) show the difference between LIM3 and LIM2 and (f, l) the difference between LIM3 and LIM3SC. Sea-ice concentration differences are computed only where both values are present. Only areas where the sea-ice concentration is greater than 15% are plotted. In (a, ~~d~~e), thick black lines show the observed Meier et al. (2013) sea-ice edge as the 15% sea-ice concentration isopleth. Hatching indicates regions with statistically significant differences at the 5% level, based on unequal variances t-test.

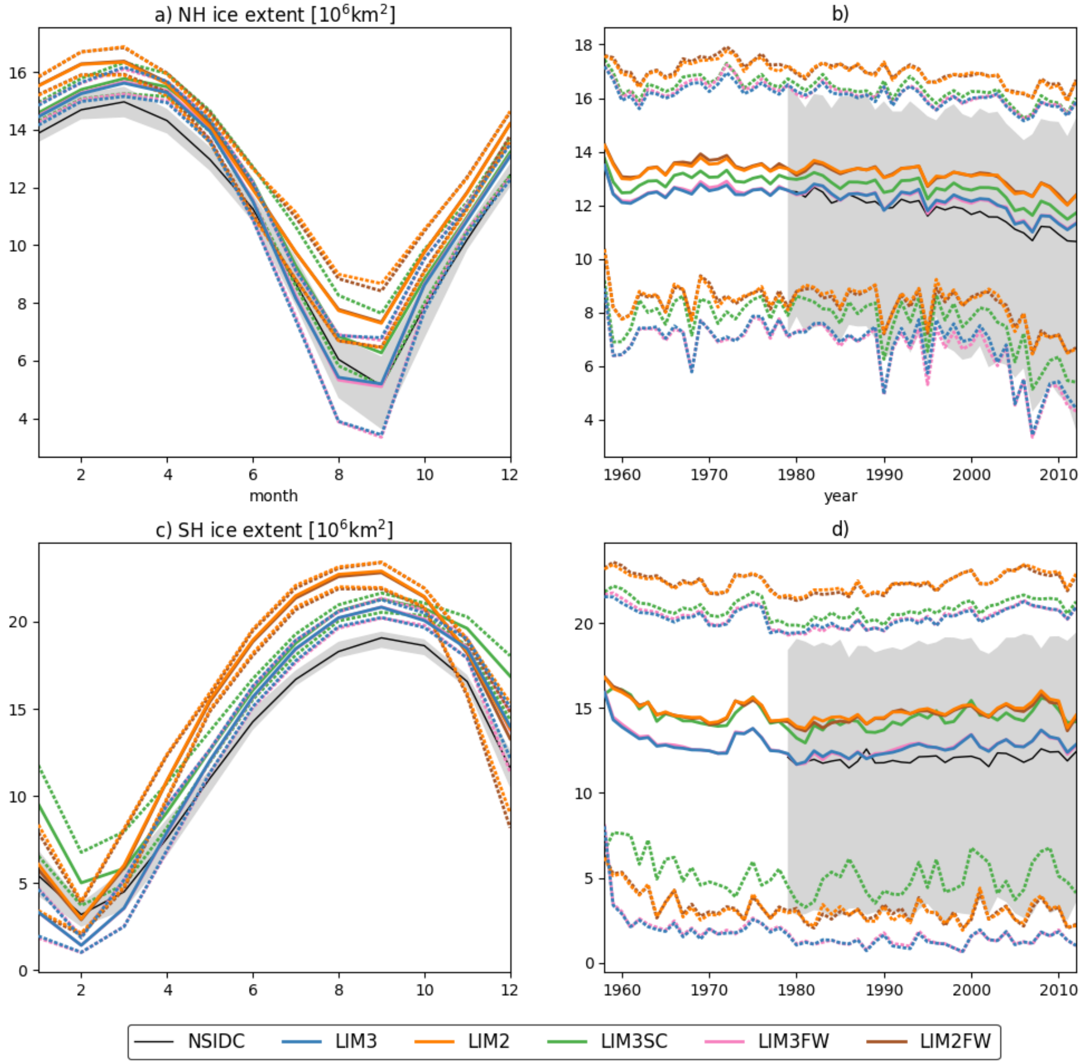

Figure 2. Simulated (coloured lines) and observed (black lines and grey shadings; NSIDC Fetterer et al., 2002) mean seasonal cycle (a, c) of monthly mean sea-ice extent over the period 2003–2012, for the (a) northern (NH) and (c) southern (SH) hemispheres. The sea-ice extent is calculated as the area with sea-ice concentration 15% or more. Dashed lines and grey shadings denote the minimum and maximum annual monthly extents during the same period. In the rightmost panels (b, d), annual maximum, mean and minimum time series of simulated and observed sea-ice extents in (b) the NH and (d) SH over the period of 1958–2012 are presented. LIM3 (~~red~~ blue lines) denote the reference LIM3 simulation, LIM2 (~~green~~ orange lines) denote the reference LIM2 simulation, ~~and LIM3MC~~ LIM3SC (~~blue~~ green lines) denote the LIM3 single-category sea-ice simulation, LIM3FW (magenta lines) denote the LIM3 simulation without the freshwater flux adjustments, and LIM2FW (brown lines) denote the corresponding LIM2 simulation.

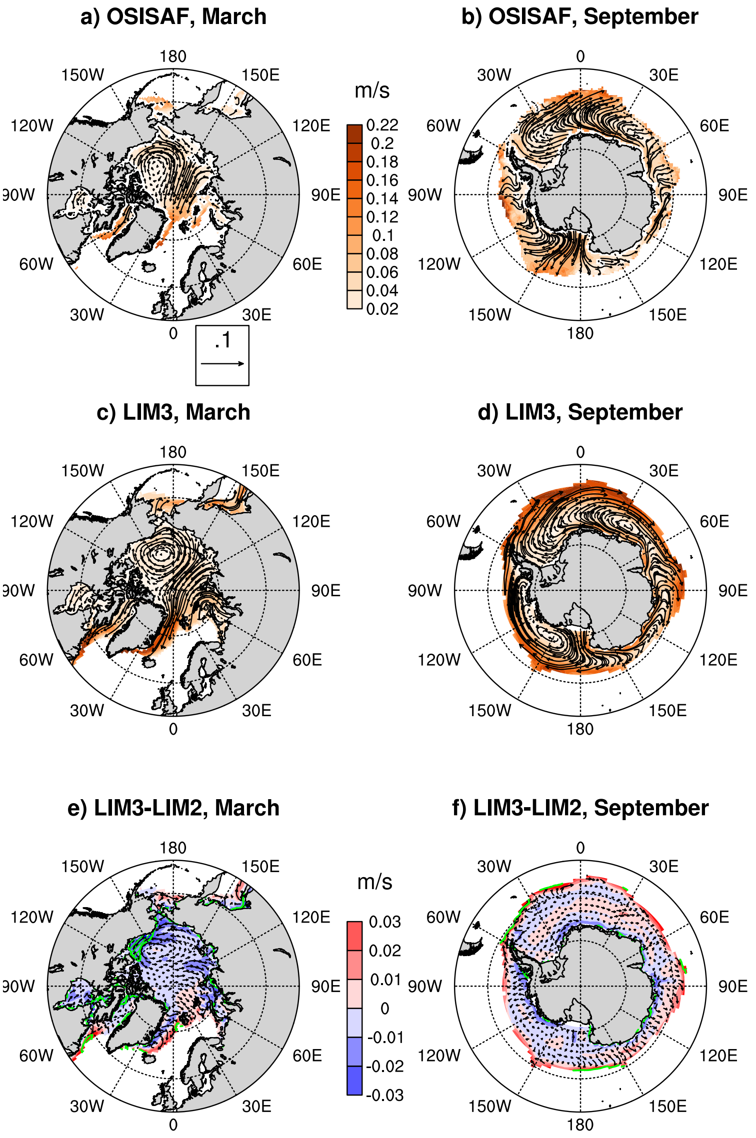

Figure 3. (a) Observed satellite-based average Arctic sea-ice velocity in March (Lavergne et al., 2010) as arrows and the corresponding vector magnitude (speed, $\mathrm{m/s}$) as filled coloured contours based on years 2009–2015. (b) as (a), but for the Antarctic in September and based on years 2013–2015. (c) is similar to (a), and (d) is similar to (b), but for LIM3 ice velocity and speed based on years 2003–2012. In (e), mean differences between LIM3 and LIM2 ice velocity and speed are shown in the NH in March, while (f) displays the corresponding differences in the SH in September. In (e) and (f) green hatched regions show areas with statistically significant differences between LIM3 and LIM2 sea-ice speed at the 5% level based on unequal variances t-test.

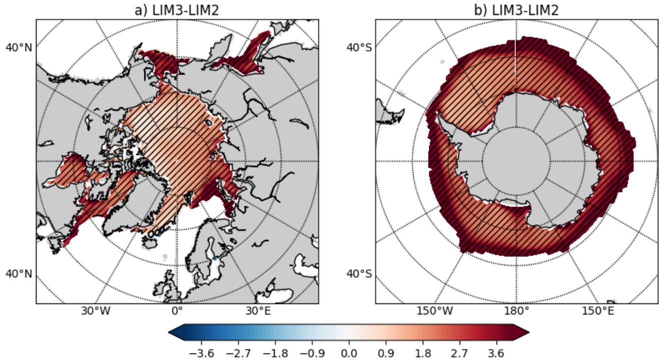

Figure 4. The sea-ice salinity difference (in ppm) between LIM3 and LIM2 (a) in the Arctic in March and (b) in the Antarctic in September. Note that the LIM2 sea-ice salinity is constant 4 ppm. Hatching indicates regions with statistically significant differences between LIM3 and LIM2 at the 5% level based on unequal variances t-test.

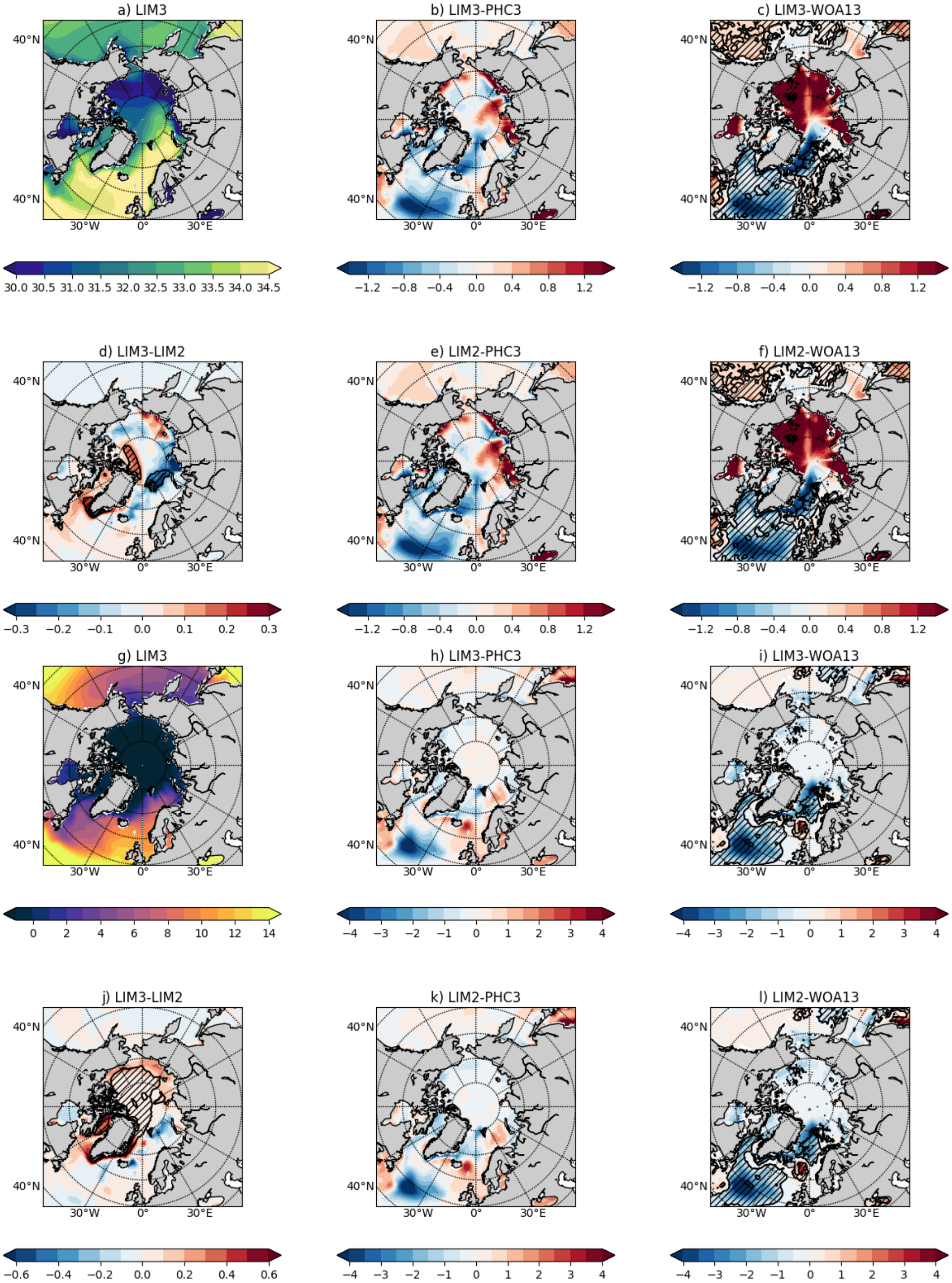

Figure 5. (~~a–d~~a–f) Arctic sea-surface salinity in psu (SSS) and (~~e–h~~g–j) sea-surface temperature in °C (SST) averaged over the period of 2003–2012. (a, ~~e~~g) show the LIM3 averages, (b, ~~f~~h) the difference between PHC3 (Steele et al., 2001) and LIM3, (c, ~~g~~i) the difference between WOA13 (Boyer et al., 2013) and LIM3, (e, f, k, l) the corresponding differences for LIM2, and (d, ~~h~~j) show the ~~difference~~ differences between LIM3 and LIM2. WOA13 data are averaged over the years 2005–2013, while PHC3 data contain observations from 1900–1998, as in WOA98, plus all Arctic observations until 2004. Hatching indicates regions with statistically significant differences at the 5% level based on unequal variances t-test. As PHC3 does not include standard deviation and sample size, the statistical significance levels of LIM–PHC3 differences could not be estimated.

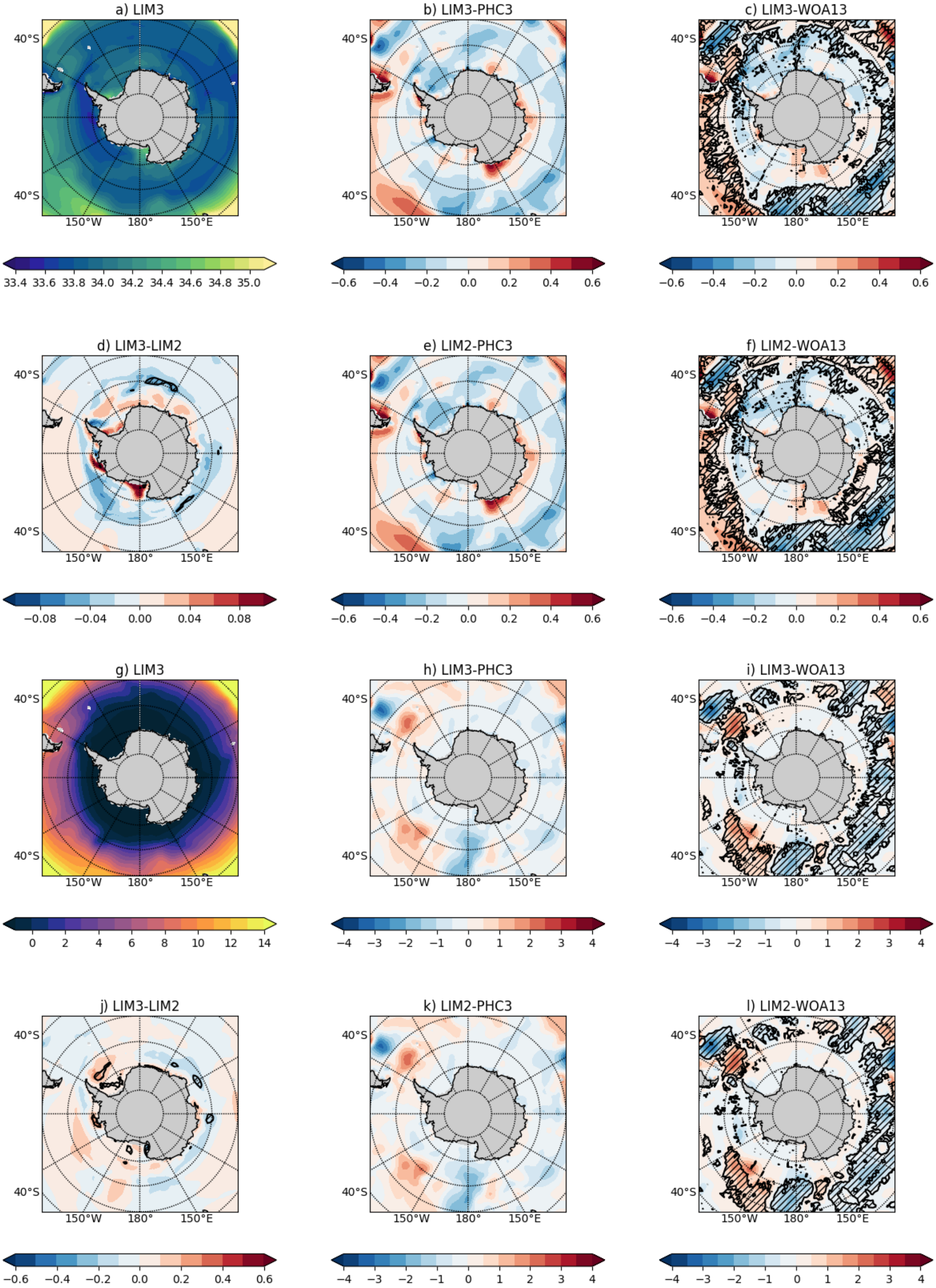

Figure 6. As Figure 5, but for the Southern Hemisphere.

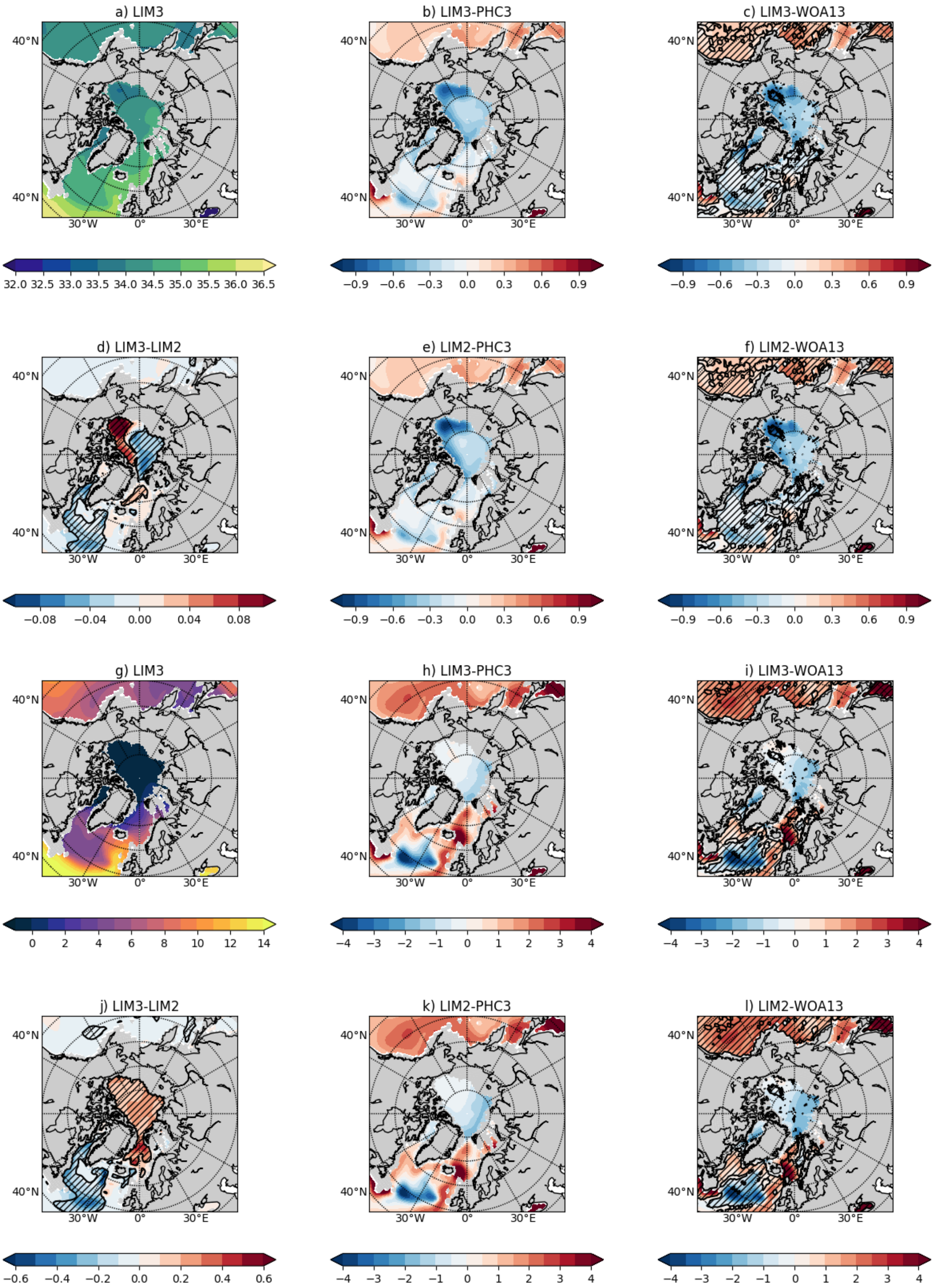

Figure 7. As Figure 5, but for the Arctic ~~Intermediate Water~~ intermediate water (AIW) at 250 m.

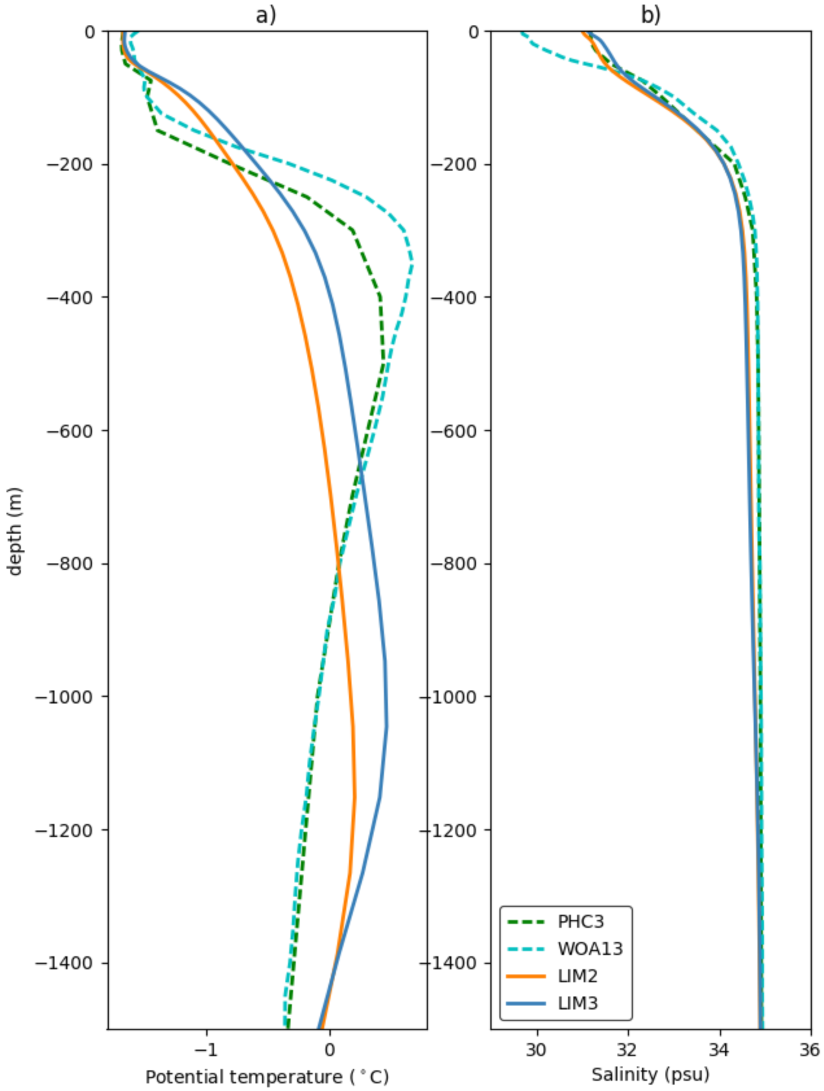

Figure 8. Vertical profiles of (a) potential temperature (°C) and (b) salinity (psu) at a grid point close to the North Pole (85.5°N, 140°W). Green dashed lines are based on the PHC3 climatology by Steele et al. (2001), ~~magenta~~ cyan dashed lines are based on the WOA13 2005–2012 climatology by Boyer et al. (2013), ~~blue~~ orange lines show values from the NEMO-LIM2 simulation and ~~red~~ blue lines from the NEMO-LIM3 simulation. NEMO-LIM profiles are averages over the years 2003–2012. Note that the PHC3 data were used to initialise two NEMO-LIM simulations, after which they largely lost their initially warm Atlantic Intermediate Water.

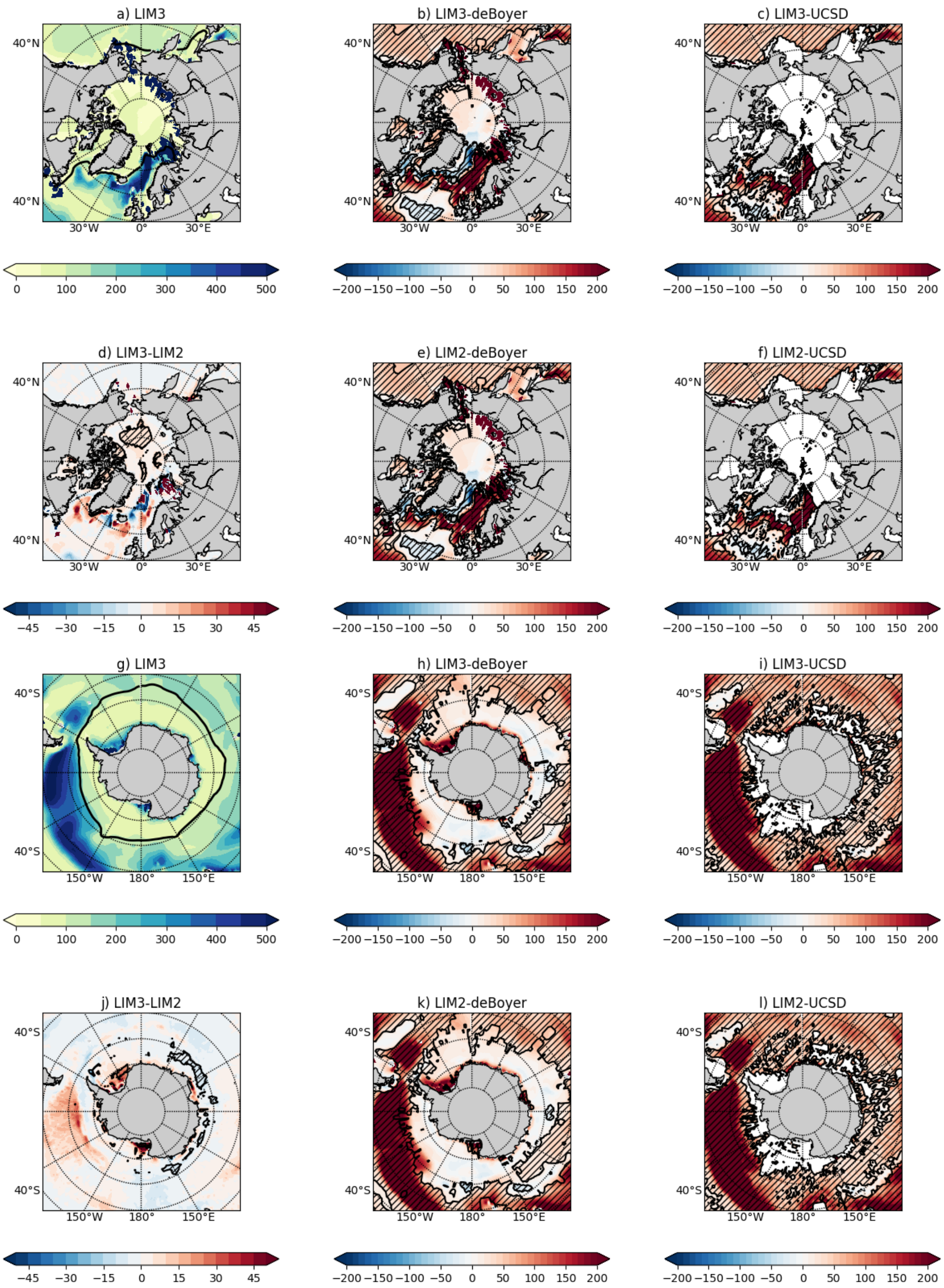

Figure 9. (a, ~~d~~g) mixed layer depths (in metres) as simulated by NEMO-LIM3, their ~~departure~~ departures from the observed ~~climatology~~ climatologies of de Boyer Montégut et al. (2004) (b, h) and Holte et al. (2016) (c, i), the corresponding departures for NEMO-LIM2 (e, f, k, l) and differences between LIM3 and LIM2 (~~e~~d, ~~f~~j). Top two row ~~plots~~ panels (a–f) represent March averages in the Northern Hemisphere (NH) and bottom two row ~~plots~~ panels (g–l) present September averages in the Southern Hemisphere (SH). Monthly averages were calculated from 2003–2012. Mixed layer depths are based on the potential density threshold value difference of 0.03 kg m^{-3} from the density value at 10 m depth. In (a, ~~d~~g), thick black lines show the ~~observed~~ LIM3 sea-ice edge as the 15% ~~isopleth of Meier et al. (2013)~~ sea-ice concentration isopleth. Hatching indicates regions with statistically significant differences at the 5% level based on unequal variances t-test.

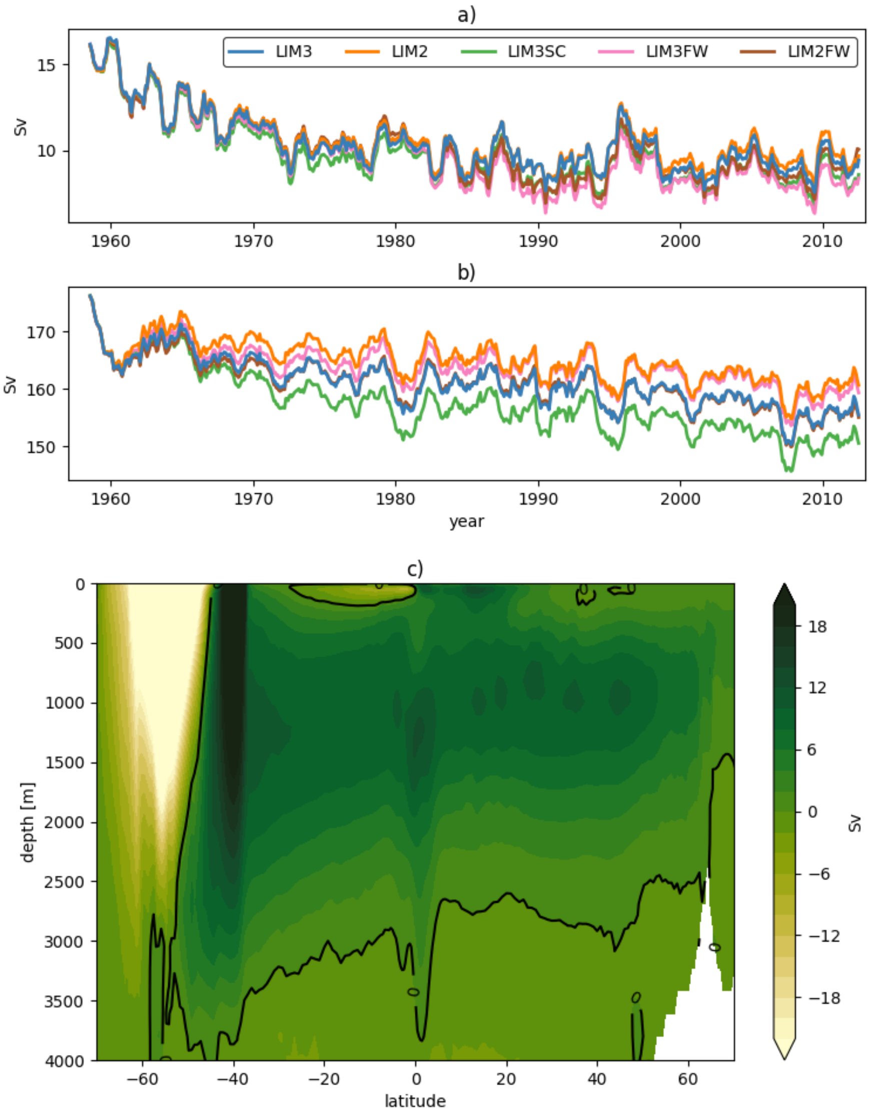

Figure 10. (a) Time series of the Atlantic Meridional Overturning Circulation (AMOC) in Sverdrups (Sv = 10^6 m^3 s^{-1}) for NEMO-LIM3 simulation (~~red~~ blue line)~~and~~ , NEMO-LIM2 simulation (orange line), NEMO-LIM3SC simulation (green line), NEMO-LIM3FW simulation (magenta line) and NEMO-LIM2FW simulation (brown line) integrated zonally across the Atlantic along the 50–53°N latitudinal band. In (b) the corresponding volume transport time series through the Drake Passage are shown. Time series in (a) and (b) represent 12 month running means. In (c), the Atlantic meridional transect of MOC (in Sv) for the NEMO-LIM3 simulation averaged over 2003–2012 as a function of depth and latitude is presented.

Table 1. NEMO3.6-LIM simulations analysed in this study.

#	simulation name	number of sea-ice categories	snow thickness initialisation	sea-ice concentration initialisation	sea-ice strength	sea-ice salinity	sea-surface salinity restoring	freshwater budget correction
1	LIM3	5	0.3 m	90%	2×10^4 Nm^{-1}	prognostic	true	annually
2	LIM2	1	0.5 m in NH, 0.1 m in SH	90% in NH, 95% in SH	1×10^4 Nm^{-1}	constant, 4 ppm	true	annually
Sensitivity experiments:								
3	LIM3SC	1	as in #1	as in #1	as in #1	as in #2	true	none
4	LIM3FW	5	as in #1	as in #1	as in #1	as in #1	false	none
5	LIM2FW	1	as in #2	as in #2	as in #2	as in #2	false	none