Reply to Editor

Interactions between Arctic sea ice drift and strength modelled by NEMO-LIM3.6

Docquier *et al.* (2017), tc-2017-60

We would like to thank the editor Dirk Notz and the two anonymous reviewers for their comments and feedback related to our manuscript. We have answered both reviewers' comments by making a point-by-point response to their input. Please note that the title of our manuscript has been changed based on both reviewers' comments (see our response to the first major point of Referee #2) and that a co-author has been added since he performed the new sensitivity experiments.

Please find below:

- **our answers to the editor's technical corrections in orange**
- **our answers to Referee #1 in blue**
- **our answers to Referee #2 in red**
- a track change version of the manuscript.

Our corresponding corrections in the revised manuscript are marked **in blue** when they refer to **Referee #1**, **in red** for **Referee #2** and **in orange** for other corrections including the editor's technical corrections.

Editor's technical corrections

Thank you very much for submitting your paper to The Cryosphere. As you might know, before the paper is published for online discussion, it is pre-evaluated to ensure that it is within the scope of our journal and that it meets a basic scientific quality. Both clearly is the case for your paper, and I am happy to recommend publication of your study for open review.

However, I note a few issues in the evaluation part of your paper that you might want to address before the paper is made publicly available. As these are minor issues, I only mark them as technical corrections to allow you to address these issues as you feel is suitable:

1. Observational uncertainty of sea-ice concentration products: note that the observational uncertainty is always evaluated during times without melt ponds. During summer, all these products (including OSI-SAF) cannot discriminate melt ponds from open water, giving rise to large uncertainty of total ice cover of more than 20 % in many regions. This might be reflected in your discussion.

This information has been added in the beginning of Section 3.1.

2. Correction of PIOMAS speeds: I was wondering if the correction of the PIOMAS speed to account for their monthly time resolution should be spatially uniform. I would expect that you have large differences between the monthly and daily speeds in areas where there is a lot of back and forth movement (central Arctic, for example), but much smaller differences in areas where the ice is directed into one direction (Fram Strait). I am hence not sure if I fully trust you simple "factor 2"

correction. Could you maybe compare monthly speeds from NEMO-LIM3.6 with PIOMAS output, and calculate a spatially varying correction factor? Or at least show that the correction factor is spatially quite uniform?

Based on both reviewers' remarks, we have decided to remove PIOMAS drift speed from our analysis.

3. Note that sea-ice extent is often much smaller in observational products compared to models because the observational grid resolution is higher. In winter, on average the observed sea-ice extent is 1 million km² below the average extent calculated across CMIP5 model grids. Might be worthwhile to repeat your model evaluation for sea-ice area to account for this issue (see http://www.the-cryosphere.net/8/229/2014/).

We computed sea ice area from the model and OSI SAF satellite observations, added some text in the beginning of Section 3.1 and plotted this quantity in Fig. 3a in the revised manuscript.

Don't worry if you don't feel you have the time to address these issues for the version in open discussion, but these points might at least be worthwhile considering.

Reply to Referee #1

Interactions between Arctic sea ice drift and strength modelled by NEMO-LIM3.6

Docquier *et al.* (2017), tc-2017-60

We would like to thank Referee #1 for his/her very constructive feedback, which has helped us improve the paper quality. Below we present our detailed responses to the comments and suggestions proposed by the reviewer in **blue**. The corresponding corrections are in **blue** in the revised manuscript.

1. Overview and major comments

In this paper, the authors analyse the results from the ice-ocean model NEMO-LIM3.6, forced with atmospheric reanalysis, in order to better understand the drift-strength feedback in the Arctic. Based on previous work the authors propose new metrics and use those, as well as other metrics and diagnostics to evaluate their model against observations and results from the PIOMAS model. They then discuss how their evaluation relates to the drift-strength feedback and do a sensitivity experiment to evaluate how ice strength in their model affects the modelled drift-strength feedback.

It's always nice to see modellers evaluate their model results against data and the authors should be commended for making the effort here. It was also nice to see an evaluation that goes beyond considering just the concentration and extent and I enjoyed seeing that the authors are trying to push for new methods of analysing their model.

My main reservation, though, regarding the paper is the premise of the drift-strength feedback, as presented here. In particular, the authors state that larger sea-ice drift leads to larger exports, but this does not seem to be the case. It is well established that the drift speed of ice in the Arctic is increasing, but at the same time there seems to be no clear increase in (Fram Strait) export. Some studies do find an increase, while others find no increase or a decline in the export. The authors themselves choose (very rightly I think) to cite Döscher et al., which say that there is no significant long-term trend in the area export and a slight decrease in the volume export (p. 2, l. 20 of the manuscript). Thus, we have established increase in the drift speed and no increase in export and we therefore cannot connect the "Drift" and "Export out of Arctic Basin" boxes in figure 1. This puts in question the premise of the paper and some of its contents (though not nearly all).

The reason we don't see an increase in export even if the drift speed increases is that the increase in drift speed is in the synoptic-scale back-and-forth movement of the ice, not the long-term, large-scale drift. This is highlighted by Olason and Notz when concentration is low, but it also seems to be the case when concentration is high. I consider this a major shortcoming of the paper and recommend that the authors re-think and re-structure its contents. There is good material here which, with some re-structuring and extra work can be made into a good paper.

We agree with the reviewer that the drift-strength feedback that we present in our study has not been formally demonstrated by any previous study. Rampal et al. (2011) suggest it might be an important feedback but its existence has never been proved formally. Due to the lack of observational evidence to confirm this feedback, the results we obtain with our sensitivity experiments and the remarks from both reviewers, we decided to change the focus of our article. We now concentrate more on the interactions between sea ice drift speed and strength (concentration and thickness) rather than on the feedback itself. Please see also our response to the first major point of Referee #2.

2. Minor comments

- p. 1 l. 11: You say "We demonstrate that … leading to lower heat conduction fluxes …", but there is no analysis of the fluxes provided. As it is you don't "demonstrate", but "suggest" or "speculate". An actual demonstration of this would be very interesting to see, especially since I don't think this is what's happening. I would think that higher ice strength results in less ridging which then results in less volume. This is the result of Steele et al. (1997), as well as Flato and Hibler (1995) and I tend to think this is what you get as well.

We do not have the model outputs of heat conduction flux for the sensitivity experiments with varying λ. However, we performed new sensitivity experiments in which we vary P* based on the comments from both reviewers, and for these experiments we made sure to compute heat conduction fluxes. The main results are:

- lower P* leads to higher average ice thickness (Fig. 9a in the revised manuscript) and higher ice thickness heterogeneity in space (Fig. 12 in the revised manuscript), which is in agreement with our previous λ experiments
- lower P* leads to lower heat conduction fluxes and lower thermodynamic ice production (Fig. R1 below), which is not in agreement with our initial hypothesis.
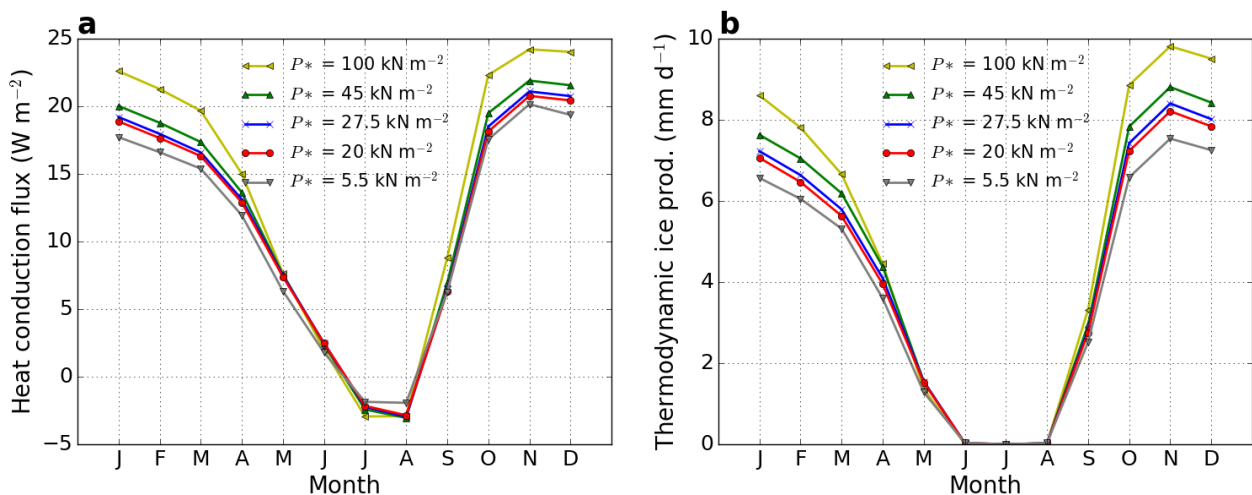

Fig. R1: Modelled (NEMO-LIM3.6) monthly mean seasonal cycles of (a) heat conduction flux at the ice bottom (positive from the ocean to the atmosphere) and (b) thermodynamic ice production temporally averaged over the period 1979-2013 and spatially averaged over the SCICEX box for five different P* values.

Therefore, our initial hypothesis (lower initial ice strength leads to higher sea ice thickness heterogeneity, which results in higher heat conduction flux and higher ice production, hence larger ice thickness) is not the right reasoning that explains why ice thickness is higher with lower initial ice strength. We agree with the reviewer that the process is simpler: lower ice strength leads to higher deformation and more ice piling up (Fig. 11 and Table 2 in the revised manuscript), which results in higher ice thickness. We adapted the manuscript accordingly.

It is important to note that the results obtained by Steele et al. (1997) and Flato and Hibler (1995) arise from a different experimental setup than the one used in our study and do not exactly support the hypothesis that higher ice strength leads to less ridging and less volume, as we discuss now.

In the former study (Steele et al., 1997), the standard value $P^* = 27.5$ kN/m² is used in a sea ice model based on Hibler (1979) with a grid resolution of 40 km. This standard value is decreased and increased by a factor of 5 respectively. In the case of P^* decreased by a factor of 5, the mean ice motion is faster (the ice is nearly in free drift) and the mean wintertime ice thickness is 35% higher than in the standard case. Increasing P^* by a factor of 5 locks sea ice and motion of sea ice ceases, which produces an ice thickness that is essentially determined by equilibrium thermodynamics. In this case, the mean wintertime ice thickness is also slightly higher than in the standard case (by about 6%). A range of further sensitivity experiments performed by Steele et al. (1997) shows that the dependence of mean ice thickness h on P^* is nonlinear (see their Fig. 16), with a sharp decrease of h with increasing P^* for $P^* <= 27.5$ kN/m² and then a slight increase of h with increasing P^* for $P^* > 55$ kN/m². Furthermore, ridging is not mentioned in their study. Therefore, not only the experimental setup of Steele et al. (1997) is different from ours, but also the results show a nonlinearity that we do not find (maybe because our λ values and P^* values were not increased enough). The comparison of these results with our results is now discussed in our revised manuscript (Section 4.1).

In the second study, Flato and Hibler (1995) use a sea ice model based on the thickness distribution theory of Thorndike et al. (1975), which has a resolution of 160 km (which is much lower than the one used in our study), and perform sensitivity experiments by varying different ridging parameters. Since these experiments use a different model and a different experimental setup, we think it is difficult to perform a detailed comparison of their results with ours. But the results of Flato and Hibler (1995) do generally support the idea that more sea ice ridging leads to greater sea ice thickness.

- p. 3 l. 29-32:

* You use $P^* = 20$ kN/m^2. This is quite small. The "canonical" value of Hibler and Walsh is 27.3 and that was using daily forcing. What is the temporal resolution of your forcing? If it's something like every 6 hours then you should be using a larger value than Hibler and Walsh, not smaller. You need a reference for this value.

We agree with the reviewer that the value of $P^* = 20$ kN/m² used here is smaller than the value of $P^* = 27.5$ kN/m² found in Hibler and Walsh (1982), which provides the best agreement between their model and observations in terms of mean drift rates. However, $P^* = 20$ kN/m² is the commonly used value in the NEMO-LIM model and has been chosen via a tuning of mean sea ice

thickness and mean Fram strait ice export (Vancoppenolle, personal communication). It is also the value used in the viscous-plastic models of the Sea Ice Model Intercomparison Project (SIMIP) (Kreyscher et al., 1997) as well as in other modelling studies (Lipscomb et al., 2007; Juricke et al., 2013). Tremblay and Hakakian (2006) find that the most likely value of P* lies in the range 30-45 kN/m² based on satellite observations. Therefore, a wide range of P* values is used in the literature and not a single value is considered as a reference (Feltham, 2008). Since our new sensitivity experiments consider different values of P*, the precise choice of P* is no longer a concern. This information has been added to the revised manuscript (Section 2.1). The temporal resolution of our forcing (DFS5.2) is 6 hours.

* You give no justification for the lambda parameter in equation (1). This is non-standard and requires at least a reference to back it up.

Based on the comments from both reviewers, we performed new sensitivity experiments in which P* is varied. We decided not to show the results of the λ experiments anymore. We only discuss them in Section 4.2.

The main goal of introducing a λ parameter was to test the impact of a change in the strength parameterisation on sea ice drift speed and thickness. Previous studies have performed similar tests by using a square dependence of ice strength on thickness (Overland and Pease, 1988; Häkkinen and Mellor, 1992). Moreover, in the CICE model the ice strength P increases as a proportion of $h^{1.5}$ instead of h in order to improve the physical realism (Lipscomb et al., 2007). According to Leppäranta (2011), the value of λ is an open question (just as P*). Other reasons for choosing λ experiments are also given in response to the second major point of Referee #2.

* Why don't you try different values of P* instead of changing lambda? It is well known to be an extremely uncertain parameter and I'm already suspicious of the value you use.

As said earlier, we performed new sensitivity experiments in which we vary P* based on values found in the literature. We describe these experiments in the revised manuscript (Section 2.1). The chosen values provide an ice strength P range that is comparable to the λ experiments:

- P* = 5.5 kN/m²: lowest value used by Steele et al. (1997) in their model sensitivity study, corresponding to 27.5 kN/m² divided by 5; this experiment is comparable to λ = 0.5 in terms of strength-thickness dependence
- P* = 20 kN/m²: value commonly used in NEMO-LIM3.6 and other modelling studies; experiment comparable to λ = 1
- P* = 27.5 kN/m²: reference value found by Hibler and Walsh (1982)
- P* = 45 kN/m²: highest value of the likely range found by Tremblay and Hakakian (2006) based on satellite sea ice drift observations; experiment comparable to λ = 1.5
- P* = 100 kN/m²: value providing ice strength comparable to λ = 2 and close to the highest value of Steele et al. (1997), i.e. 27.5 x 5 = 137.5 kN/m².

The main result of these experiments is similar to our λ experiments, i.e. ice thickness increases with decreasing P* (Fig. 9a in the revised manuscript, to compare to Fig. 10a in the previous version of the manuscript).

- p. 4 l. 28: You should really calculate the model speed the same way the observation speed is calculated, not calculate a one-day average from a two-day observation. But the effect here is probably very small.

We also computed the modelled sea ice drift speed the same way OSI SAF observations provide drift speed (i.e. two-day average) but did not find any significant difference compared to our method. Moreover, since we mainly compare our modelled drift speed to IABP buoy data, for which the temporal coverage and resolution are higher than OSI SAF, we prefer keeping the daily temporal resolution. This information has been added in the revised manuscript.

- p. 4 l. 29: PIOMAS is a model, not observations, and I would like to ask you to please not treat it as observations. It has plenty of shortcomings and uncertainties all on its own.

We agree with the reviewer that PIOMAS is not observations and we do not aim to treat it as such. The title of Section 2.2 ('Observations') is probably misleading since we include a brief description of PIOMAS into this section: the goal is more to put all data against which we evaluate our model in the same section rather than providing observations strictly speaking. We renamed Section 2.2 as 'Reference products'.

We also agree that PIOMAS has shortcomings and uncertainties. We now also use ULS submarine observations for sea ice thickness (the multiple regression model of Rothrock et al. [2008]) as well as the merged product of Tschudi et al. (2016) for sea ice drift speed. The manuscript has been revised accordingly.

However, observations also have uncertainties and suffer from sparse temporal and spatial coverage, especially for sea ice thickness (Stroeve et al., 2014; Zygmuntowska et al., 2014; Lindsay and Schweiger, 2015). Upward-looking sonar (ULS) measurements cover the period 1979-2005 but have incomplete spatial coverage and limited records for each year. Airborne (e.g. IceBridge) and satellite (e.g. ICESat, CryoSat) measurements only cover the recent period with very short temporal coverage for ICESat and limited spatial coverage for IceBridge. Lindsay and Schweiger (2015) conclude that 'more research to understand, characterize, and correct these errors [in sea ice thickness measurements] is clearly required before we can homogenize the observational ice thickness record'.

Furthermore, Schweiger et al. (2011) find that PIOMAS ice thickness estimates agree well with ICESat observations in the area for which submarine data are available, i.e. the SCICEX box. Therefore, we think PIOMAS still represents a valuable tool against which we can compare our modelled sea ice thickness since we use the SCICEX box in our study and due to the high spatial and temporal coverage of PIOMAS. We have however tempered our statements to reflect the uncertainty of PIOMAS.

Given the uncertainties of both observational products and PIOMAS, using all of the products together allows us to obtain a range of 'reference values' that is more reliable than the range based on observational products alone.

For drift speed, since we now include the merged product from Tschudi et al. (2016) and due to the temporal resolution of PIOMAS sea ice velocity vectors (monthly), we decided to remove PIOMAS drift speed from our analysis.

- p. 5 l. 20: I guess the paragraph on p. 4 l. 29 belongs here. Just keep in mind that even though Schweiger et al. (2011) is a very nice paper, then PIOMAS is not the truth. I would ask you to reduce considerably your reliance on PIOMAS in this study and try to compare to actual observations instead, as flawed as they may be. You also haven't considered the Rothrock et al. (2008) multiple regression model, which is well worth taking into account here.

Based on the comments from both reviewers regarding PIOMAS, we now use ULS submarine ice thickness observations as well as the drift speed merged product of Tschudi et al. (2016) in our study, and we removed PIOMAS drift speed. Please see our response to the previous comment related to the criticism of PIOMAS.

- p. 6 l. 6: This is not the right reasoning for choosing daily time scales. With daily time scales you capture synoptic-scale variability, but with monthly time scales you average these out and capture the longer-term, large-scale drift.

We rephrased according to the reviewer's suggestion.

- p. 6 l. 8: Given my comment above it should be clear that you cannot use the monthly values from PIOMAS in this way. They contain different physics and you can't just scale with factor two!

We decided to remove PIOMAS drift speed from our analysis due to the error linked to this scaling and the poor results obtained with this reanalysis in terms of drift speed.

According to our results with NEMO-LIM3.6, the scaling between monthly sea ice drift speed derived from daily components of velocity and the one derived from monthly components is two (Fig. 2 in the revised manuscript). A recent study focussing on Arctic sea ice drift speed using 22 CMIP5 models shows that this factor 2 is valid for all the models (Tandon et al., submitted). Therefore, we think that it is a good approximation, even if we agree that there is an uncertainty linked to this scaling.

- p. 6 l. 21: From here on out this section becomes increasingly hard to understand. I had to re-read and then re-read again to completely understand which metrics and diagnostics you use. It's all there, but you're making your reader work way too hard to get the point. Please rewrite and try to make it clearer and better organised.

We re-organised this part of the text to make it clearer.

- p. 6 l. 28: The novelty here is really that you use this method as a way to evaluate your model.

We removed this sentence after the re-organisation made in response to the previous comment.

- p. 6 l. 29: You don't normalise with wind friction speed, but Olason and Notz (2014) say they do this to take atmospheric stability into account. It is interesting that you find that this is not necessary, it is not what they find. However, I don't understand why you don't normalise with the 10 m wind speed at least, since we know there should be a close correlation between drift speed and wind speed. My main concern, however, is that your figure 9b gives a completely different shape for the curve than figure 6 from Olason and Notz (2014). Why is that?

When normalising sea ice drift speed by wind friction speed (Fig. R2 below), we obtain very similar drift-concentration and drift-thickness relationships compared to these relationships without normalisation (compare Fig. R2 below to Fig. 8a-b in the revised manuscript). That is why we decide not to normalise. We think it is easier to interpret (physically speaking) direct data instead of normalised data. Please see also our response to the specific comment of Referee #2 (page 9, line 16-17).
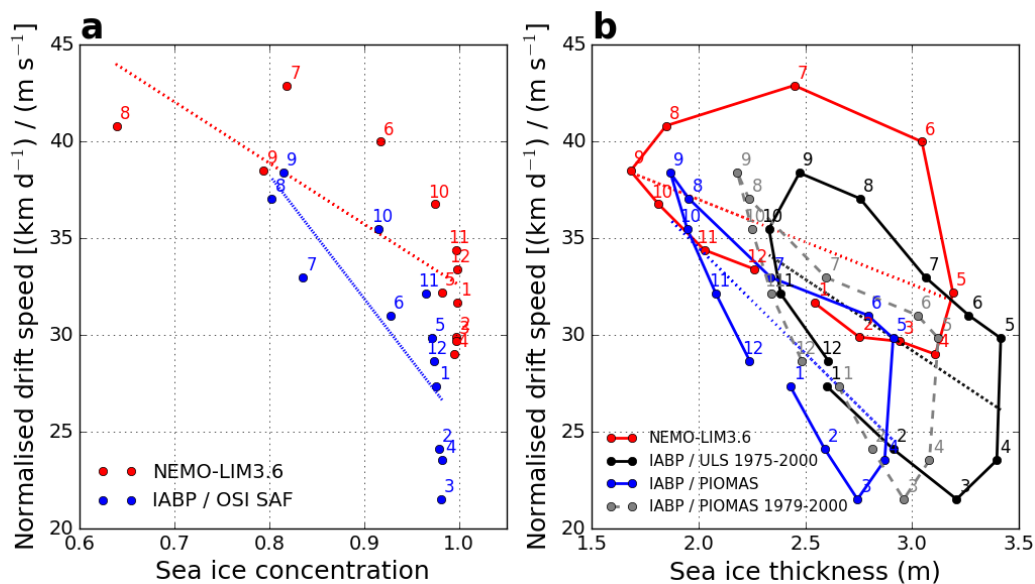

Fig. R2: Scatter plots of modelled (NEMO-LIM3.6) and observed monthly mean normalised sea ice drift speed against (a) concentration and (b) thickness spatially averaged over the SCICEX box and temporally averaged over the period 1979-2013 (except when stipulated in the legend). Drift speed is normalised by wind friction speed (derived from DFS5.2) as in Olason and Notz (2014).

We do not think we obtain a completely different shape for the observed drift-thickness relationship compared to Olason and Notz (2014). Please see Fig. R2b above, where our black curve (IABP/ULS) is very similar to the blue curve of Fig. 6b in Olason and Notz (2014). Our blue curve (IABP/PIOMAS) in Fig. R2b shows thinner ice compared to the red curve of Fig. 6b in Olason and Notz (2014) but we think that is mainly due to the period used, i.e. 1979-2013 in our study and probably 1979-2000 in Olason and Notz (2014) in order to compare to ULS observations. We demonstrate this effect of the period by also plotting sea ice thickness from PIOMAS averaged over 1979-2000 (see gray dashed curve in Fig. R2b): the resulting curve is much closer to the red curve of Fig. 6b in Olason and Notz (2014). The remaining differences probably arise from the slightly different period: Olason and Notz (2014) do not say over which period they compute the mean seasonal cycle in their Fig. 6b.

- p. 7 l. 9: These are probably good metrics you've developed, but you don't use them enough and you don't discuss them enough to make me want to use them too.

We make use of these metrics in Sections 3.2 and 3.3 as well as in Figs. 8 and 13 in the revised manuscript. We also discuss the use of process-based metrics in the framework of a model intercomparison in Section 4.4.

- p. 7 l. 15: Mention (again) the period you average over.

Done.

- p. 7 l. 16: What are the (main) differences between your set up and Rousset's et al. (2015)? If it's just the resolution then remind the reader which resolution you use.

The resolution is different (1° for our study and 2° for Rousset et al. [2015]) as well as the atmospheric forcing (DFS5.2 for our study and CORE normal year for Rousset et al. [2015]). We added this detail in the text.

- p. 7 l. 27 (all paragraph): I'm concerned that you rely too much on comparison with PIOMAS. Again, it's only a model so you should try hard(er) to compare to observations before resorting to comparing with PIOMAS.

We considered the remarks from both reviewers by using other observational datasets. Please see our response to the comment 'p. 4 l. 29'. Furthermore, we also compare the modelled sea ice thickness to ICESat in this paragraph. However, as explained before, the temporal coverage of the latter dataset is very limited (2003-2008) and the measurements suffer from uncertainties.

- p. 8 l. 6 (the paragraph and this section in general) You jump a lot between the SCICEX box and your "wider domain" and I'm having trouble keeping up. Try to decide which is more important, stick to it and mention the other one only when necessary.

We removed all results related to the wider domain from Section 3 (Results) and synthesised this information in Section 4.3 (Impact of domain choice) to make it less confusing.

- p.8 l. 26: What conclusion should I draw from this paragraph? Is the trend significant or a post-processing glitch?

We rephrased to make it clearer. The main conclusions are that modelled trends are good for sea ice concentration and thickness, are less good for sea ice extent (model underestimation, especially in winter) and do not capture the observed positive summer trends in drift speed provided by IABP buoys.

- p. 10 l. 6: You need a justification for using lambda and not tuning P*

We now use P* experiments. Please see our response to a previous comment (p. 3 l. 29-32).

- p. 10 l. 14: It's not counter-intuitive to me, as I mentioned earlier when commenting on the abstract.

We removed this sentence following our results explained above (comment p. 1 l. 11).

- p. 10 l. 25: It's not really a hysteresis loop. Physically the drift speed depends on ice thickness only when the concentration is high, so the change in drift speed only relates to the change in thickness in winter.

We think it is a hysteresis loop in the sense that for a given sea ice thickness, two different drift speed values are found for a given thickness depending on the season (summer vs. winter). As we show in Fig. 8b in the revised manuscript, drift speed does not only depend on thickness when concentration is high (October to March) but also when concentration is low (May to September).

- p. 11 l. 2: Your heat-flux theory contradicts the results of Steel et al. and Flato and Hibler. You need to show that it's true by actually showing the ocean-atmosphere heat flux and analysing that.

We found that our 'heat-flux theory' was not confirmed by the results obtained with the P* experiments (see our response to comment p. 1 l. 11). The manuscript has been revised accordingly.

- p. 11 l. 22: It's only a physical correlation in winter. See my comment for p. 10 l. 25

We do not have enough arguments to make such a statement (only physical correlation in winter). What we observe when we plot drift speed against thickness is an anti-correlation between both variables in both summer and winter. This does not infer causality.

- p. 11 l. 28: I don't know what you mean by "large-scale effects"

This has been removed.

- p. 13 l. 16: I can draw no concrete conclusions from this sub-section

This has been revised. Please see also our response to a previous comment (p. 8 l. 6).

- Figures 5, 6, 8, and 12: These figures are very small and hard to read. It would be better if they focused on the central Arctic. I don't think you would lose much information doing that. Figure 6 is particularly hard to read and I can't see the directions of the vectors at all. It would also be nicer to have the magnitude and direction of the difference, rather than the way it's done now.

Done.

<div align="center">

Reply to Referee #2

Interactions between Arctic sea ice drift and strength modelled by NEMO-LIM3.6

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We would like to thank Referee #2 for his/her very constructive feedback, which has helped us improve the paper quality. Below we present our detailed responses to the comments and suggestions proposed by the reviewer in **red**. The corresponding corrections are in **red** in the revised manuscript.

1. Summary

The authors conducted ocean-sea ice model NEMO-LIM3.6 numerical experiments to investigate interaction and/or feedback mechanisms between sea ice drift speed and ice strength, focusing on the Arctic Ocean. As measures of ice strength, the authors employ ice concentration and thickness, and then examined relation between ice drift speed and them. In order to assess the model performance, sea ice observation data derived from satellite and ice-tethered buoys (ice concentration, ice drift speed and ice thickness) were exploited. The authors introduced a systematic model validation method based on sea ice diagnostics (ice extent, ice concentration, ice thickness and ice drift speed) as well as process-based diagnostics (relation between different ice properties, e.g., ice drift speed and concentration). They also introduced metrics which quantify modeled or observed ice dynamics as scalar variables. Using these diagnostic and metric approaches, the author assessed model performance, and then conducted sensitivity experiments varying ice strength parameter to see the effect of ice strength change on the relation between drift speed and ice concentration (or ice thickness) simulated in the model.

2. General comments

The authors provided a good review regarding relation between ice drift speed and ice concentration (and thickness) in the Arctic Ocean, mainly focusing on observational studies. The diagnostics and metrics used to validate model performance and the thorough assessments on the simulated ice properties are very helpful to assess the capability and limitation of the model, although I have an additional suggestion regarding ice thickness evaluation (see comments below). The results of the sensitivity experiment, in which ice strength parameterization is changed, are interesting to me (and probably informative to many sea ice modellers), while the whole strategy used to assess the feedback between ice drift and other ice properties seems to me not always suitable nor convincing for the purpose of the study. As far as I know, "feedback" is a term originally introduced to describe an electric circuit which has a recursive input, and is widely used in other study area to explain similar concept. Also in geo-scientific studies, the term "feedback" is widely used to explain a recursive interaction between different processes or subsequent chain of phenomena, sometimes without clear definition nor quantification. Although the authors invoked the term "feedback", the strategy does not seem to be designed so as to extract a feedback mechanism from a complicated system. For this reason, I would recommend to change the focus of the study to more specific issues (e.g.,

sensitivity of ice strength parameterization to ice drift, concentration and thickness) or to reorganize experiment design so as to quantify the feedback between them. Even without feedback issue, the manuscript contains interesting model results.

We thank the reviewer for his comments. Since his point related to the feedback methodology is related to the first major point below, we provide our answer there.

3. Major points

1) The strategy used to extract (and quantify) the drift-strength feedback is not always suitable nor convincing. I think more consideration is necessary about how to quantify a "feedback". Since ice drift, concentration and thickness are described by a set of simultaneous partial differential equations in numerical models, it is a matter of course that there is some sort of 'feedback' between them. An important point is how to extract and quantify a feedback in a simple formula so as to abstract the essence of the complicated system. Mathematically, a feedback between two variables (most simple case) can be described by a set of equations,

$$\frac{d\overline{|V|}}{dt} = F(\overline{T}) \qquad (1)$$

$$\frac{d\overline{T}}{dt} = G(\overline{|V|}) \qquad (2)$$

where |V| and T are respectively mean ice drift velocity and ice strength (or thickness) in the present case (e.g., |V|= 1/TS ∬ |V|dxdydt , T: one month or one year period, S: SCICEX box). F and G are the functions describing a feedback. The equations mean that the temporal evolution of mean ice drift is controlled (or affected) by mean ice strength, while at the same time, the evolution of ice strength is also controlled by drift speed. The most simple solution is an exponential formula, $Ce^{\alpha t}$, and then temporal evolution of |V| and T depends on α. The system has a positive feedback if α > 0, while a negative feedback if α < 0. If the authors intend to clarify and quantify the feedback mechanism between ice drift and thickness, a definite formula (not necessarily means complicated formula) in such a simple theoretical framework should be provided. Otherwise, we cannot learn anything about the quantitative features of the feedback between ice drift and thickness (or concentration) at all. Note that the system also needs a higher order stabilizing term to prevent exponential growth of a positive feedback. (At least discussion for such a damping mechanism is necessary.)

We agree with the reviewer that our study probably lacks a robust mathematical framework to quantify the sea ice drift-strength feedback. Due to the complexity of this feedback (see sensitivity experiments) and the lack of observations confirming the existence of this feedback in real life (see main reservation of Referee #1), we decided to change the focus of this study by analysing the interactions between sea ice drift and strength (concentration and thickness) rather than the feedback itself. The main results stay similar but the wording is now slightly different in the revised manuscript: we talk more about interactions between drift speed and strength and about the impact of changes in strength parameterisation on the resulting drift speed and thickness, rather than about the feedback itself. We also changed the article title accordingly.

2) The design of the sensitivity experiment seems to me not suitable for examining the effect of ice strength change on ice drift, ice thickness and concentration. Since the authors change the ice strength, P, by changing exponent of ice thickness h, the associated change of ice strength has an opposite sign between h > 1 and h < 1. This is easily confirmed by calculating P value for different λ used in the sensitivity experiment: if h > 1, P λ=2 is larger than P λ=1 , while P λ=2 is smaller than P λ=1 if h < 1 (this is also confirmed by closely looking Fig. 2). Due to this experiment design, we cannot directly relate the change of parameter λ to the change of ice strength and therefore, to changes of the ice thickness and ice concentration, which makes interpretation of the results complicated and difficult (There are many misinterpretation in sec. 3.3 due to this fact, see the specific points below). Generally speaking, changing exponent of h in the ice strength equation is not equivalent to changing ice strength, but to changing sensitivity of ice strength to h. My recommendation is to use more simple formula for the sensitivity experiment (e.g., P = P* λh exp[-C (1 - A)] , which is equivalent to change P*), or to redo analyses based on the actual ice strength P used in the model (i.e., calculate P= 1/TS ∬ P(x , y , t) dxdydt and examine relation between P and modeled ice properties; ice drift, ice concentration and thickness).

We agree with the reviewer that an increase (decrease) in λ for thickness h < 1 m leads to smaller (higher) ice strength P. Due to this problem and the remarks of both reviewers regarding the design of our sensitivity experiments, we performed new sensitivity experiments in which we change the P* parameter according to values found in the literature. The chosen P* values are described in our response to Referee #1 (see his minor comment p. 3 l. 29-32) and a detailed explanation of the P* experiments has been added to the manuscript (Section 2.1). Results are presented in Section 3.3 and lead to the same conclusions as for λ experiments, i.e. a higher (smaller) initial ice strength, caused by higher (smaller) P*, leads to lower (higher) sea ice thickness.

In the revised manuscript, we decided not to show the results from λ experiments but we discuss them in Section 4.2 as they are still interesting for several reasons:

   a. **Some sea ice models use P scaling as h[1.5] (e.g. Lipscomb et al., 2007) since it is more physically realistic than P scaling as h (but less numerically stable); therefore it makes sense to test the sensitivity of the model to different λ values.**
   b. **Even if it is true that P decreases with increasing λ for h < 1 m, the differences in P between the four different experiments for h < 1 m are very small; these differences become more important for h > 2 m as shown in Fig. 2 in the previous version of the manuscript; moreover, the mean ice thickness averaged over the SCICEX box (the quantity we use in our study) is always higher than 1 m, even in September when ice is the thinnest (Fig. 10a in the previous version of the manuscript).**
   c. **These experiments are original (most modelling studies change P*) and this is the first time that four λ values are used (the existing studies only look at λ = 1 and λ = 2).**
   d. **The λ experiments are more complex than the P* experiments (due to their exponential nature), but they confirm the results obtained with the latter experiments.**
   e. **Leppäranta (2011) states that the value of λ is an open question.**

3) I admire the systematic approach used in this study to assess the model performance using observational data, whereas I have a concern about the use of ice drift and thickness data derived from PIOMAS, instead of direct observations. The authors did not utilize two important dataset for ice drift and thickness, which have sufficient spatial and temporal coverage for the present study. One is ice drift data provided from Colorado University group (Tschudi et al., 2016), the other is the long-term ice thickness estimate by Lindsay and Schweiger (2016). Both estimates provide error of the estimates as well. Since these data were derived from in-situ and satellite measurements while PIOMAS did not assimilate ice drift and thickness, I recommend to use these two data instead of PIOMAS simulation. Note that the bias (or error) of ice drift field in Tschudi et al. (2016) reported by Szanyi et al. (2016) is a crucial issue, only if the data is used for divergence/convergence calculation. Since the divergence/convergence features reported by Szanyi et al. (2016) always appear as a divergence/convergence pair around buoy-data merged location, a spatial averaging (e.g., SCICEX box) can eliminate the error.

Following the remarks related to PIOMAS from both reviewers, we now use the multiple regression model from Rothrock et al. (2008) based on ULS submarine ice draft measurements to derive sea ice thickness. These data constitute the longest record in terms of sea ice thickness (1975-2000), they cover the SCICEX box that we mainly use in our study and they are integrated into the Lindsay and Schweiger (2015) dataset.

For the observed drift speed, we now include the NSIDC merged dataset from Tschudi et al. (2016), which includes IABP buoy data. We call this dataset 'NSIDC' throughout the paper. However, we are a bit skeptical about the mean seasonal cycle derived from these data (Fig. 3d in the revised manuscript), which gives drift speed values up to 4 km/d lower than the IABP buoy drift speed values. The amplitude of the seasonal cycle of the merged product is also much lower than the one from the buoy data. These features were already noticed by Olason and Notz (2014) who used the previous version of the NSIDC merged product (Fowler et al., 2013) (see their Fig. 10).

Please note that we already use IABP buoy data from the Tschudi et al. (2016) dataset as well as OSI SAF data for drift speed, and ICESat for ice thickness. We decided to remove PIOMAS drift speed from our analysis due to the poor results associated with this reanalysis for drift speed as well as the scaling problem (factor 2).

4. Specific points / additional comments

- Page 2, line 1-8: I would suggest the author to use the term 'feedback' more carefully, particularly when mentioning 'positive feedback'. Since a positive feedback has an exponential growth feature by its definition, it always needs damping or stabilizing mechanism in higher order, when the concept is used to explain things occurring in the nature.

Please see our response to the first major point above.

- Page 2, line 9-22: I appreciate the good summary of the former studies here, which is useful to survey the current status of our understanding on this issue. On the other hand, I am a little bit skeptical to provide conceptual illustration like Fig. 1, since such an illustration sometimes goes out of authors' control if once published, even if each arrow in the figure is not really examined.

We removed the diagram (Fig. 1 in the previous version of the manuscript) due to our decision not to focus on the feedback but rather on interactions (see our response to the first major point).

- Page 3, line 29-30: Why the authors conducted the sensitivity experiment by changing exponent of h in the ice strength equation, instead of changing P* or C? If the authors intend to increase ice strength in the entire h range, changing P* seems to be more suitable approach (as many modellers do). I request more explanation.

As mentioned in our response to the second major point, we ran new P* experiments and we decided not to show results from λ experiments (but we discuss them in Section 4.2). Finally, we had already carried out experiments by varying C between 16 and 22, but we found negligible differences in sea ice thickness and drift speed, so we decided not to include them in our study.

- Page 4, line 1-7: Since we cannot directly relate the increase of λ to increase of ice strength in the present experiment design, more careful explanation is needed. For example, ice thickness during the summer season in the SCICEX box may thinner than 1 m, at least part of the area. In this case, an increase of λ leads to decrease of ice strength.

Please see our response to the second major point above.

- Page 4, line 26-34: Why the authors did apply ice drift data provided from PIOMAS instead of satellite- and buoy-based data as a long-term ice drift observation? Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors (Tschudi et al., 2016, now version 3 is available via NSIDC website) provides Arctic-wide long time series from 1979 to present. Although PIOMAS reasonably reproduced sea ice extent and ice concentration field as a result of ice concentration assimilation, there is no reason to believe that ice drift and thickness from PIOMAS are consistent with observation, since these variables are not assimilated. I think the ice drift data from PIOMAS should be dealt with a great care (Since PIOMAS applies strong constraint on ice concentration by an optimal interpolation, the simulated ice field never breaks down, even if ice drift is totally unrealistic). Use of Polar Pathfinder data is much more reliable approach, since the uncertainty of the estimates are also provided. The problem of the Polar Pathfinder data reported by Szanyi et al. (2016) is not a critical issue for the present application (see my major point as well).

We removed PIOMAS drift speed from our analysis and now use the NSIDC dataset from Tschudi et al. (2016).

- Page 5, line 20-24: For long-term ice thickness estimates in the Arctic Ocean, I strongly recommend to use the estimate presented in Lindsay and Schweiger [2015]. They provided an empirical function describing the spatially and temporally varying ice thickness field over the Arctic Ocean, by exploiting all available in-situ and satellite measurements of ice thickness. As far as I know this is the most reliable long-term estimate of ice thickness field based on measurement for the time being (One can calculate seasonally varying long-term ice thickness field by the description in Lindsay and Schweiger).

We are aware of the sea ice thickness dataset from Lindsay and Schweiger (2015). However, we decided to use only one source of data, namely ULS submarines, due to the fact that these data cover the SCICEX box (which we use as a region of interest in our study) with sufficient accuracy.

- Page 6, line 1-4: How did the authors define the daily ice drift in Eq. (2)?

$$u_d = \frac{1}{T_{day}} \int_{t_1}^{t_2} v(t)\,dt$$ (i.e., temporal average of instant velocity in x and y direction)

or $$u_d = \frac{|x_{t_2} - x_{t_1}|}{T_{day}}$$ (zonal or meridional displacement for 24 hours)?

The definition of satellite- or buoy-derived ice drift is the latter. I don't think the difference between the two definitions is large, but it would be nice if the authors clarify their definition for comparison with other model results.

For our model, daily mean ice drift speed is defined by Eq. (2), where u_d and v_d are daily <u>mean</u> ice velocity components. We articulate this in the revised manuscript. u_d and v_d are computed in the model by averaging values over the 8 model time steps covering each day, i.e. following the first equation mentioned by the reviewer above.

- Page 7, line 27-30, Page 8, line 1-5: I think the comparison with PIOMAS thickness data provides useful insights, while I am skeptical to regard PIOMAS thickness data as substitution for observation, since we cannot distinguish bias or error of the estimates, which are always provided for observational data.

We added observations from ULS submarines. However, we also think that PIOMAS is useful since its thickness is realistic compared to observations (Schweiger et al., 2011) and due to high uncertainties related to ice thickness observations. Please also see our response to the third major point above as well as our response to the comment 'p. 4 l. 29' of Referee #1.

- Page 8, line 1: Do the authors have an explanation why the peak shifts?

Modelled sea ice thickness averaged over the SCICEX box and over the domain north of 50°N is shown below (Fig. S1 below). As shown, the SCICEX maximum occurs in May while the 50°N maximum occurs in June with a second peak in August. We do not have an explanation for this shift. However, the 50°N is a very large domain that takes into account coastal areas, so we are a bit skeptical of the representativeness of the 50°N seasonal cycle.
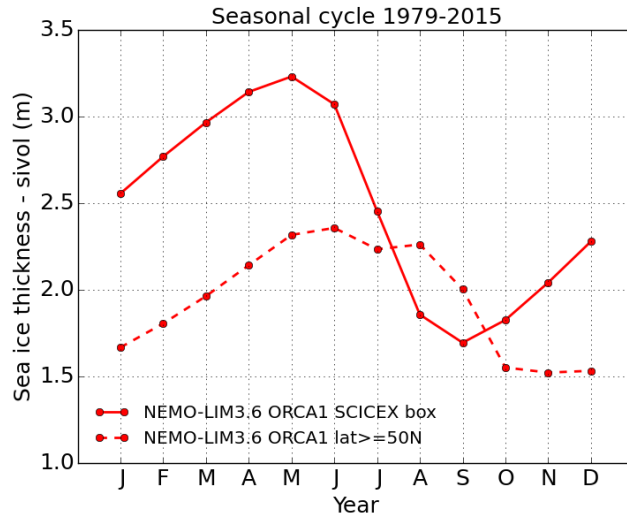
Fig. S1: Modelled (NEMO-LIM3.6) monthly mean seasonal cycle of Arctic sea ice thickness (sea ice volume per area) temporally averaged over the period 1979-2013 for two different domains (solid line: SCICEX box; dashed line: north of 50°N with A >= 0.15).

- Page 8, line 23-24: How the IABP ice drift data were processed to calculate spatial (and temporal) average over the SCICEX box? Since the spatial coverage of the buoy data is not sufficient, one needs to interpolate/extrapolate the data. How did the author define influential radius of the buoy data? How much uncertainty should we expect from the interpolation/extrapolation process? Since the IABP data averaged over the SCICEX box is an important measure to validate the model, a description is necessary.

For IABP drift speed data, we first computed daily spatial means by taking all buoys within the SCICEX box. Then, we computed monthly means from these results. By doing so, we do not need to interpolate / extrapolate and there is no error due to the spatial sampling. The spatial coverage of buoy data within the SCICEX box is fairly good (Fig. S2 below, coming from Rampal et al. [2016], Fig. 2). However, we acknowledge that comparing buoy and model drift speed has to be done with caution, as buoys measure the drift speed at one particular location while the model is meant to give the grid-cell average. This information has been added in the manuscript (Section 2.3).
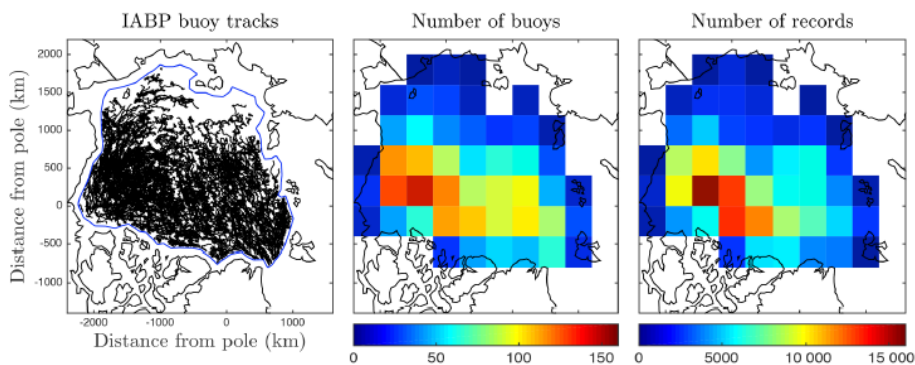

Fig. S2: Buoy tracks from the IABP dataset for the winter periods 1979–2011 (left panel) and the corresponding number of buoys (middle panel) and records (right panel). Source: Fig. 2 from Rampal et al. (2016).

- Page 9, line 2-3: Why the authors show the relationships in terms of mean seasonal cycle, not by scatter plots based on the relations in each month? I mean, for example, a scatter plot for drift-concentration relation in each month can more clearly show the validity of the regression line.

Our aim is to show how changes in drift speed are linked to changes in concentration and thickness for each month of the year (mean seasonal cycle) for both the model and the observations as in Olason and Notz (2014). We agree with the reviewer that it is also interesting to show these relationships for each month of every year but this produces a noisier picture (especially for the thickness loop). Please see Fig. S3 below, where we plot scatter plots for every month of each year. They show that drift-concentration and drift-thickness slopes are similar to the ones using the mean seasonal cycle (Fig. 8a-b in the revised manuscript), with slightly lower model performance. This information has been added in the revised manuscript.
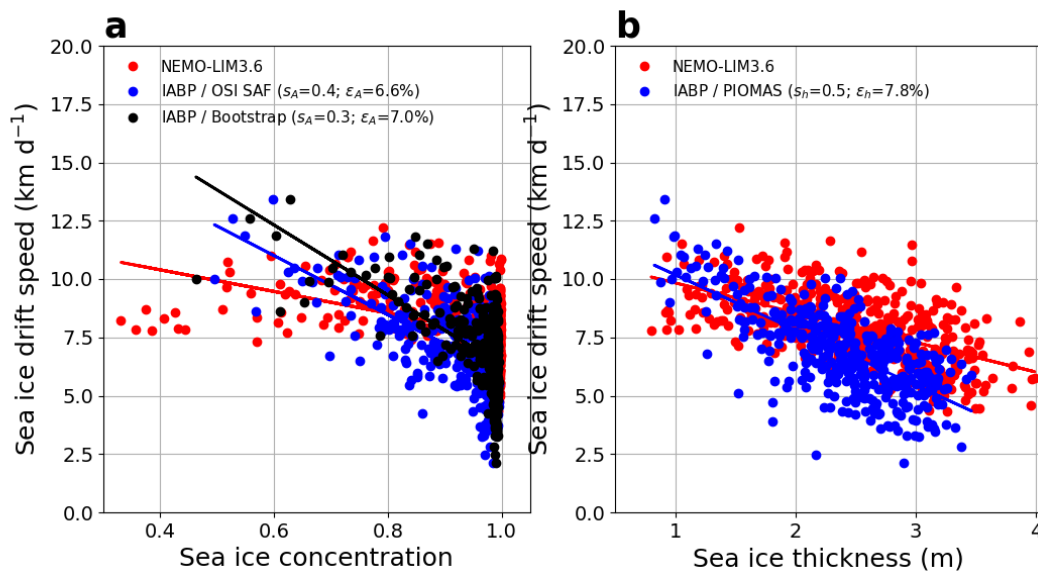
Fig. S3: Scatter plots of modelled (NEMO-LIM3.6) and observed monthly mean sea ice drift speed against (a) concentration and (b) thickness spatially averaged over the SCICEX box for each month of the period 1979-2013. Slope ratios and normalised distances between NEMO-LIM3.6 and the different observation/reanalysis datasets are shown in brackets in the legends.

- Page 9, line 16-17: Why the authors did not apply normalization by wind stress? Since the wind stress may differ between each month, it is difficult to derive a general relation between drift speed and other variables. If there is a reasonable explanation for not to apply normalization, please describe in the text.

For normalising drift speed by wind friction speed, we use the same methodology as in Olason and Notz (2014), except that we use wind speed from DFS5.2 since this is the atmospheric forcing of our model. We also use air density of 1.225 kg/m³ and drag coefficient of 0.0015. As shown in Fig. S4 below, the normalised drift-concentration and normalised drift-thickness relationships look very similar to drift-concentration and drift-thickness relationships without normalisation (compare to Fig. 8a-b in the revised manuscript). Therefore, we decided not to perform the normalisation, which facilitates the interpretation of data. Please see Section 2.3 of the manuscript: 'A key difference with Olason and Notz (2014) is that we do not normalise drift speed by wind friction
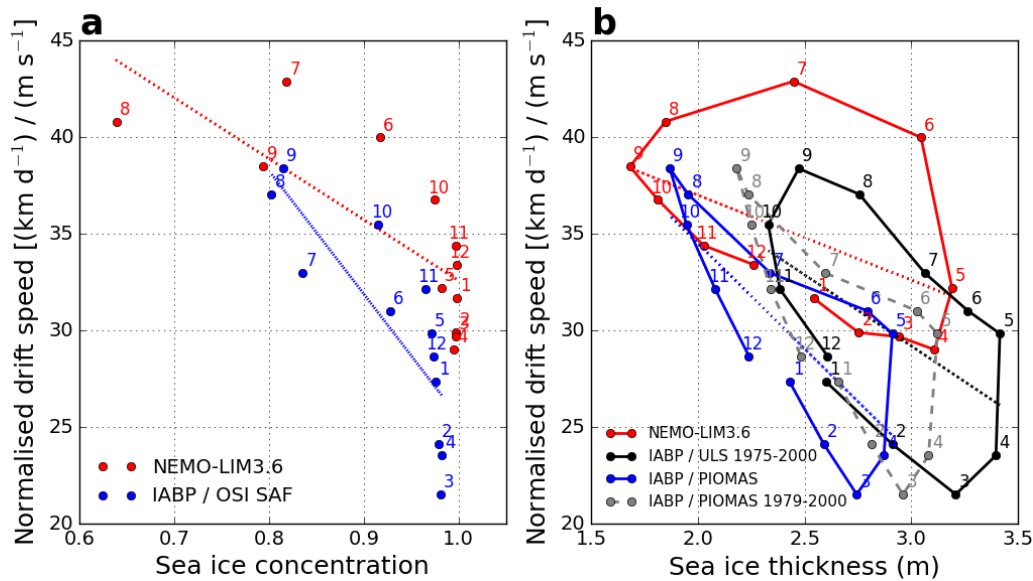
Fig. S4: Scatter plots of modelled (NEMO-LIM3.6) and observed monthly mean normalised sea ice drift speed against (a) concentration and (b) thickness spatially averaged over the SCICEX box and temporally averaged over the period 1979-2013. Drift speed is normalised by wind friction speed (derived from DFS5.2) as in Olason and Notz (2014).

- Page 9, line 30-31: I think the use of 'feedback' in this sentence is not appropriate. The result in this section (sec. 3.2) shows that there is a (linear) relationship between drift speed and strength (thickness or concentration) as equilibrium states (A feedback system does not reach an equilibrium state unless α = 0, or having oscillating solution. see my major point). I don't mean the analysis in this section is meaningless, but is not appropriate to show the existence of feedback (see also major point).

We changed the term 'feedback' into 'interactions' as we think it is more appropriate. Please also see our response to the first major point above.

- Page 10, line 9-20: There are a number of incorrect sentences here. Please keep in mind that higher λ does not directly correspond to larger ice strength, due to the current formulation, Eq. (1). Particularly, it is not true, when discussing relation between ice drift and thickness (or concentration) in summer season. The thickness may thinner than 1 m at least part of the SCICEX box.

This part has been re-written due to the inclusion of new P* experiments and in response to the second major point of the reviewer.

The mean seasonal cycle of ice strength P for the different λ values is shown in Fig. S5a below, where we see that ice strength is higher for higher λ most of the time, with very small differences in summer compared to winter. The zoom in summer months (Fig. S5b below) reveals that this relationship still holds (higher strength for higher λ), except for the λ = 2 curve in summer, which is located between λ = 1 and λ = 1.5 in July, and between λ = 0.5 and λ = 1 in August and September.
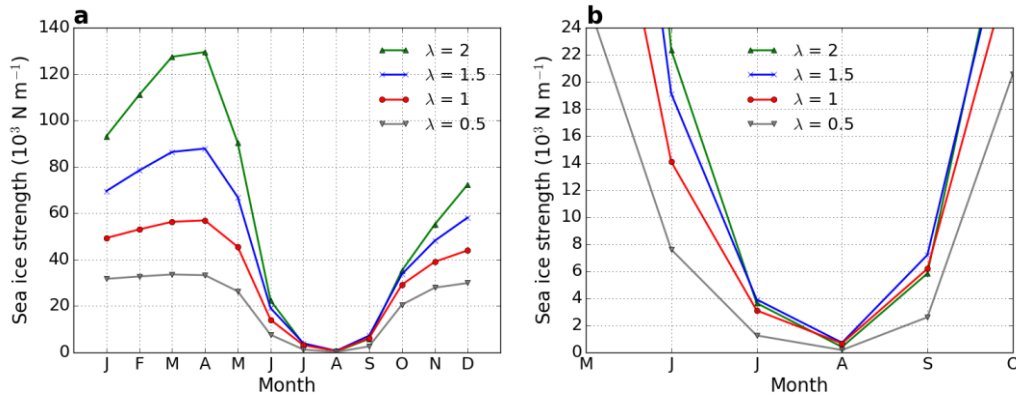
Fig. S5: (a) Modelled (NEMO-LIM3.6) monthly mean seasonal cycles of sea ice strength temporally averaged over the period 1979-2013 and spatially averaged over the SCICEX box for four different λ values (see Eq. (1)). (b) Snapshot of (a) for June-September.

- Page 10, line 16-20: I think this interpretation is wrong, probably due to the fact which I described in major point. Since the ice thickness during summer season is close to (or even smaller than 1 m), the ice strength for larger λ becomes smaller than that for smaller λ. Therefore, the larger drift speed for larger λ can be simply the result of smaller ice strength.

As demonstrated in our response to the previous comment and in Fig. S5, higher λ leads to higher strength when averaging over the SCICEX box, except for the λ = 2 curve from July to September. Therefore, the larger drift speed for larger λ in summer in Fig. 10b in the previous version of the manuscript is not driven by lower ice strength P (except maybe for λ = 2). Furthermore, a similar behaviour is observed with P* experiments: higher P* leads to higher drift speed in summer (except P* = 100kN/m²) (Fig. 9b in the revised manuscript).

- Page 10, line 32-33: I would say the result is not counter-intuitive. Note that increase of λ leads to smaller ice strength in h < 1 area, it means ice can be easily deformed or compressed in h < 1 area, compared to small λ.

We rephrased this following comments from both reviewers and due to the use of new P* experiments.

- Page 10, line 4 - page 11, line 8: Section 3.3 needs additional figure showing the relation between λ and mean ice strength in SCICEX box (a seasonal cycle for each λ should be shown), otherwise, we cannot relate ice strength with ice thickness (and concentration) nor examine the relation between ice strength and ice drift.

Please see our response to the comment 'Page 10, line 9-20' and Fig. S5. However, the main focus is now on P* experiments, which are simpler to interpret. We only discuss λ experiments in Section 4.2.

10

- Page 10, line 33 - page 11 line 6: I think the reason for the increase of modal thickness for larger λ (Fig. 13) can be simply explained. The experiment with increased λ has larger ice strength for h > 1 (winter season), which prevents ice thickening due to ridging, while it has smaller ice strength for h < 1 (summer season), which enhance ice thickening due to ridging. As a result, larger λ leads to larger peak at modal thickness.

We are not sure about the validity of this hypothesis since we obtain similar results with the new P* experiments (in which larger P* always lead to larger ice strength P), i.e. decrease of modal thickness and decrease of ice thickness heterogeneity for larger P* (Fig. 12 in the revised manuscript).

- Page 11, line 14-15: I would say that this study also did not 'quantify' the magnitude of the drift-strength feedback. To quantify a feedback, one should present growth rate of the feedback.

We rephrased this paragraph since we focus now on the interactions (and not on the feedback) between drift speed, concentration and thickness. Please see our response to the first major point above.

- Page 11, line 23-24: Due to the analyses without normalization by wind stress, it is difficult to distinguish the reason for the hysteresis loop shown in Fig. 9b and Fig. 11b. Can the hysteresis loop be observed if the ice drift speed is normalized by wind stress?

As shown in Fig. S4b, a hysteresis loop is also present when normalising drift speed by wind friction speed.

- Page 12, line 14 - page 13, line 15: As pointed in major point, I think the basic strategy for the sensitivity experiment and analyses are not suitable for quantifying 'feedback'. If the authors intend to quantify 'feedback', the entire framework should be reconsidered.

Please see our response to the first major point above.

- Page 14, line 16-18: Why such hysteresis loops are observed in the modeled sea ice? Since observation (IABP) does not show such a feature, I guess this is an artifact coming from insufficient modeled physics.

As shown in Fig. 8b in the revised manuscript and in Fig. 4b of Olason and Notz (2014), observed drift-thickness relationships are marked by a hysteresis loop: for a given thickness, two different drift speed values exist depending on the season.

- Page 14, line 21-28: The summary provided here should be reconsidered, by taking the second paragraph of the major point into account. Although the authors generally provided descriptive result of their analyses on ice drift - thickness relations, they did not show any results on thermodynamic analyses. Therefore I cannot follow nor rely on the arguments associated with thermodynamic effects.

We re-wrote this part of the text since a new set of P* experiments have been performed. Concerning the thermodynamic analyses, we refer the reviewer to our response to the first minor comment of Referee #1 (p. 1 l. 11).

5. References

- Lindsay, R. and A. Schweiger, 2015: Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations, The Cryosphere, 9, 269-283, doi:10.5194/tc-9-269-2015.

- Szanyi, S., J. V. Lukovich, D. G. Barber, and G. Haller, 2016: Persistent artifacts in the NSIDC ice motion data set and their implications for analysis, Geophys. Res. Lett., pp. 10800-10807, doi:10.1002/2016GL069799.

- Tschudi, M., C. Fowler, J. Maslanik, J. S. Stewart, and W. Meier, 2016: Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors. Version 3. Boulder, Colorado, USA. (https://nsidc.org/data/docs/daac/nsidc0116_icemotion.gd.html).

Additional references included in this reply that are not in the revised manuscript:

- **Fowler, C., W. Emery, and M. Tschudi, 2013: Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors, version 2, NSIDC, Boulder, Colorado.**

Interactions between Arctic sea ice ~~drift-strength feedback~~ drift and strength modelled by NEMO-LIM3.6

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Preliminary remark for the revised manuscript (not the track change version):

– corrections related to Referee 1 are in blue

– corrections related to Referee 2 are in red

– other corrections are in orange.

5 **Abstract.** Sea ice cover and thickness have substantially decreased in the Arctic Ocean since the beginning of the satellite era. As a result, sea ice strength has been reduced, allowing more deformation and fracturing and leading to increased sea ice drift speed. ~~The resulting increased sea ice export is thought to further lower sea ice concentration and thickness.~~ We use the version 3.6 of the global ocean-sea ice ~~NEMO-LIM3.6~~ NEMO-LIM model (Nucleus for European Modelling of the Ocean coupled to the Louvain-la-Neuve sea Ice Model), satellite ~~and buoy~~, buoy and submarine observations, as well as reanalysis data over the

10 period from 1979 to 2013 to study ~~this positive feedback for the first time in such detail~~ these interactions. Overall, the model agrees well with observations in terms of sea ice extent, concentration and thickness. Although the seasonal cycle of sea ice drift speed is reasonably well reproduced by the model, the recent positive trend in drift speed is weaker than buoy observations in summer. NEMO-LIM3.6 is able to capture the relationships between the seasonal cycles of sea ice drift speed, concentration and thickness ~~in terms of seasonal cycle~~, with higher drift speed for both lower concentration and lower thickness, in agreement

15 with observations. Sensitivity experiments are carried out by varying the initial ice strength ~~and~~, and these show that higher values of ice strength lead to lower sea ice ~~thickness. We demonstrate that higher ice strength results in a more uniform sea ice thickness distribution, leading to lower heat conduction fluxes, which provide lower ice production, and~~ thus lower ice ~~thickness. This shows that the positive feedback between sea ice drift speed and strength is more than just dynamic, more complex than originally thought and that other processes are at play~~ deformation and lower sea ice thickness. The methodology

20 proposed in this analysis provides a benchmark for a further model intercomparison related to the interactions between sea ice drift speed and strength, which is especially relevant in the context of the upcoming Coupled Model Intercomparison Project 6 (CMIP6).

1

1 Introduction

The motion or drift of sea ice results from a balance of wind stress, ocean stress, ice internal stress, Coriolis force and ocean surface tilt. Scale analysis shows that the main drivers of drift are the first three terms, and that both Coriolis force and ocean surface tilt are an order of magnitude smaller (Steele et al., 1997; Leppäranta, 2011). For individual ice floes and for ice fields with low compactness, ice internal stress is generally neglected: sea ice is in free drift. Otherwise, ice internal stress is an important driver of sea ice motion and is a key element of the ~~positive feedback~~ interactions between sea ice drift speed and strength described hereafter. In this paper, we focus on the Arctic Ocean, for which a sufficient network of observations is available.

At large scale, sea ice strength mainly depends on two quantities, namely sea ice concentration (defined as the relative amount of ocean area covered by sea ice) and sea ice thickness. A decrease ~~of~~ in concentration or thickness, as observed in ~~the~~ recent decades in the Arctic Ocean (Stroeve et al., 2012; Vaughan et al., 2013; Lindsay and Schweiger, 2015), leads to a reduced ice strength and internal stress, which allows more deformation and fracturing within the ice, hence larger sea ice drift speed (Rampal et al., 2011; Spreen et al., 2011; Kwok et al., 2013). This in turn ~~provides~~ could provide higher export of sea ice out of the Arctic Basin (Rampal et al., 2011), resulting in lower sea ice concentration and further thinning (Langehaug et al., 2013). ~~On the contrary, an initial increase in concentration or thickness leads to lower drift speed, which finally results in higher concentration or thickness. The mechanism of this~~ However, this hypothetical positive feedback, which we ~~name~~ call 'drift-strength feedback' throughout this paper, ~~is shown in Fig. ??~~ has been poorly studied and its existence has not been shown in observations.

A clear increase in Arctic sea ice drift speed has been detected since the 1950s using buoy observations and satellite measurements (Häkkinen et al., 2008; Rampal et al., 2009, 2011; Spreen et al., 2011; Vihma et al., 2012; Kwok et al., 2013; Olason and Notz, 2014). While increased wind speed seems to be the likely cause of the increase in sea ice motion before 1990, the reduced ice strength (caused by reduced thickness and concentration) is the dominant driver since then (Döscher et al., 2014). ~~A direct consequence of higher drift speed is a rise in~~ It has been suggested that an increase in drift speed leads to higher sea ice export ~~out of~~ from the Arctic Basin, which mainly occurs through Fram Strait. However, a distinction needs to be made between area and volume exports: ~~the former~~ area export is the product of sea ice drift speed, concentration and transect length, while ~~the latter~~ volume export is the product of area export and ice thickness. Several studies show an increase of ice area export at Fram Strait since the late 1970s (Langehaug et al., 2013; Krumpen et al., 2016; Smedsrud et al., 2016), while Kwok et al. (2013) show a small decrease between 1982 and 2009. In terms of volume export, the amount of studies is limited by the relatively low ice thickness temporal coverage at Fram Strait. Spreen et al. (2009) show no significant change in ice volume export between 1990 and 2008. The review from Döscher et al. (2014) ~~summarises this question by stating that~~ addresses this question and concludes that there is no significant long-term trend in sea ice area export ~~is seen~~ due to a balance between increased drift speed and decreased concentration, while volume export slightly falls due to a decreased sea ice thickness. A summary of these studies related to drift speed trend and its cause as well as sea ice export at Fram Strait is provided in Table 1.

Olason and Notz (2014) investigate the interactions between Arctic sea ice drift speed, concentration and thickness using satellite and buoy observations. They show that both seasonal and recent long-term changes in sea ice drift are primarily correlated to changes in sea ice concentration and thickness. ~~At~~ On seasonal time scales, when sea ice concentration is low (from June to November), drift speed increases with decreasing concentration, while for high concentration (from December to March), drift speed changes are largely driven by changes in thickness (higher drift speed with lower thickness).

An analysis of sea ice ~~outputs coming~~ output from the Coupled Model Intercomparison Project 3 (CMIP3) multi-model dataset suggests that thicker and more packed sea ice drifts faster, contrary to what is observed (Rampal et al., 2011). The same study also shows that models with a stronger long-term thinning trend do not exhibit faster drift speed, suggesting that the ~~positive feedback~~ coupling between drift and strength is underestimated in CMIP3 models. According to the authors, this could explain the too low trends in sea ice area, thickness and drift speed.

~~In the studies previously mentioned, several highlight the drift-strength feedback as an important element of sea ice dynamics but there is no detailed study on its impact on the Arctic sea ice and its relative importance.~~ The main goal of this study is to investigate ~~this feedback using the new version~~ the interactions between Arctic sea ice drift speed and strength using version 3.6 of the Nucleus for European Modelling of the Ocean coupled to the Louvain-la-Neuve sea Ice Model (NEMO-LIM3.6). ~~In order to perform this analysis, we first study the interactions between drift speed, concentration and thickness by applying~~ We first apply the methodology developed by Olason and Notz (2014) to ~~a model~~ the model to see how changes in ice drift speed are related to changes in ice concentration and thickness throughout the year. However, good agreement between the modelled and observed drift-strength relationships is not a guarantee that the model is able to capture ~~the~~ drift-strength ~~feedback~~ interactions. Thus, we carry on additional sensitivity experiments where initial ice strength is varied, and we investigate the impact on the resulting drift speed, concentration and thickness of sea ice. The methodology proposed in this analysis ~~constitutes~~ provides a benchmark for ~~a~~ further model intercomparison related to ~~the~~ drift-strength ~~feedback~~ interactions and could be used in the analysis of sea ice outputs from the upcoming High Resolution Model Intercomparison Project (HighResMIP) (Haarsma et al., 2016) and CMIP6 Sea-Ice Model Intercomparison Project (SIMIP) (Notz et al., 2016).

In Section 2 we describe the model, the observations as well as the diagnostics and metrics. Then, results from the model evaluation against different observational and reanalysis datasets are presented (Section 3.1). Section 3.2 details the interactions between drift speed and strength ~~at~~ on seasonal time scales. Results from the sensitivity experiments are shown in Section 3.3. These results are discussed in Section 4. Finally, a summary is provided in Section 5.

2   Methodology

2.1   Model description and sensitivity experiments

The model used in this study is version 3.6 of the global ocean-sea ice coupled model NEMO-LIM (SVN revision 6631). The ocean component NEMO3.6 is a finite difference, hydrostatic, primitive equation model (Madec, 2016). The sea ice component LIM3.6 is a dynamic-thermodynamic model that uses the elastic-viscous-plastic (EVP) rheology on a C-grid and includes an explicit ice thickness distribution (ITD) (Vancoppenolle et al., 2009; Rousset et al., 2015).

The atmospheric forcing is the Drakkar Forcing Set (DFS) 5.2 (Dussin et al., 2016), which is based on the ERA-Interim atmospheric reanalysis dataset. The model is run on the global tripolar ~~ORCA1~~ eORCA1 grid (about $1°$ spatial resolution) from January 1958 to December 2015. Model outputs that are used in this study are sea ice concentration, thickness and velocity components over the period 1979-2013. This period is chosen to match the satellite period. Sea ice thickness used in this study is the sea ice volume per grid cell area taking into account open water (named 'sivol' according to SIMIP nomenclature) rather than the actual thickness ('sithick'), since the former is more physical in representing global interactions between sea ice dynamics and thermodynamics, and this is the variable used in the ~~strength equation (1) below~~formulation of sea ice strength detailed below.

Four different simulations are performed in order to test the sensitivity of sea ice drift speed, thickness and concentration to changes in initial sea ice strength P. The latter is computed as a function of ice thickness h and concentration A using the formulation of Hibler (1979):

$$P = P^* h^{\lambda} \exp[-C(1 - A)], \tag{1}$$

where ~~P^* and~~ C $(= 20)$ and P^* are fixed empirical constants~~set to~~. Five different values of P^* (5.5, 20, 27.5, 45 and 100 kN m^{-2}~~and 20 respectively. An exponent parameter λ is introduced into the original Hibler formulation and takes four values corresponding to the four different simulations ($\lambda = 0.5, 1, 1.5, 2$)~~) are used in order to perform sensitivity experiments to test how a change in the strength parameterisation impacts the ice drift speed, concentration and thickness. The experiment with ~~$\lambda = 1$ (original Hibler formulation)~~ $P^* = 20$ kN m^{-2} is the control simulation that is analysed in Sections 3.1 and 3.2. The results from the other ~~three~~ four experiments are presented in Section 3.3.

The value of $P^* = 20$ kN m^{-2} is the commonly used value in NEMO-LIM3.6 and has been chosen through tuning of mean sea ice thickness and mean Fram Strait ice export (Vancoppenolle, personal communication). This is also the value used in the viscous-plastic models of SIMIP (Kreyscher et al., 1997) as well as in more recent modelling studies (Lipscomb et al., 2007; Juricke et al., 2 Hibler and Walsh (1982) find that $P^* = 27.5$ kN m^{-2} provides the best agreement between their 222 km-resolution sea ice model and observations from the Soviet ice station NP-22 in terms of mean drift rates in 1974-1975. Tremblay and Hakakian (2006) find that the most likely value of P^* lies in the range 30-45 kN m^{-2} based on satellite observations. Therefore, the value of P^* in Eq. (1) is highly uncertain and not a single value is considered as a reference (Feltham, 2008). The different sensitivity experiments carried out in this study account for this uncertainty.

The experiment with ~~$\lambda = 0.5$~~ $P^* = 5.5$ kN m^{-2} provides lower ice strength ~~than the original formulation ($\lambda = 1$~~P than the control simulation ($P^* = 20$ kN m^{-2}) for a given thickness~~, while the experiments with $\lambda = 1.5$ and 2 give higher strength~~. It is the lowest value used by Steele et al. (1997) in their model sensitivity study, corresponding to the value of 27.5 kN m^{-2} (Hibler and Walsh, 1982) divided by 5. The experiment with $P^* = 27.5$ kN m^{-2} gives higher ice strength P than the control simulation and corresponds to the value found by Hibler and Walsh (1982). The experiment with $P^* = 45$ kN m^{-2} is the largest value of the likely range found by Tremblay and Hakakian (2006). The experiment with $P^* = 100$ kN m^{-2} is close to the highest value of Steele et al. (1997). Figure 1 shows how sea ice strength varies as a function of sea ice thickness and concentration for the ~~four λ values.~~The sensitivity experiments presented here allow us to test the representation of the

~~drift-strength feedback in the model. An increase of λ (increase of ice strength) should lead to a decrease in drift speed and a consequent increase in thickness and concentration according to the drift-strength feedback (Fig. **??**). If this chain of results is not reproduced by the model, it suggests either that the model can not accurately represent the feedback or that another process is at play.~~ five P^* values.

2.2 ~~Observations~~Reference products

In this study, we use several observational and reanalysis datasets for a given variable in order to evaluate model results, following the recommendations of Notz (2015) and Massonnet et al. (2016).

2.2.1 Sea ice drift speed

For sea ice drift speed, the International Arctic Buoy Programme (IABP) C buoy dataset is retrieved from the National Snow and Ice Data Center (NSIDC) (Tschudi et al., 2016). ~~The merged product from Tschudi et al. (2016) suffers from artifacts of the method used to incorporate buoy data (Szanyi et al., 2016), so we prefer using only buoy data rather than the merged product.~~ This dataset provides 12-hourly sea ice velocity vectors derived from buoy positions over the period extending from ~~January~~ 1979 to ~~May~~ 2015. Ice motion derived from buoys is more accurate than that obtained from satellites (error of less than 1 cm s^{-1} for the average velocity over 24 h according to NSIDC), but the coverage is very limited and the number of buoys and their locations varies from year to year. In addition, buoys have not been placed on ice in the Eastern Arctic. The daily mean sea ice drift speed is computed for each buoy from 12-hourly data.

We also include the merged product from Tschudi et al. (2016), which provides daily sea ice motion vectors on the Equal-Area Scalable Earth (EASE) Grid with a resolution of 25 km from 1979 to 2015. This dataset, available on the NSIDC website, is a compilation of velocity vectors from IABP buoy data, satellite observations from Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E), Advanced Very High Resolution Radiometer (AVHRR), Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager Sounder (SSMIS), as well as NCEP-NCAR reanalysis. The different sources of data are combined through a weighting that depends on the accuracy of each dataset. This merged product suffers from artifacts of the method used to incorporate buoy data, especially in terms of ice divergence and convergence (Szanyi et al., 2016). In our manuscript, we call this product 'NSIDC'.

We ~~also~~ use the low resolution sea ice drift product (OSI-405-b) from the European Organisation for the Exploitation of Meteorological Satellites Ocean and Sea Ice Satellite Application Facility (EUMETSAT OSI SAF, 2015b; Lavergne et al., 2010). This dataset covers the period from October 2006 to present. No data is available from May to September (inclusive) for the Arctic region due to high atmospheric liquid water content and to ice surface melting. Despite this low temporal coverage compared to other sea ice drift products, the quality of OSI SAF data is superior to other satellite products based on a recent uncertainty estimate (Sumata et al., 2014). This dataset combines satellite measurements of both the brightness temperature using passive microwave instruments from ~~Special Sensor Microwave/Imager~~ (SSM/I~~), Special Sensor Microwave Imager Sounder (SSMIS), Advanced Microwave Scanning Radiometer - Earth Observing System (~~, SSMIS, AMSR-E ~~)~~ and Advanced Microwave Scanning Radiometer 2 (AMSR2) and the radar backscatter using Advanced Scatterometer (ASCAT). Sea ice drift

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vectors are provided every 2 days at a spatial resolution of 62.5 km, and we calculate daily mean drift speed from these data. We compared modelled drift speed averaged over two days to original OSI SAF data but we did not find any significant difference. Since we mainly compare the modelled sea ice drift speed to buoy data instead of satellite data (which have a lower temporal coverage), we have decided to keep daily averages of sea ice drift speed as a benchmark for comparison.

5 ~~Monthly mean ice velocity vectors from the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) are also used to derive drift speed of sea ice from 1979 to present. PIOMAS is a multi-category thickness and enthalpy distribution sea ice model coupled with the Parallel Ocean Program developed at the Los Alamos National Laboratory (Zhang and Rothrock, 2003). The model assimilates observed sea ice concentration and sea surface temperature and is driven by daily NCEP-NCAR reanalysis surface forcing fields. The mean horizontal resolution in the Arctic is 22 km.~~

10   2.2.2   Sea ice concentration

For sea ice concentration, the global reprocessed dataset (OSI-409-a) from OSI SAF (EUMETSAT OSI SAF, 2015a) is used. It covers the period from October 1978 to April 2015 using passive microwave data from ~~Scanning Multichannel Microwave Radiometer (SMMR)~~SMMR, SSM/I and SSMIS. The OSI SAF algorithm to retrieve concentration from brightness temperature is a linear combination of the Bootstrap algorithm in frequency mode over open water (Comiso, 1986; Comiso et al., 15   1997) and the Bristol algorithm over ice (Smith, 1996). This is one of the best concentration algorithms in terms of precision (standard deviation) according to a recent evaluation (Ivanova et al., 2015). The spatial resolution for this dataset is 10 km. We compute the monthly mean concentration from daily data.

We also retrieve the monthly mean sea ice concentration (1979-2015) computed from the AMSR-E Bootstrap algorithm with daily varying tie-points (Comiso, 2015). This dataset is derived using measurements from SMMR, SSM/I and SSMIS. 20   Due to orbit inclination, data do not cover the region north of 84.5 °N for SMMR and 87.2 °N for SSM/I and SSMIS. Data are gridded on the SSM/I polar stereographic grid with a 25 km resolution. Largest errors related to this dataset are found in summer when melt is underway.

2.2.3   Sea ice thickness

For sea ice thickness, ~~the~~ we use the multiple regression model of Rothrock et al. (2008), based on 34 US Navy submarine 25   cruises spanning the period 1975-2000 within the Scientific Ice Expeditions (SCICEX) box. This dataset includes more than 2000 records of sea ice draft (mostly in spring and autumn) measured from the first-return echo. A positive mean bias of 0.29 m in ice draft is identified by Rothrock and Wensnahan (2007) and is taken into account in our study. Sea ice thickness is derived from the draft using the methodology of Rothrock et al. (2008).

The gridded data at a spatial resolution of 25 km from ten Ice, Cloud, and land Elevation Satellite (ICESat) campaigns is also 30   used (Kwok et al., 2009). The Geoscience Laser Altimeter System (GLAS) is the laser altimeter on board ICESat that measures sea ice freeboard height, from which sea ice thickness is derived using snow depth and densities of ice, snow and water. The coverage period is limited to the months of October-November and February-March starting in late September 2003 and ending in March 2008. The Kwok et al. (2009) dataset provides the mean sea ice thickness for each of the ten campaigns. The mean

absolute uncertainty of sea ice thickness derived from ICESat is 0.21 m in October-November and 0.28 m in February-March (Zygmuntowska et al., 2014).

~~Since there is no long-term consistent ice thickness data set that covers our study period and due to~~ Due to the spatial and temporal gaps of sea ice thickness measurements and the high uncertainty inherent to thickness retrievals (Stroeve et al., 2014; Zygmuntowska et al., 2014), we also use monthly mean thickness derived from ~~PIOMAS~~ the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) over the period 1979-2013. ~~Sea~~ PIOMAS is a multi-category thickness and enthalpy distribution sea ice model coupled to the Parallel Ocean Program developed at the Los Alamos National Laboratory (Zhang and Rothrock, 2003). The model assimilates observed sea ice concentration and sea surface temperature and is driven by daily NCEP-NCAR reanalysis surface forcing fields. The mean horizontal resolution in the Arctic is 22 km. PIOMAS data are primarily model-generated, and must therefore be interpreted with caution. Nevertheless, sea ice thickness from PIOMAS agrees well with ICESat data over the region for which submarine data are available (Schweiger et al., 2011) ~~.~~ and constitutes a valuable tool in our analysis. Given the uncertainties of both observational products and PIOMAS, using all of the products together allows us to obtain a range of 'reference values' that is more reliable than the range based on observational products alone.

2.3 Diagnostics and metrics

A diagnostic is a measure of one characteristic of a model or an observational dataset, while a metric is a scalar number that compares a diagnostic to some reference (typically observations). In this study, we use both 'standard' diagnostics as well as process-based diagnostics and metrics. The ~~four~~ standard diagnostics that we use are:

- sea ice extent, defined as the total area of ocean with sea ice concentration higher than 0.15

- sea ice area, which is the total area of sea ice cover, computed due to uncertainties linked to sea ice extent (Notz, 2014)

- sea ice concentration, which is the relative amount of ocean area covered by sea ice

- sea ice thickness, defined as the sea ice volume per grid cell area

- sea ice drift speed, which is the velocity of sea ice computed at the daily time scale.

It is important to note that for drift speed, all values given in this study are computed from ~~daily~~ the daily mean components of sea ice velocity u_d and v_d:

$$D_d = \sqrt{u_d^2 + v_d^2}. \tag{2}$$

where D_d is the daily mean drift speed. Monthly mean drift speed computed from the daily components of sea ice velocity is approximately twice higher than monthly mean drift speed computed from monthly components of sea ice velocity with NEMO-LIM3.6 due to higher temporal variability at the daily timescale (Fig. 2). ~~Since we express both modelled and observed drift speeds in km per day (km d^{-1}) in this study, using daily components makes more sense than using monthly components. PIOMAS provides only monthly velocity components, so we correct the resulting monthly drift speed by multiplying its value~~

~~by two based on our previous results (Fig. 2).~~A recent analysis also shows that such a factor of two is also apparent within the CMIP5 models (Tandon et al., submitted). Using daily components is more accurate for our study because we can capture synoptic-scale variability.

From daily values of these ~~four~~ standard diagnostics, we compute monthly means temporally averaged over the period 1979-2013 and monthly trends (i.e. linear regression slopes) over the same period. The maps shown in this paper (Figs. 4, 5, 7, 10) provide monthly means averaged over three consecutive months for winter (January, February, March) and summer (July, August, September) for each grid cell. The plots of mean seasonal cycles (Figs. 3, 6, 9, 11) provide spatial means over the ~~Scientific Ice Expeditions (SCICEX) box from US Navy submarine cruises~~ SCICEX box (Rothrock et al., 2008), which is also the domain used by Olason and Notz (2014) in their study. The SCICEX box is representative of sea ice processes happening in the Central Arctic region and is well covered by observational datasets of sea ice concentration, thickness and drift speed. All maps in this study show the contours of the SCICEX box. We have also tested computing spatial means over a much wider domain taking into account all grid cells between 50 and 90 °N with a concentration threshold of $A \geq$ ~~0.1~~0.15. Unless specifically mentioned in the text, the default domain that is used in the following sections is the SCICEX box. Since IABP buoy data are not gridded, we use all buoys within the SCICEX box to compute the spatial mean over that region. We acknowledge that comparing buoy and model drift speed has to be done with caution, as buoys measure the drift speed at one particular location while the model is meant to give the grid-cell average. For computing spatial means, a weight is given to each grid cell proportional to the grid cell area.

~~We also use three process-based diagnostics and four metrics that are based~~ Based on the 'standard' diagnostics described above, we use two process-based diagnostics in order to quantify the ability of NEMO-LIM3.6 to capture the ~~sea ice drift-strength feedback~~ interactions between sea ice drift speed and strength in the Arctic. The ~~use of process-based diagnostics and metrics to try to understand the causes of model biases is highly important (Notz, 2015). They allow us not only to quantify model misfits with respect to sea ice state but also yield insight on the origins of these biases.~~

~~The first two~~first process-based ~~diagnostics measure the relationship between~~ diagnostic is a scatter plot of sea ice drift speed ~~and concentration and the relationship between drift speed and thickness over~~against sea ice concentration for each month of the mean seasonal cycle as in Olason and Notz (2014)~~(Figs. 8, 13).~~ The second diagnostic is similar to the first diagnostic with sea ice thickness instead of concentration. All values are ~~monthly means temporally averaged over 1979-2013 and~~ spatially averaged over the SCICEX box ~~. The novelty compared to Olason and Notz (2014), who only use observations, is that we introduce model results in this analysis. Another~~and temporally averaged over the period 1979-2013. A key difference with Olason and Notz (2014) is that we do not normalise drift speed by wind friction speed since our findings were not sensitive to such normalisation.

~~The third process-based diagnostic provides the number of ice-covered grid cells in each sea ice thickness bin range (Fig. 12). In this study, we define 11 equally-spaced classes (0.5 m), except for the last class that includes all grid cells with a thickness above 5 m. This diagnostic provides a way to quantify the heterogeneity of the sea ice thickness distribution~~These two diagnostics are presented in Figs. 8 and 13.

~~The four metrics are based on the first two diagnostics and~~ Based on the previous process-based diagnostics, four metrics are computed over the mean seasonal cycle ~~(i.e. 12 points). The first two metrics are slope ratios, while the last two metrics are normalised distances~~. The first metric s_A measures the ratio of the modelled drift-concentration slope to the observed drift-concentration slope. ~~Drift-concentration slopes are computed as the linear regression slopes of the relationships between drift speed and concentration over the mean seasonal cycle.~~ The closer the ratio to 1, the closer the model to the observations. The second metric s_h is similar to the first metric, except that the ratio involves drift-thickness slopes.

The third and fourth metrics quantify the normalised ~~distance~~ distances (in %) between the model and observations for both the drift-concentration (ϵ_A) and drift-thickness (ϵ_h) relationships respectively:

$$\epsilon_A = \frac{1}{n} \sum_{i=1}^{n} \sqrt{\left| \frac{A_{m,i} - A_{o,i}}{\overline{A_o}} \right|^2 + \left| \frac{D_{m,i} - D_{o,i}}{\overline{D_o}} \right|^2} \times 100, \tag{3}$$

$$\epsilon_h = \frac{1}{n} \sum_{i=1}^{n} \sqrt{\left| \frac{h_{m,i} - h_{o,i}}{\overline{h_o}} \right|^2 + \left| \frac{D_{m,i} - D_{o,i}}{\overline{D_o}} \right|^2} \times 100, \tag{4}$$

where n is the number of months (i.e. 12), the m and o subscripts stand for 'model' and 'observations' respectively, $\overline{A}$, $\overline{h}$ and $\overline{D}$ are the mean concentration, thickness and drift speed (respectively) over the 12 months.

3 Results

3.1 Model evaluation

The modelled mean seasonal cycle of Arctic sea ice extent is in ~~the range of the~~ good agreement with OSI SAF observational reference over the period 1979-2013. However, a too low extent is simulated in August (bias of 1.6 million km^2) (Fig. 3a, solid lines). This feature is similar to Rousset et al. (2015) who use NEMO-LIM3.6 at 2° resolution ~~.~~ forced by the CORE normal year forcing proposed by Large and Yeager (2009), which is based on a combination of NCEP/NCAR reanalyses and diverse satellite products and superimposes the 1995 synoptic variability on the mean 1984–2000 seasonal cycle (we use a resolution of 1° and DFS5.2 forcing). The amplitude of the modelled seasonal cycle of sea ice area is higher than the observed one (Fig. 3a, dashed lines). Note that satellite observations perform better in winter compared to summer due to the presence of melt ponds in summer (Ivanova et al., 2015).

The modelled mean seasonal cycle of sea ice concentration is very close to OSI SAF observations for all months, except in August when the model underestimates the mean concentration by $\sim$0.15 (Fig. 3b). This partly explains the too low extent at that time of the year (Fig. 3a). The Bootstrap algorithm provides higher concentration than OSI SAF, especially in summer, but the spatial coverage is limited due to the absence of data close to the North Pole (Section 2.2 and Fig. 4f). ~~When the mean concentration is spatially averaged over the wide domain (north of 50 °N), the model bias is much lower in August but is higher during the rest of the year compared to spatial means computed over the SCICEX box (not shown).~~ A more careful spatial analysis reveals that the model ~~accurately reproduces observed concentration patterns in winter with an overestimation~~

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overestimates sea ice concentration in winter, especially at the ice front (Figs. 4a, 4b, 4c). Furthermore, the model clearly underestimates the observed concentration in the Central Arctic in summer (Figs. 4d, 4e, 4f).

The mean seasonal cycle of sea ice thickness ~~is fairly well reproduced by the model compared to PIOMAS when computing the mean over the SCICEX box~~ modelled by NEMO-LIM3.6 underestimates the seasonal cycle derived from submarine

5 observations and is in better agreement with PIOMAS with a maximum in May and a minimum in September (Fig. 3c). ~~The~~ Compared to PIOMAS, the model overestimates ice thickness when ice is thicker (January to July) and slightly underestimates it when ice is thinner (August to October). ~~The differences between the model and PIOMAS are much larger when computing the mean over the wide domain (north of 50 °N) and the seasonal cycle is less consistent, with the model showing peak values from June to August (not shown).~~ We do not show the seasonal cycle of ice thickness from ICESat due to the sparse temporal

10 coverage of these satellite data. However, the model reproduces well the spatial distribution of ICESat thickness with thicker ice north of Greenland and in the Canadian archipelago. The model slightly overestimates the sea ice thickness provided by ICESat in February, March and April (mean bias of 0.07 m), and underestimates it in October and November (mean bias of -0.65 m).

Compared to IABP buoy observations, the model overestimates sea ice drift speed for all months with higher differences

15 from December to March and for June and July (Fig. 3d). The too strong intensity of the modelled sea ice velocity was already shown with NEMO3.1-LIM2 (Dupont et al., 2015). However, the model captures the seasonality of drift speed with higher values in summer, when concentration and thickness are the lowest, and lower values in winter, when concentration and thickness are high. The minimum modelled drift speed lags the observed minimum by one month (March) and the maximum occurs two months earlier than the observed maximum (September). ~~The recalibrated drift speed in PIOMAS reanalysis is in~~

20 ~~the range of values given by buoy observations and NEMO-LIM3.6 but there is no clear minimum and the maximum occurs in October. When the mean drift speed is averaged over the wide domain (north of 50 °N), the model bias (NEMO-LIM3.6) is much higher compared to IABP (not shown)~~The NSIDC drift speed from Tschudi et al. (2016) does not show a clear seasonal cycle and has values up to 4 km d^{-1} lower than the IABP product. This is ~~partly caused by too high modelled drift speed in the straits (particularly at Fram Strait, Fig. 5).~~also shown by Olason and Notz (2014) with the previous NSIDC product. Sea

25 ice drift speed from OSI SAF is not shown in Fig. 3d due to the absence of data in summer, but a spatial analysis shows that NEMO-LIM3.6 overestimates these satellite observations during the rest of the year (mean bias of 0.91 km d^{-1}; Fig. 5c). The main patterns of sea ice circulation, i.e. Beaufort Gyre and Transpolar Drift, are reasonably well represented by the model (Figs. 5a and 5d).

Monthly mean trends in sea ice extent are clearly negative all year long in the model and OSI SAF observations, especially

30 in summer, but the model underestimates these trends (Fig. 6a). For sea ice concentration trends~~averaged over the SCICEX box~~, the agreement between the model and observations is ~~much better~~ relatively good but the model overestimates the negative trend in August and September (Fig. 6b). ~~Furthermore, monthly~~ Monthly mean thickness trends lie within the PIOMAS range but the seasonal cycle amplitude is lower (Fig. 6c). Finally, monthly mean trends in drift speed simulated by the model agree well with IABP from November to June ~~but are clearly out of range from July to October , with a negative modelled trend in~~

35 ~~August~~ but can not reproduce the positive observed trend from August to October (Fig. 6d). ~~However, modelled trends are not~~

~~significant at the 5% level from July to September and agree well with PIOMAS at that time of the year. It is also important to reiterate that these results are valid for means computed over the SCICEX box and do not take into account grid cells outside of this box.~~The model produces drift speed trends that are closer to the NSIDC dataset in summer.

Figure 7 shows spatial variations of modelled monthly mean trends in sea ice drift speed and concentration. Interest-

5   ingly, the summer trend in drift speed is positive in the western part of the SCICEX box and negative in the eastern part (Fig. 7b). This effect is particularly enhanced in August (Fig. 7c), which explains the slightly negative trend in drift speed ($-0.18 \text{ km d}^{-1} \text{ decade}^{-1}$) when averaged over the whole SCICEX box (Fig. 6d). The cause of the negative drift speed trend in August in the eastern Central Arctic is due to the removal of sea ice in this region after 1979, as shown by the modelled trend in sea ice concentration in August (Fig. 7f). When considering grid cells with ice concentration higher than 0.15, the August

10   mean drift trend averaged over the SCICEX box is slightly positive ($0.09 \text{ km d}^{-1} \text{ decade}^{-1}$). Therefore, the model bias in summer drift speed trend is ~~probably~~ partly due to the absence of summer sea ice in the eastern Central Arctic.

3.2   How does sea ice drift relate to ice strength?

The ~~feedback~~ interactions between sea ice drift speed and strength can be quantified via the relationships between drift speed and concentration on the one hand and drift speed and thickness on the other hand. In this study, we analyse these relationships

15   in terms of mean seasonal cycles. The linear relationship between drift speed and concentration is clear for both the model and the observations when concentration is relatively low (i.e. in summer): the lower the concentration, the higher the drift speed, ~~with significant slopes~~ with slopes significantly different from zero at the 5% level (Fig. 8a). ~~However, this relationship does not hold with the drift speed from PIOMAS (the slope is not significant at the 5% level).~~ The modelled drift-concentration slope is weaker than the observed ones (using IABP for drift speed) mainly due to too low mean modelled sea ice concentration in

20   August and too high mean modelled drift speed in March and April. The modelled drift-concentration relationship is in better agreement with the observed IABP/OSI SAF pair (slope ratio s_A = 0.5 and normalised distance ϵ_A = ~~3~~3.7%) compared to IABP/Bootstrap (s_A = 0.3 and ϵ_A = ~~3.5~~4.2%).

The relationship between drift speed and thickness shows a similar general pattern as the drift-concentration relationship with higher drift speed for lower thickness, with significant slopes at the 5% level (Fig. 8b). However, the drift-thickness relationship

25   is more complex with a hysteresis loop for ~~both~~ NEMO-LIM3.6, the IABP/Submarines pair and the IABP/PIOMAS pair. From May to ~~August~~September, during the melting season, sea ice thickness decreases and drift speed increases. Then, from September to March, drift speed decreases and thickness increases. The behaviour is slightly different between the model and observations, with a clearer linear relationship from May to ~~August for observations~~September for observations, but the general shape of the scatter plot is similar. For both the model and observations, for a given thickness, the drift speed can take two

30   values depending on the season: a high value in summer when sea ice melts and a low value in winter when sea ice forms and grows. ~~PIOMAS drift speed does not reproduce this loop, although the slope ratio and normalised distance between the model and the PIOMAS/PIOMAS pair (s_h = 1.1, ϵ_h = 3.3%) are better than between the model and the IABP/PIOMAS pair (s_h = 0.5, ϵ_h = 3.5%).~~

~~Similar scatter plots are produced~~ We also show scatter plots for the monthly mean trends~~and show larger differences than monthly mean values~~, and these show large differences between the model and the observed pairs ~~using IABP for drift speed~~ (Figs. 8c and 8d). The positive slope of the modelled relationships is largely driven by low trends in summer, while the observations (~~with~~ using IABP for drift speed) show a decrease in drift speed trend with more positive trends in

5   concentration and thickness. The pair using the NSIDC dataset produces a closer drift-thickness slope ratio and normalised distance compared to NEMO-LIM3.6. However, the low trends in modelled drift speed in summer are due more to a progressive removal of sea ice rather than an actual decrease in sea ice motion in past years as previously shown (Section 3.1 and Fig. 7). ~~Modelled trends in drift speed and concentration in winter are very close to each other, while the spread is larger for observations. The agreement is better between the model and the pair using PIOMAS for drift speed, but the drift-concentration~~

10   ~~and drift-thickness relationships (in trends) are likely not reliable for PIOMAS based on previous results (Figs. 8a and 8b).~~

The analysis of drift-concentration and drift-thickness relationships demonstrates that NEMO-LIM3.6 captures reasonably well ~~the~~ drift-strength ~~feedback at~~ interactions on seasonal timescales. Note that relating drift speed to concentration and thickness for every month of the time series (and not only for the mean seasonal cycle) also gives similar slopes with slightly lower model performance ($s_A = 0.5$ and $\epsilon_A = 6.6\%$ compared to the IABP/OSI SAF pair; $s_h = 0.5$ and $\epsilon_h = 7.8\%$ compared

15   to the IABP/PIOMAS pair). The trend relationships are less convincing but two months (August and September) particularly dominate the signal due to a progressive removal of sea ice in the past years within the domain of study~~(SCICEX box). The use of a wide domain (all grid cells north of 50 °N) provides results for drift-concentration and drift-thickness relationships that clearly diverge compared to observations due to the inclusion of coastal grid cells that have high model biases (not shown). Computing mean concentration, thickness and drift speed over the Central Arctic (SCICEX box in our analysis) provides~~

20   ~~values that are much more consistent with observations and more representative of Arctic conditions~~.

3.3   Sensitivity to changes in ice strength

The previous scatter plots (Fig. 8) are valuable to provide insight regarding the interactions between sea ice dynamics and ~~state variables~~ strength (concentration and thickness), but they do not quantify the impact of a change in sea ice ~~state on the dynamics of the system.~~ strength on the resulting ice thickness and drift speed. In order to do this, we ~~introduce a λ parameter~~

25   perform experiments in which we vary P* in Eq. (1), as described in Section 2.1 and in Fig. 1~~, and vary it between 0.5 and 2 (λ = 1 is the original value in Hibler (1979)) to test the sensitivity of an initial change in ice strength on the resulting sea ice drift speed, concentration and thickness~~.

Varying ~~this exponent parameter~~ P* leads to tiny differences in mean sea ice concentration (not shown) but has a significant impact on sea ice thickness and drift speed (Fig. 9). For higher values of ~~λ~~ P*, i.e. larger ice strength~~for a given thickness~~, the

30   mean sea ice thickness is lower throughout the whole year (Fig. 9a) and the mean drift speed is lower in winter and spring and higher during summer and fall (Fig. 9b). ~~The amplitude of seasonal cycles in thickness and drift speed is lower with all λ values when using the wide domain (north of 50 °N) but the general trend is similar (not shown). Lower sea ice thickness with higherice strength~~

Increasing ice strength via the P^* parameter leads to lower thickness values (Fig. 9a). A more careful spatial analysis allows us to see that the lower ice thickness with higher P^* appears everywhere in the Arctic and during all months of the year, with the most visible differences occurring north of Greenland and the Canadian Archipelago where ice is the thickest (Fig. 10). In the experiments with larger (lower) P^*, the mean ice thickness is lower (higher) due to lower (higher) deformation rates (Fig.

5 ~~9a) is counter-intuitive with respect to the drift-strength feedback~~ 11a) and less (more) ice piling up (Fig. 10); this finding is similar as Steele et al. (1997). Deformation rates are computed from strain rate divergence and shear following Eq. (5) from Spreen et al. (2017). However, deformation rates from the experiment with $P^* = 100$ kN m^{-2} are relatively high compared to other experiments, especially in winter (Fig. 11a), despite the relatively low thickness arising from this experiment (Fig. ~~??). This is further discussed later~~ 9a). The net ice production resulting from this experiment, which combines all sea ice mass

10 balance processes described in Rousset et al. (2015), is 1.5 times lower than the four other experiments on average, which all provide a very similar seasonal cycle (Fig. 11b). Therefore, relatively high deformation rates with $P^* = 100$ kN m^{-2} are compensated by relatively low net ice production, which provides low ice thickness. Table 2 provides a summary of mean ice thickness, drift speed, deformation rates and net ice production averaged over the whole period and over the SCICEX box.

The experiments with higher P^* also provide a more uniform sea ice thickness distribution resulting from a higher ice

15 strength. Figure 12 shows the distribution of ice-covered grid cells in each thickness bin for both winter and summer months: the higher the ice strength (higher P^*), the higher the number of grid cells in the modal class (2.5-3 m in winter and 1.5-2.5 m in summer), and the more uniform (i.e. peaked) the thickness distribution.

Higher sea ice drift speed with higher ice strength from ~~July to September~~ June to August, except for $P^* = 100$ kN m^{-2} (Fig. 9b) ~~is also in contradiction with the expectations from the positive drift-strength feedback. It~~ , probably stems from the fact

20 that for higher strength, ice thickness is lower at the beginning of the summer (Fig. 9a), leading to higher drift speed values. The modelled drift speed is closer to observations with ~~λ = 2~~ $P^* = 5.5$ kN m^{-2} in June and July, $P^* = 27.5$ kN m^{-2} in May and from September to ~~March, λ = 1.5 in April and May, λ = 0.5 in August, and all the modelled curves are out of the observed range in June and July.~~ November, $P^* = 45$ kN m^{-2} from December to February and in April, $P^* = 100$ kN m^{-2} in March. Therefore, there is no single ~~λ~~ P^* value that provides a best ~~estimate for~~ fit to observed drift speed.

25 Figure 13 shows the drift-concentration and drift-thickness relationships for the model with different ~~initial λ values(only λ = 1 and λ = 2 are shown for the drift-thickness relationship)~~ P^* values as well as observations in terms of mean seasonal cycle averaged over the period 1979-2013 and over the SCICEX box. All model simulations but one (~~λ = 0.5~~ $P^* = 5.5$ kN m^{-2}) provide coherent relationships with significant slopes at the 5 % level, i.e. a decreasing drift speed with increasing concentration and thickness as well as a hysteresis loop for the drift-thickness relationship. For the drift-concentration relationship (Fig. 13a),

30 the ~~λ = 1.5~~ $P^* = 45$ kN m^{-2} curve is closer to observations in terms of slope ratio ($s_A = 0.7$) and normalised distance ($\epsilon_A =$ ~~2.3~~ 2.5%). For the drift-thickness relationship (Fig. 13b), the slope ratio is the highest with ~~λ = 2~~ $P^* = 100$ kN m^{-2} ($s_h = 0.8$) and the normalised distance is the smallest with ~~λ = 1.5~~ $P^* = 20$ kN m^{-2} ($\epsilon_h =$ ~~2.7~~ 6%). It is also clearly apparent from Fig. 13b that a higher ~~λ~~ P^* parameter value leads to lower thickness and a higher amplitude of the seasonal cycle of drift speed.

~~Increasing ice strength via the λ parameter leads to lower thickness values (Fig. 9a). A more careful spatial analysis allows~~

35 ~~us to see that this lower ice thickness appears everywhere in the Arctic and during all months of the year, with the most visible~~

differences occurring north of Greenland where ice is the thickest (Fig. 10). This counter-intuitive result (given the positive drift-strength feedback) is due to the more uniform sea ice thickness distribution resulting from a higher strength. Figure 12 shows the distribution of ice-covered grid cells in each thickness bin for both winter and summer months: the higher the ice strength (λ), the higher the number of grid cells in the modal class (2.5-3 m in winter and 1.5-2.5 m in summer), and the

5 more uniform (i.e. peaked) the thickness distribution. This higher uniformity in thickness distribution results in smaller heat loss to the atmosphere compared to a more heterogeneous thickness distribution, which leads to lower sea ice production in winter. This is confirmed by the analysis of sea ice thickness in the beginning of model simulations (i.e. in 1958), when thickness differences between the four simulations are caused only by strength differences (and not by the mean state). Thus, thickness gets lower with higher initial ice strength. The best λ option related to this diagnostic lies between 1.5 and 2 when

10 compared to PIOMAS thickness. Therefore, we conclude that the negative thermodynamic feedback between sea ice thickness and heterogeneity competes with (and dominates) the positive drift-strength feedback in these sensitivity experiments.

4 Discussion

4.1 Novelties of the present study

The main novelty of the present study is the in-depth analysis of the ~~positive feedback~~ interactions between Arctic sea ice

15 drift and sea ice ~~state~~ strength (concentration and thickness) ~~in great detail~~ via an extension of the work carried out by Olason and Notz (2014) and a series of model sensitivity experiments in which the sea ice strength is varied. Rampal et al. (2011) mention ~~this feedback~~ these interactions as an important element of Arctic sea ice processes and other studies analyse interactions between some elements of the system (Spreen et al., 2011; Kwok et al., 2013; Langehaug et al., 2013; Olason and Notz, 2014), but none of these studies quantifies the magnitude of ~~the~~ drift-strength ~~feedback~~ interactions in detail. Here

20 we address this issue using NEMO-LIM3.6 at 1° resolution with several process-based diagnostics and metrics as well as sensitivity experiments with different values of initial sea ice strength.

The drift-concentration and drift-thickness diagnostics and metrics used here are based on the work ~~from~~ of Olason and Notz (2014). They analyse the interactions between the three variables using different observational datasets within the SCICEX box. ~~At the seasonal timescale~~ On seasonal timescales, they find that sea ice concentration controls sea ice drift speed in summer

25 (when concentration is relatively low) and sea ice thickness is the main driver in winter (when concentration is relatively high). In our analysis, we include model results and we also find that drift speed is anti-correlated to concentration during summer months in the same SCICEX box (Fig. 8a). ~~However, we do~~ We also find that drift speed is anti-correlated to thickness not only during winter months but also during summer (with a clearer relationship for the observations compared to the model, Fig. 8b). In our study, we do not normalise sea ice drift speed by wind friction speed as in Olason and Notz (2014) because the same

30 relationship is found with and without normalisation. In sum, we find that on seasonal timescales drift speed is controlled by both thickness and concentration.

A previous study demonstrated the impact of increased ice strength using a coupled ice-ocean model to account for large-scale effects (Häkkinen and Mellor, 1992). They use both the classical Hibler parameterisation for ice strength as well as a square

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~~dependence of ice strength on thickness for first-year sea ice to account for large-scale effects following Overland and Pease (1988) and compare both approaches. They show that increased ice strength leads to thicker ice , which is different from what we find in this study (increased strength leads to thinner ice)~~There are some similarities between the results arising from our sensitivity experiments and the findings from Steele et al. (1997), which use a 40 km-resolution sea ice model based on Hibler (1979) over 7 model years. They explain that, as P^* decreases (for $P^* < 30\text{-}40$ kN m^{-2}), internal stress gradient decreases and mean ice motion increases (with ice nearly in free drift for $P^* = 5.5$ kN m^{-2}), which leads to higher ice thickness. However, ~~Häkkinen and Mellor (1992) do not use an ITD scheme and the sea ice extent is better simulated by the Hibler parameterisation compared to Overland and Pease (1988). Since the presence of an ITD scheme in a sea ice model modifies the relationship between thickness and strength (Holland et al., 2006), this may explain the discrepancies between our results and Häkkinen and Mellor (199~~ ~~Some sea ice models that include an ITD scheme use P scaling as $h^{3/2}$ so that the sensitivity of strength to thickness is higher (Lipscomb et al., 2007).~~ for $P^* > 55$ kN m^{-2}, ice thickness slightly increases with increasing P^* in Steele et al. (1997) due to the progressive locking of sea ice (the ice motion ceases), providing an ice thickness mainly determined by equilibrium thermodynamics. We do not observe this nonlinearity in our sensitivity experiments as ice thickness continues decreasing with increasing P^* for $P^* \geq 45$ kN m^{-2} (Fig. 9a). Several reasons could explain this difference between Steele et al. (1997) and our study, including differences in model physics (e.g. ice thickness distribution included in our model), model parameters (e.g. grid resolution, time step), experimental setup (e.g. model years) and averaging domain. However, in our experiments, ice thickness from February to June is very similar between $P^* = 45$ kN m^{-2} and $P^* = 100$ kN m^{-2} (Fig. 9a) and deformation rates with $P^* = 100$ kN m^{-2} are relatively high (Fig. 11a). Therefore, this nonlinearity may occur for $P^* > 100$ kN m^{-2}.

Our study can also be used to identify ~~what is the best option for λ in the Hibler equation (1) by comparing the different simulations to observations. However,~~ which P^* values yield results close to reference products (observations and reanalyses). Our findings suggest that the best match is strongly dependent upon the month of the year. For sea ice thickness, the amplitude of the modelled seasonal cycle is higher ~~than the observed one~~than the ones derived from submarine observations and PIOMAS renalysis, so that all ~~λ~~ P^* values ranging from ~~0.5 to 2~~5.5 to 100 kN m^{-2} could be used depending on the month ~~($\lambda = 1.5$ for January-March and June-July, $\lambda = 2$ for April-May, $\lambda = 1$ for August and November-December, and $\lambda = 0.5$ for September-October)~~ (Fig. 9a). For drift speed, the highest values ~~($\lambda = 1.5$ and 2~~of P^* (45 and 100 kN m^{-2}) better match observations in winter, and ~~it is difficult to find a best option in summer~~the lowest value (5.5 kN m^{-2})) is more suitable in summer (Fig. 9b). ~~Therefore~~In agreement with Massonnet et al. (2014), we do not ~~particularly recommend a given value of λ but rather recommend to exclude~~ recommend a specific value of P^*, since the optimal value for that parameter is dependent on many factors (resolution, atmospheric forcing, values chosen for other parameters, initial conditions, model). We still recommend excluding the lowest value ~~(λ $P^* = 0.5$)~~5.5 kN m^{-2}) from the possibilities due to a weaker representation of the drift-concentration and drift-thickness relationships (Fig. 13). This shows the limitations of the parameterisation from Hibler (1979) and could support the use of new sea ice rheologies, such as the elasto-brittle rheology ~~(Girard et al., 2009)~~(Girard et al., 2011; Dansereau et al., 2016).

4.2 Complexity of ~~the~~ drift-strength ~~feedback~~interactions

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~~The chain of causality involved in the~~

The potential positive feedback between sea ice drift and strength ~~, as initially presented and understood from the literature, is represented by blue boxes and arrows in Fig. ??. An~~ that is described in Rampal et al. (2011) proposes that an initial decrease in sea ice concentration or thickness leads to a decrease of sea ice strength and internal stress. This results in larger deformation and ~~enhances drift speedand the subsequent~~ enhanced drift speed. According to Rampal et al. (2011), this would lead to an increased export of sea ice out of the Arctic Basin~~. All this finally leads~~. This finally would lead to further decreases in sea ice concentration and thickness. ~~However, this~~ However, observations do not show an increase in ice export (Döscher et al., 2014) while there is a clear decrease in concentration and thickness (Stroeve et al., 2012; Vaughan et al., 2013) and increase in drift speed (Spreen et al., 2011). Furthermore, our study shows that ~~the feedback loop~~, even if this positive feedback exists, it is more complex than Rampal et al. (2011) suggest for two main reasons.

The first complication is the fact that a change in export of sea ice is not only a cause but also a consequence of changes in concentration and thickness. The volume export is the product of sea ice drift speed, concentration and thickness. Therefore, a decrease ~~of~~ in concentration or thickness will both emphasize the positive feedback by increasing drift speed and the resulting export of sea ice, and reduce its magnitude by directly decreasing export of sea ice ~~(red arrows in Fig. ??)~~. This will balance the resulting sea ice export.

We compute sea ice export at Fram Strait from sea ice drift speed, thickness (which takes into account concentration, since our thickness is the sea ice volume per area) and transect length at two different latitudes ($76°N$ and $80°N$) following Spreen et al. (2009). From 1979 to 2013, the volume flux modelled by NEMO-LIM3.6 decreases with a negative trend of $1.8 \text{ km}^3 \text{ d}^{-1}$ decade^{-1} in the control simulation ($\lambda P^* = \cancel{1}20 \text{ kN m}^{-2}$) but interannual variations are very large, especially at the southern transect ($76°N$). Increasing ice strength (by increasing λP^*) results in a decreasing volume flux at Fram Strait mainly due to the lower thickness. Therefore, in our model the direct effect of decreasing concentration and thickness is more important than the impact of increasing drift speed on the export at Fram Strait.

The second ~~difficulty is the addition of another negative thermodynamic feedback linked to~~ source of complexity is the fact that sea ice thickness ~~and strength, which explains the decreasing sea ice thickness for an initially increasing~~ decreases with higher ice strength (Section 3.3). If the drift-strength feedback dominated in our P^* experiments, ice thickness would be higher for higher ice strength (~~Section 3.3~~higher P^*), due to lower drift speed and export. However, ice thickness decreases with higher ice strength due to lower deformation (Figs. 9a and 11a). ~~A higher strength results in a less heterogeneous sea ice thickness distribution during all months of the year (Fig. 12), which leads to smaller heat losses to the atmosphere, smaller production of sea ice in winter, and thus thinner ice. We update our initial~~ Thus, isolating the drift-strength ~~feedback diagram by taking into account this negative feedback (yellow boxes in Fig. ??). These findings are consistent with results obtained with NEMO-LIM3.6 using two different spatial resolutions: the lower resolution also results in a more uniform thickness distribution, which~~ feedback with a set of sensitivity experiments is difficult.

A previous study demonstrated the impact of increased ice strength using a coupled ice-ocean model to account for large-scale effects (Häkkinen and Mellor, 1992). They use both the classical Hibler parameterisation for ice strength as well as a square dependence of ice strength on thickness for first-year sea ice following Overland and Pease (1988) and compare both approaches.

They show that increased ice strength leads to thicker ice, which is different from what we find in this study (increased strength leads to thinner ice). However, Häkkinen and Mellor (1992) do not use an ITD scheme, which may explain the difference with our results. Some sea ice models that include an ITD scheme use P scaling as $h^{3/2}$ since it is more physically realistic than P scaling as h (Rothrock, 1975). However, using such a scaling is less numerically stable (Lipscomb et al., 2007) and leads to poorer agreement with observations (Ungermann et al., 2017). According to Leppäranta (2011), the exact value of the thickness exponent remains an open question.

To test the impact of such a scaling on the resulting ice thickness and drift speed, we also performed sensitivity experiments in which we introduce an exponent λ in the ice strength equation (1), varying between 0.5 and 2 ($\lambda = 1$ corresponds to the original formulation of Hibler (1979)):

$$P = P^* h^\lambda \exp[-C(1-A)]. \tag{5}$$

These experiments are more complex than the P^* experiments since they introduce a nonlinear dependence between ice strength P and ice thickness h but they provide insight into the understanding of the impact of a change in the ice strength parameterisation. Overall, these experiments lead to similar conclusions as for the P^* experiments: higher λ leads to lower ice thickness. ~~Thus, isolating the drift-strength feedback with a set of sensitivity experiments is difficult.~~, lower drift speed in winter and higher drift speed in summer, lower ice thickness heterogeneity, and a similar behaviour for drift-concentration and drift-thickness relationships.

An additional element that has not been studied here and could increase the complexity of the ~~feedback~~ drift-strength interactions is the interaction between the ocean-sea ice system and the atmosphere. In this analysis, we use an ocean-sea ice model forced by atmospheric reanalysis. A full coupling with the atmosphere could provide different results regarding drift-strength interactions. For example, Juricke and Jung (2014) find that the implementation of a stochastic sea ice strength parameterisation leads to different responses in ~~both~~ the coupled ECHAM6-FESOM model ~~and~~ compared to the FESOM model forced by atmospheric fluxes generated by the coupled model. In the uncoupled simulation, the Arctic sea ice volume increases compared to a reference run without parameterisation, while the volume remains largely unchanged in the coupled simulation. This suggests that a negative atmospheric feedback explains the differences between both coupled and uncoupled modes. Therefore, care needs to be taken when extrapolating results from forced simulations to coupled models. Specifically for our study, the effect of coupling on ~~the~~ drift-strength ~~feedback~~ interactions could be assessed by comparing our results to coupled simulations using NEMO-LIM3.6 (e.g. EC-Earth in the framework of CMIP6).

4.3 Impact of domain choice

In this study, we compute spatial means both over the SCICEX box, roughly corresponding to the Central Arctic, and over a wider domain encompassing all grid cells north of 50°N with a concentration threshold ($A \geq 0.15$). ~~For physical reasons and figure readability, the former domain is preferred~~ We prefer using the SCICEX box in our study ~~. Furthermore, from the results obtained and already discussed in Section 3, it is clear that the latter domain is too vast to give a good agreement with observations. Particularly, using a too wide domain such as our second~~ because it produces much better agreement between

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the model and observations. The wider domain includes the large model biases occurring in the vicinity of the ice front and of straits(~~,~~ e.g. model overestimation of drift speed at Fram Strait ~~). A decomposition of the Arctic Ocean into sub-regions such as in Koenigk et al. (2016) would be a better alternative. However~~(Fig. 5).

The use of the wider domain produces results for drift-concentration and drift-thickness relationships that clearly diverge compared to observations due to the inclusion of coastal grid cells that have high model biases. Computing mean concentration, thickness and drift speed over the Central Arctic (SCICEX box in our analysis) provides values that are much more consistent with observations and more representative of Arctic conditions.

Therefore, the comparison between our central and wide domains demonstrates the impact of domain choice, with generally ~~higher skills~~ better performance when using the central domain. A decomposition of the Arctic Ocean into sub-regions such as in Koenigk et al. (2016) would be a possible improvement compared to the use of a single wider domain.

4.4 How can this methodology help in future model intercomparisons?

The methodology proposed in this analysis, particularly the process-based diagnostics and metrics, can be used to assess the performance of other models against observational datasets, which will be an important component of SIMIP (Notz et al., 2016). It can be extended to models being forced by atmospheric reanalysis (such as the model used here) as well as fully coupled models, in order to provide a benchmark for further model intercomparison. ~~Process-based metrics, such as~~ In the framework of such a model intercomparison, the use of the process-based metrics that we developed (slope ratios and normalised distances~~, help identify~~) may be valuable for identifying which models fall within the observational range.~~However, the use of a single number always needs to be put in perspective with the broader picture. For example, a model with a good slope ratio might poorly represent drift-thickness hysteresis (e.g. the PIOMAS/PIOMAS pair in Fig. 8).~~

In this study, we only focus on one model resolution. Although some preliminary results show that a higher spatial resolution with the same model provides a higher sea ice thickness, there is a need for a deeper analysis of the impact of model resolution. The methodology proposed fits quite well into the framework of the EU Horizon 2020 PRIMAVERA project (https://www.primavera-h2020.eu/), which aims at evaluating the effect of high resolution in global climate models.

Finally, this process-based analysis provides an alternative to classic model evaluations that only look at sea ice extent and thickness. It systematically highlights the links between sea ice dynamic and thermodynamic processes. Evaluating new sea ice rheologies using this methodology will provide a stronger test of model performance.

5 Conclusions

This study first shows that the global ocean-sea ice NEMO-LIM3.6 model is able to reproduce the observed sea ice extent, concentration, thickness and drift speed reasonably well over the historical period (from 1979 to 2013). Monthly mean trends in concentration, thickness and drift speed are also in the observational range, except for the trend in drift speed during summer. We show that this model bias is linked to the removal of sea ice in the eastern Central Arctic rather than an actual decrease of drift speed.

The interactions between sea ice drift speed and strength are well represented through the relationships between drift speed and concentration on the one hand, and drift speed and thickness on the other hand. In particular, the increasing drift speed with lower concentration and thickness is reproduced by the model. The drift-thickness relationship is marked by a hysteresis loop: two drift speed values are possible for a given thickness depending on the season, with a higher sea ice drift speed during the melting season and a lower value during the growing season. When considering the relationships between the trends in drift speed, concentration and thickness, the spread between the model and observations is higher mainly due to too low summer trend in modelled drift speed.

Sensitivity experiments ~~provide counter-intuitive results related~~ show that higher initial ice strength leads to ~~the positive drift-strength feedback~~lower ice thickness. ~~With higher initial sea ice strength, we would expect higher ice thickness. However, the opposite happens due to a higher uniformity of sea ice thickness distribution with a higher initial ice strength , leading to lower conduction fluxes and smaller ice production . This negative thermodynamic feedback is therefore competing with the positive drift-strength feedback and dominates it in the context of these experiments.~~This is due to lower deformation rates that prevents ice piling up, especially north of Greenland and the Canadian Archipelago. In the case of the highest strength experiment used here, net ice production is relatively low, which compensates for relatively high deformation rates. These experiments also show that no single value of ~~thickness exponent~~ P^* is the best option for reproducing the observed drift speed and thickness, but the best option depends on the variable and on the month of the year. We ~~do not recommend an ad hoc variation of the Hibler parameterisation, and we instead~~ suggest that other rheologies might be more appropriate.

Finally, this study shows that the interactions between sea ice dynamics and state are ~~more complex than previously thought~~and cannot be summarised by a simple feedback loop. The diagnostics and metrics proposed in this study that relate drift speed to concentration and thickness are necessary conditions for representing the drift-strength ~~feedback~~interactions, but they are not sufficient. Sensitivity experiments in which sea ice strength is varied are also essential for ~~validating the feedback~~gaining insight into these interactions. While NEMO-LIM3.6 correctly represents the drift-concentration and drift-thickness relationships, sensitivity experiments show that processes other than the drift-strength feedback are more important in driving sea ice thickness and drift speed responses. ~~It is thus hard to isolate the drift-strength feedback from other processes.~~ In this analysis, we use one resolution of one model with an atmospherically forced mode. A multi-model assessment using different model resolutions, e.g. in the framework of the EU Horizon 2020 PRIMAVERA project, will provide further insight into the interactions between sea ice dynamics and state.

6   Code availability

All codes for computing and plotting the results of this article are written in Python programming language and are available upon request.

Author contributions. DD, FM and TF designed the experimental study. FM and AB performed the model simulations. DD collected the observational datasets, developed the diagnostics and metrics, analysed the results and produced the figures. NFT and OL provided substantial feedback to the analysis. DD prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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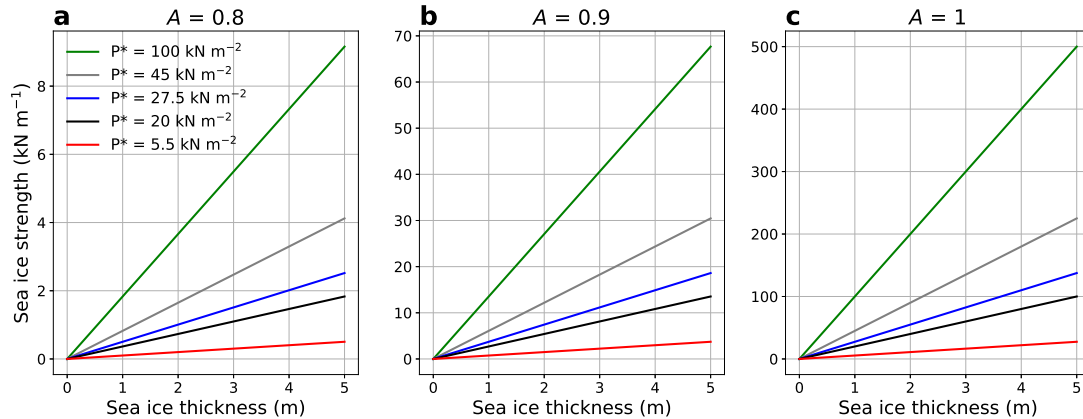
Figure 1. Sea ice strength as a function of sea ice thickness computed from ~~Hibler (1979) equation~~ Eq. (1) (Hibler, 1979) for ~~four~~ five given values of ~~λ~~P^* corresponding to the five sensitivity experiments. The three panels correspond to three different values of sea ice concentration: (a) $A = 0.8$, (b) $A = 0.9$, (c) $A = 1$. Note that the y axes are different in the three panels.
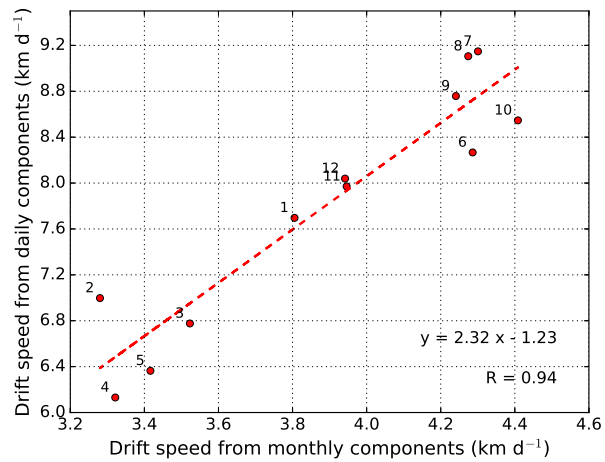
Figure 2. Scatter plot of modelled (NEMO-LIM3.6) monthly mean sea ice drift speed computed from daily components against drift speed based on monthly components. Data are temporally averaged over the period 1979-2013 and spatially averaged over the SCICEX box. Numbers denote months. The dashed line represents the linear regression. The equation of the linear regression and the Pearson correlation coefficient between both variables are shown in the lower right corner.
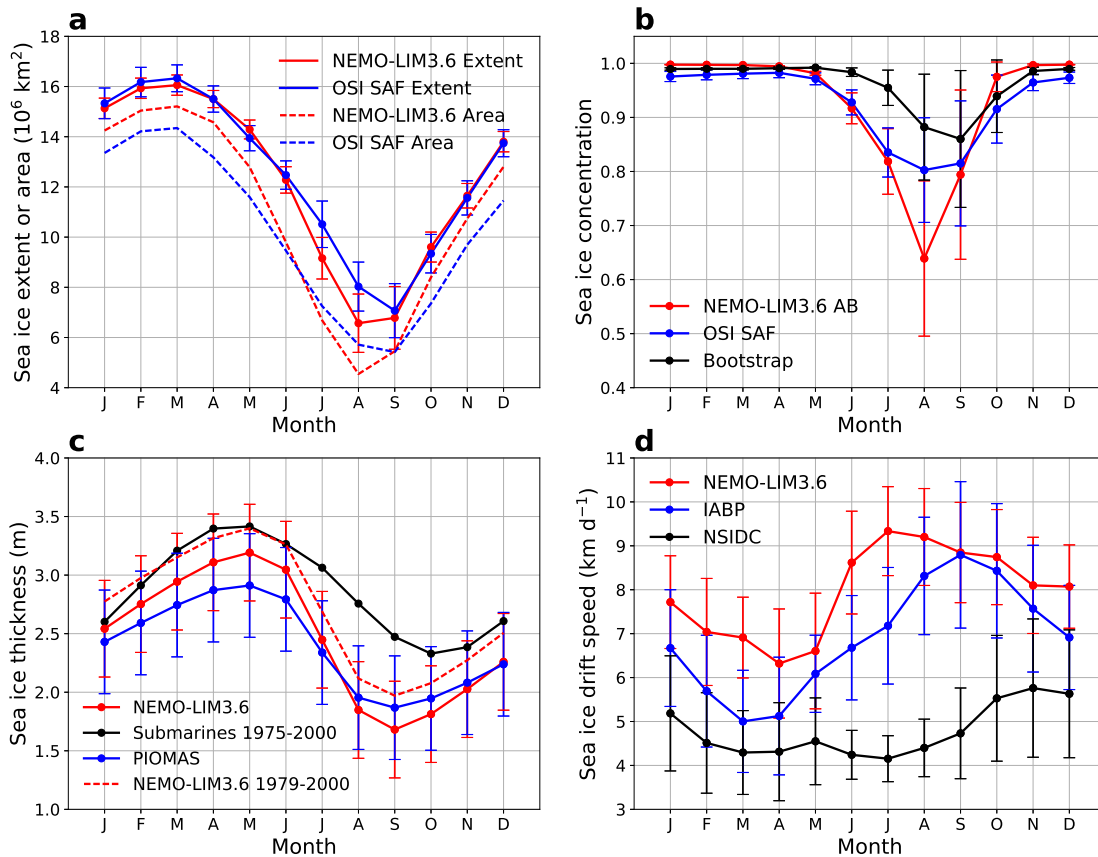
Figure 3. Modelled (NEMO-LIM3.6) and observed monthly mean seasonal cycles of Arctic sea ice (a) extent (total area of grid cells where concentration is higher than 0.15) and area, (b) concentration, (c) thickness (sea ice volume per area) and (d) drift speed averaged over the period 1979-2013 (except for submarine observations that span 1975-2000). The spatial mean over the SCICEX box is ~~represented~~ shown in (b), (c) and (d). Sources for observations and reanalysis: OSI SAF satellite data for extent and concentration, Bootstrap satellite data for concentration, submarines and PIOMAS reanalysis for thickness~~and drift speed~~, ~~and~~ IABP buoys and NSIDC (Tschudi et al., 2016) for drift speed. ~~PIOMAS drift speed data are computed from monthly velocity components and are multiplied by two to be comparable to other drift data.~~ Error bars show the temporal standard deviation of monthly values. In panel (c), the model seasonal cycle is also computed over 1979-2000 to allow for more direct comparison with submarine observations.
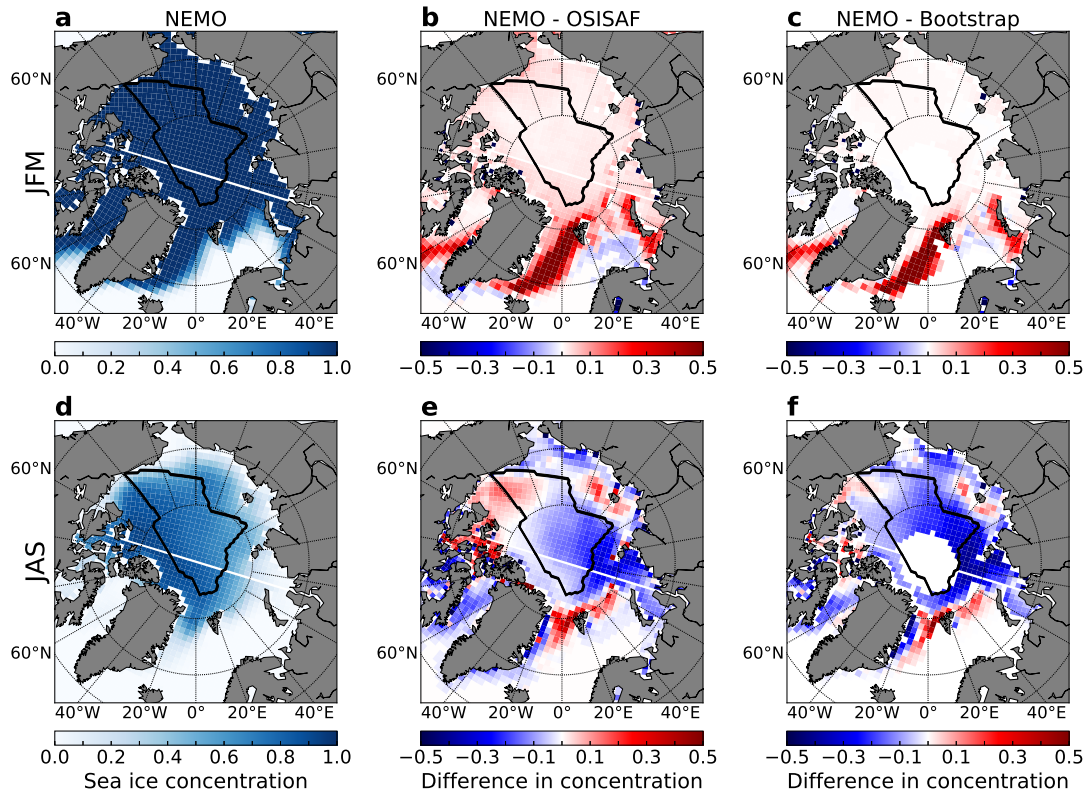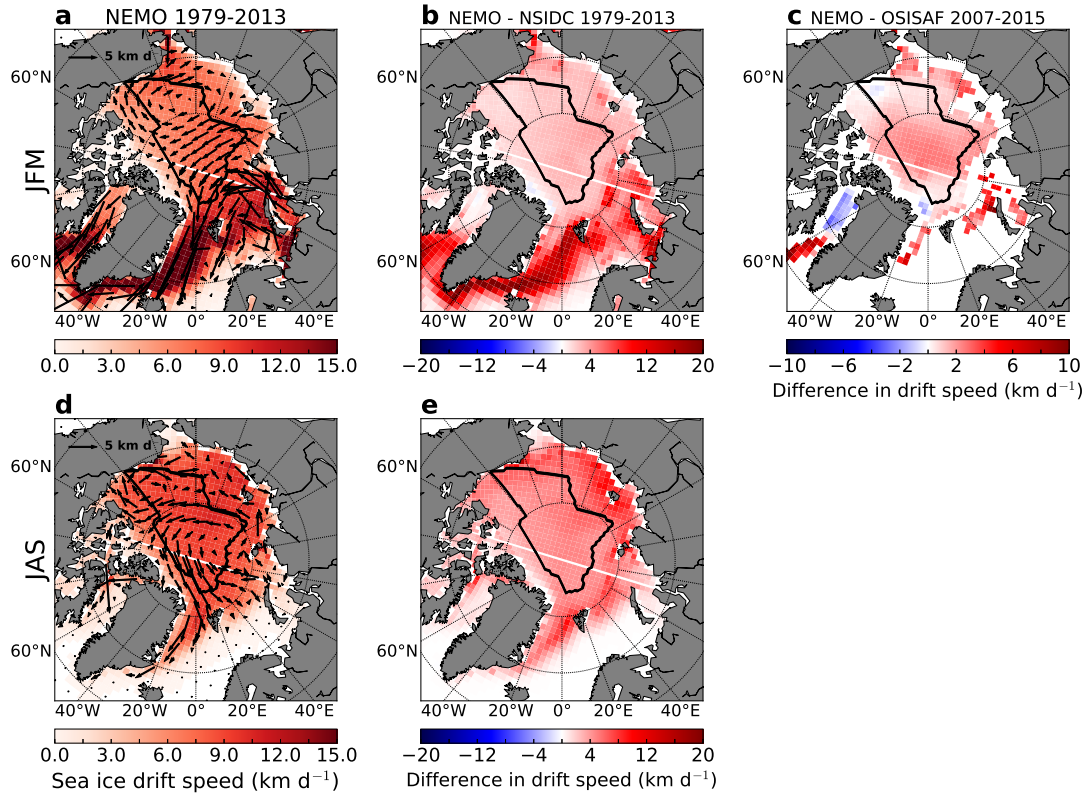
Figure 4. (a) Modelled (NEMO-LIM3.6) mean Arctic sea ice concentration averaged over the winter months (JFM, i.e. January-February-March) of the period 1979-2013. (b) Difference in concentration between NEMO-LIM3.6 and OSI SAF averaged over the winter months of the period 1979-2013. (c) Difference in concentration between NEMO-LIM3.6 and Bootstrap averaged over the winter months of the period 1979-2013. (d), (e), (f) Same as (a), (b), (c) respectively for the summer months (JAS, i.e. July-August-September). The black polygon ~~is the contour of~~ marks the SCICEX box.

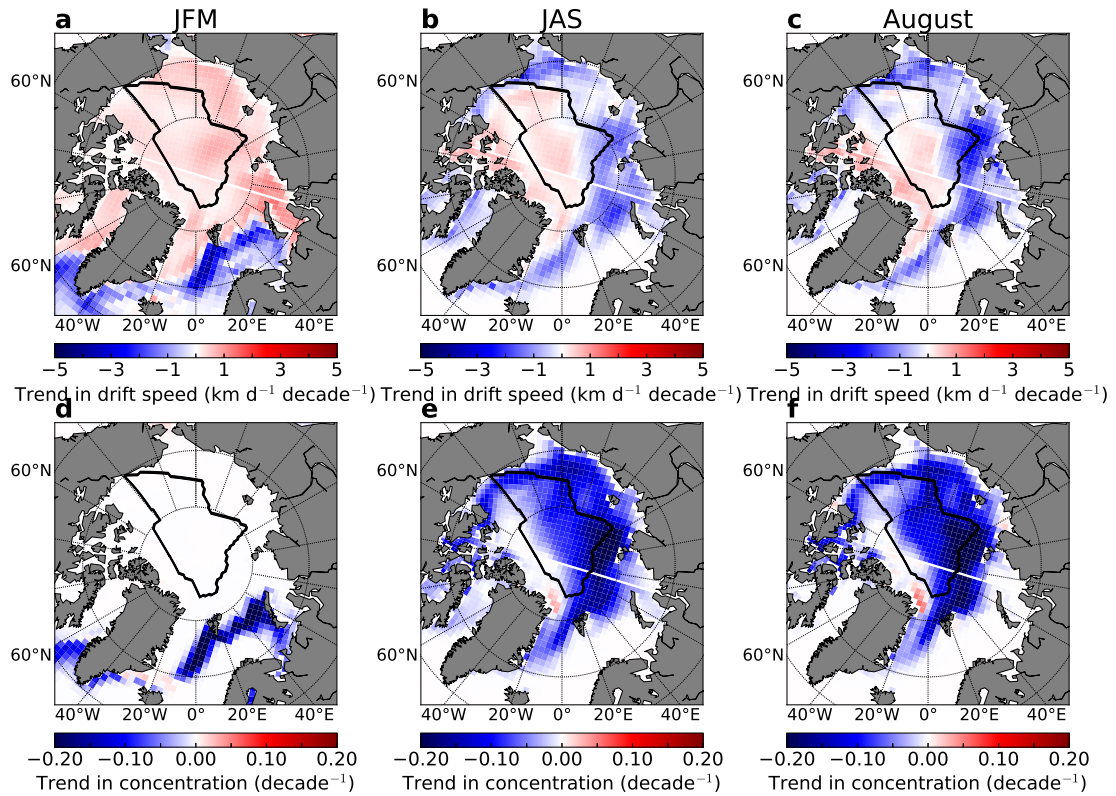**Figure 5.** (a) Modelled (NEMO-LIM3.6) mean Arctic sea ice drift speed averaged over the winter months (JFM, i.e. January-February-March) of the period 1979-2013. (b) Difference in drift speed between NEMO-LIM3.6 and ~~PIOMAS~~ the NSIDC dataset (Tschudi et al., 2016) averaged over the winter months of the period 1979-2013. (c) Difference in drift speed between NEMO-LIM3.6 and OSI SAF averaged over the winter months of the period 2007-2015. (d), (e) Same as (a), (b) respectively for the summer months (JAS, i.e. July-August-September). OSI SAF drift data are not available in summer. The black polygon ~~is the contour of~~ marks the SCICEX box.
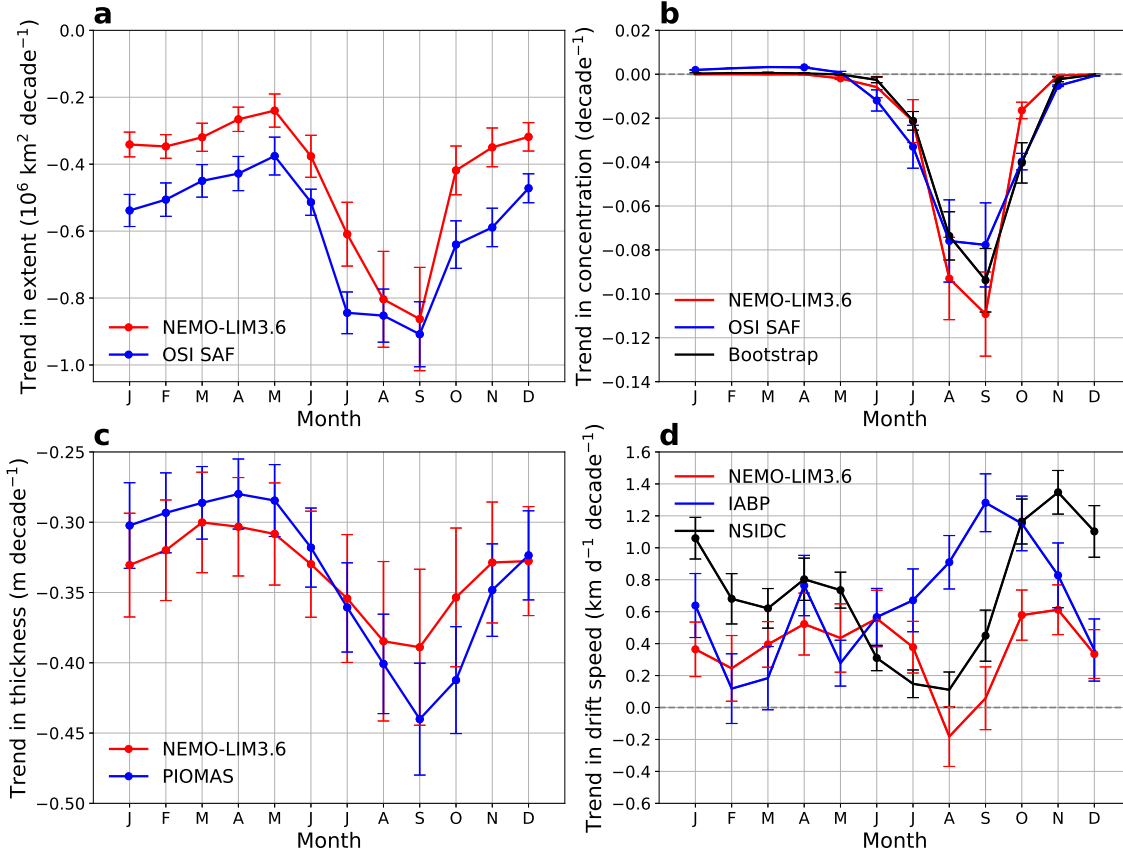
Figure 6. Modelled (NEMO-LIM3.6) and observed monthly mean seasonal cycles of trends in Arctic sea ice (a) extent, (b) concentration, (c) thickness and (d) drift speed averaged over the period 1979-2013. The spatial mean over the SCICEX box is ~~represented~~ shown in (b), (c) and (d). A dot is shown for monthly trends that are significant at the 5% level. Sources for observations and reanalysis: OSI SAF satellite data for extent and concentration, Bootstrap satellite data for concentration, PIOMAS reanalysis for thickness~~and drift speed~~, ~~and~~ IABP buoys and NSIDC (Tschudi et al., 2016) for drift speed. ~~PIOMAS drift speed data are computed from monthly velocity components and are multiplied by two to be comparable to other drift data.~~ Error bars show the temporal standard deviation of monthly values.

Figure 7. (a) Modelled (NEMO-LIM3.6) mean trend in Arctic sea ice drift speed averaged over the winter months (JFM, i.e. January-February-March) of the period 1979-2013. (b) Same as (a) for the summer months (JAS, i.e. July-August-September). (c) Same as (a) for August only. (d), (e), (f) Same as (a), (b), (c) respectively for sea ice concentration. The black polygon ~~is the contour of~~ marks the SCICEX box.
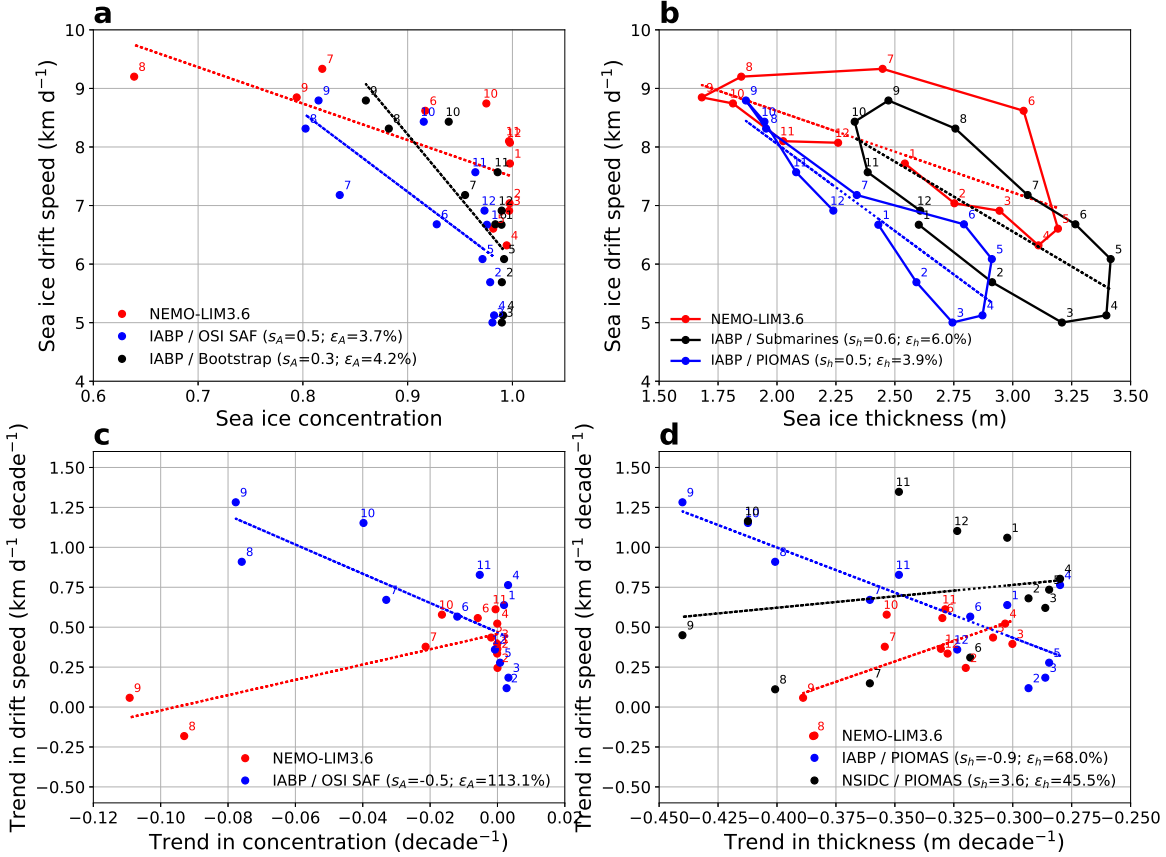
Figure 8. Scatter plots of modelled (NEMO-LIM3.6) and observed monthly mean sea ice drift speed against (a) concentration and (b) thickness temporally averaged over the period 1979-2013 <u>(except for submarine observations that span 1975-2000)</u> and spatially averaged over the SCICEX box. (c)<s>and</s><u>,</u> (d) <s>are similar plots</s> <u>Same as (a)</u><u>, (b)</u> for trends. Numbers denote months. Dotted lines show linear regressions. Sources for observations <u>and reanalysis</u>: IABP <u>and NSIDC (Tschudi et al., 2016)</u> for drift speed, OSI SAF and Boostrap for concentration, <u>submarines and</u> PIOMAS for thickness<s>and drift speed</s>. Slope ratios and normalised distances between NEMO-LIM3.6 and the different observation datasets are shown in brackets in the legends<s>of (a) and (b). PIOMAS drift speed data are computed from monthly velocity components and are multiplied by two to be comparable to other drift data.</s>
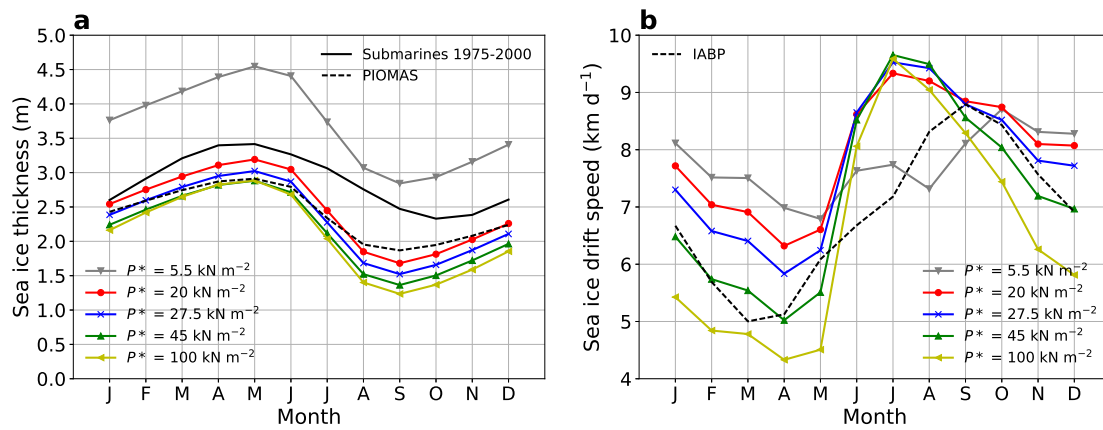
Figure 9. Modelled (NEMO-LIM3.6) monthly mean seasonal cycles of sea ice (a) thickness and (b) drift speed temporally averaged over the period 1979-2013 and spatially averaged over the SCICEX box for ~~four~~ five different λ P^* values (see Eq. (1)). Observations and reanalysis are represented as ~~dashed~~ black lines (submarine observations, spanning 1975-2000, and PIOMAS for thickness in (a) and IABP for drift speed in (b)).
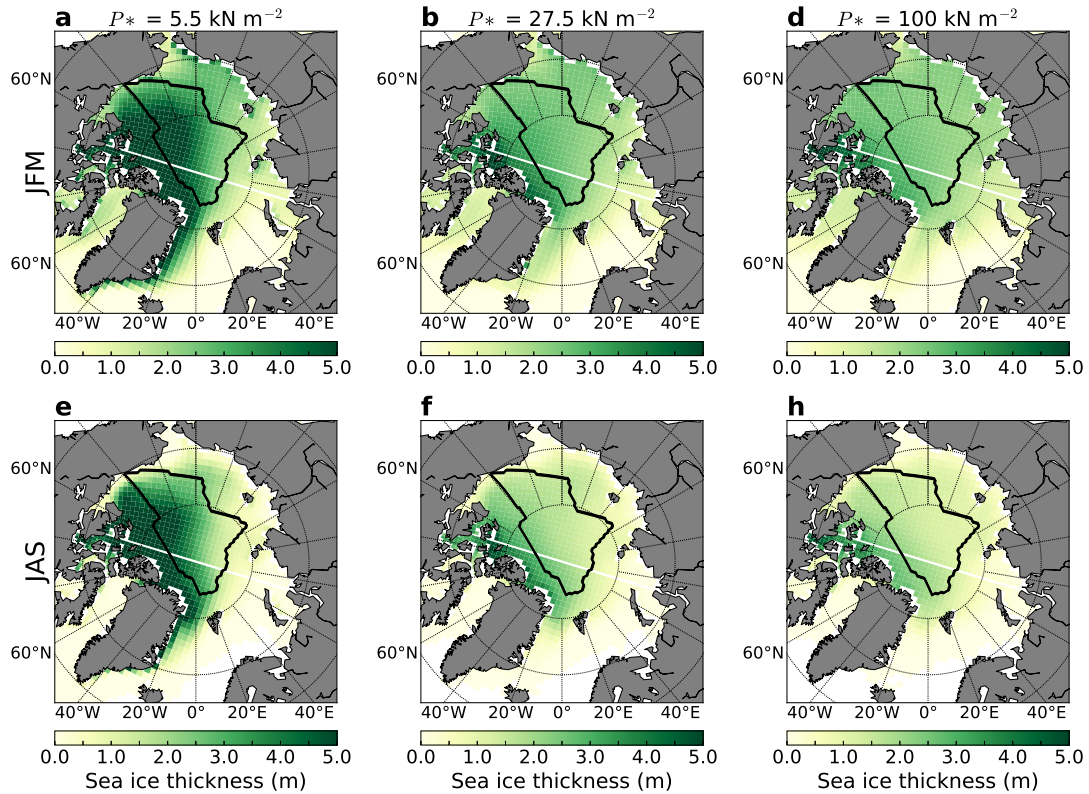
Figure 10. Modelled (NEMO-LIM3.6) mean Arctic sea ice thickness averaged over the winter months (JFM, i.e. January-February-March) of the period 1979-2013 for (a) ~~λ~~ P^* = ~~0.5~~5.5 kN m^{-2}, (b) ~~λ~~ P^* = ~~1~~27.5 kN m^{-2}, (c) ~~λ = 1.5, (d) λ~~ P^* = ~~2.~~100 kN m^{-2}. (e), (f), (g) ~~, (h)~~ Same as (a), (b), (c) ~~, (d)~~ respectively for the summer months (JAS, i.e. July-August-September). The black polygon ~~is~~ marks the ~~contour~~ SCICEX box.
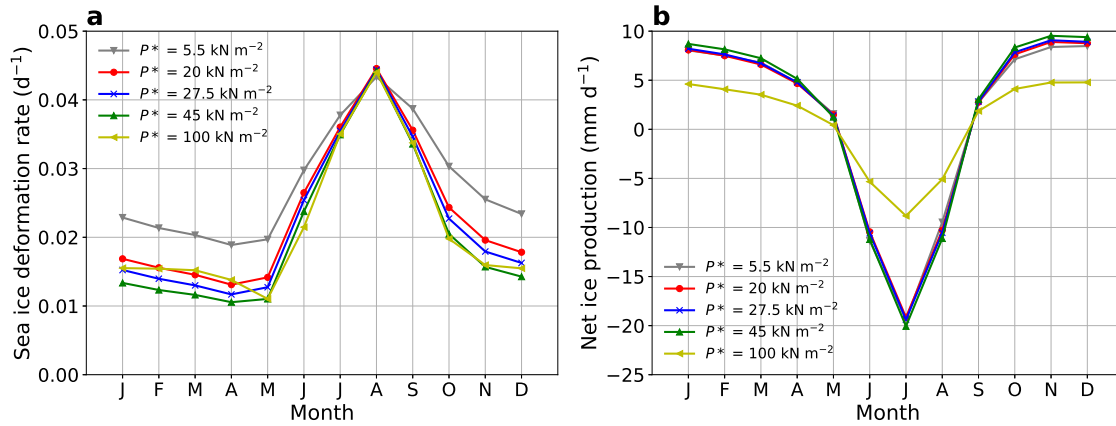
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Figure 11. Modelled (NEMO-LIM3.6) monthly mean seasonal cycles of (a) sea ice deformation rate and (b) net ice production temporally averaged over the period 1979-2013 and spatially averaged over the SCICEX box for five different P^* values.
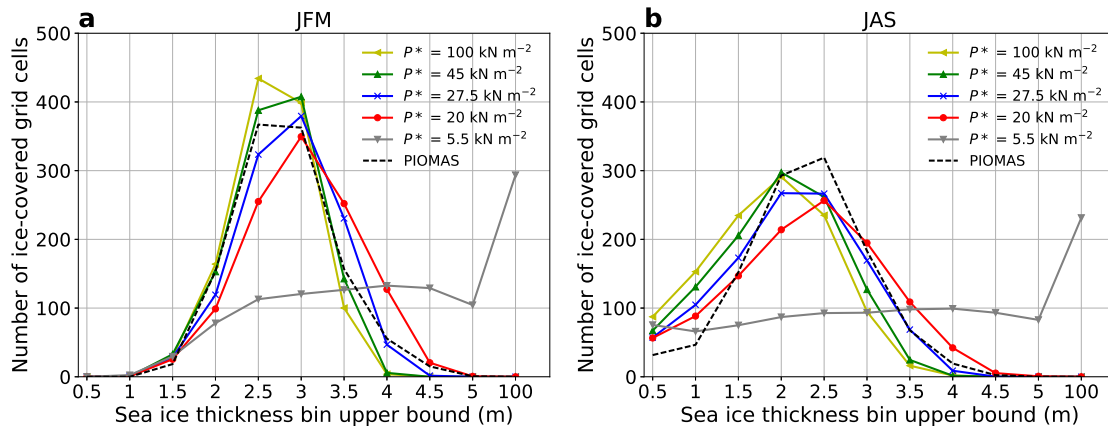

Figure 12. Number of ice-covered grid cells in each thickness bin temporally averaged over 1979-2013 and spatially averaged over the SCICEX box for both (a) winter (JFM, i.e. January-February-March) and (b) summer (JAS, i.e. July-August-September). Results are shown for NEMO-LIM3.6 (~~four~~ five different ~~λ~~ $P*$ values) and for PIOMAS reanalysis interpolated onto the ~~ORCA1~~ eORCA1 grid. The x axis shows the upper bound of each thickness bin.
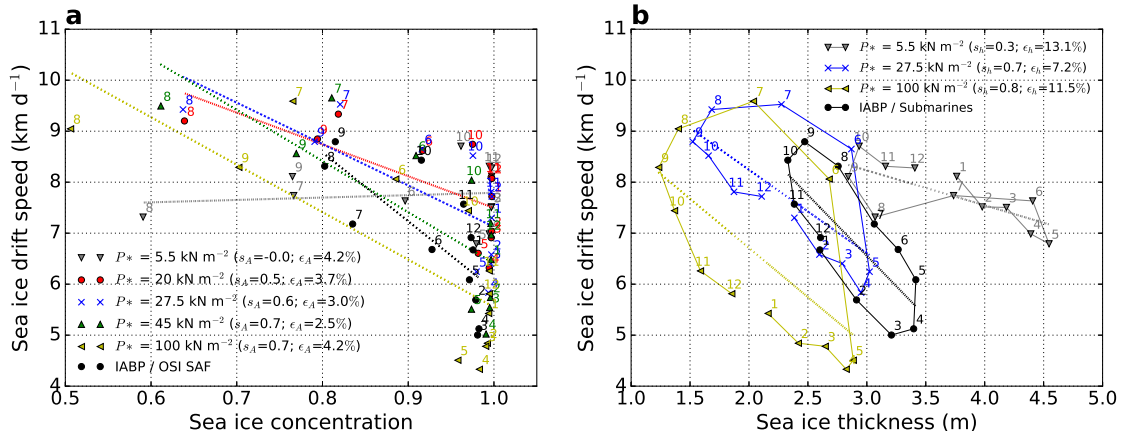
Figure 13. Scatter plots of modelled (NEMO-LIM3.6) monthly mean sea ice drift speed against sea ice (a) concentration and (b) thickness temporally averaged over the period 1979-2013 and spatially averaged over the SCICEX box for the different P^* values (only three values in (b) for readability). Numbers denote months. Observations and reanalysis are represented in black. Dotted lines show linear regressions. Slope ratios and normalised distances between NEMO-LIM3.6 and the different observation datasets are shown in brackets in the legend.

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Table 1. Summary of published literature providing observational drift speed trend and its cause, as well as area and volume export of sea ice at Fram Strait.

Reference	Drift speed	Cause of drift increase	Area export	Volume export
Häkkinen et al. (2008)	1950-2006: significant positive trend	Wind		
Spreen et al. (2009)				1990-2008: no significant change
Kwok (2009)			1979-2007: no significant trend	
Rampal et al. (2009)	1979-2007: +17% decade^{-1} in winter +8.5% decade^{-1} in summer	Ice strength		
Spreen et al. (2011)	1992-2009: +10.6% decade^{-1}	Ice strength (first) Wind (second)		
Gimbert et al. (2012)		Ice strength		
Polyakov et al. (2012)			1979-1995: increase	
Vihma et al. (2012)	1989-2009: increase	Ice strength (first) Wind (second)		
Kwok et al. (2013)	1982-2009: +6.2% decade^{-1} in winter +3.6% decade^{-1} in summer	Not wind	1982-2009: small decrease	
Langehaug et al. (2013)			1957-2005: small increase	
Döscher et al. (2014)	Increase	From 1990: ice strength Before 1990: wind	No long-term trend	Decrease
Olason and Notz (2014)	1979-2011: +1.1 km d^{-1} decade^{-1} in summer +0.4 km d^{-1} decade^{-1} in winter	Ice strength		
Krumpen et al. (2016)			1980-2012: significant positive trend	
Smedsrud et al. (2016)	Increase	Wind	1979-2014: +6% decade^{-1}	

Table 2. Mean sea ice thickness h, drift speed D, deformation rates d_r and net ice production p_i temporally averaged over the period 1979-2013 and spatially averaged over the SCICEX box for the five P^* experiments.

P^* (kN m^{-2})	h (m)	D (km d^{-1})	d_r (d^{-1})	p_i (mm d^{-1})
5.5	3.70	7.75	0.0277	1.27
20	2.47	7.96	0.0232	1.38
27.5	2.31	7.73	0.0219	1.41
45	2.16	7.23	0.0205	1.53
100	2.09	6.53	0.0214	0.95