Answer to the comments of Referee #1

We would like to thank Referee #1 for his/her suggestions to improve our paper. All comments have been addressed and a point by point response is provided below each comment. The reviewer comments are written in black, our answer in blue and the revisions in the paper are highlighted in red. The line numbers, which are used in the answers, correspond to the revised version of the manuscript (PDF file) unless otherwise indicated.

General comments

This article contains two pieces of work, the first being an assessment of the simulation of sea-ice (in particular sea-ice drift, SID) in a recent ensemble of 10 control members from a coupled regional climate model of the Arctic. The second part is then a sensitivity test, where the parameterization of surface exchange of momentum and heat between the ice and atmosphere is improved based on recent parameterization development documented in other papers. The research is state-of-the-art and an important step forward in the broader aim of trying to improve the fidelity of coupled climate models. The representation of Arctic sea ice is a long-standing known weakness in these models and improving the surface exchange parameterization is tackling one important weakness. The results of this study are mixed. Overall the model CTRL ensemble performs reasonably well compared to observational data sets (although these themselves have deficiencies). The new parameterization acts in a physically realistic way and leads to significant changes in surface variables. However, the authors state that it does not (yet) provide an improved simulation of sea ice, because no model tuning has been carried out yet, and they reserve this for future work.

Overall this is a very commendable study and an important piece of work, so I would like to see it published. I have a number of comments that would improve the manuscript that I'd like to see the authors take on board – some on the presentation that would greatly help new readers and make the work more accessible. The results of the second part of the study seem to end before the punch line! Normally upon introducing a new parameterization, authors invariably tend to find that their new parameterization improves the model. Here we seem to stop short of a full investigation of whether this is the case or not, because some tuning is required. I think this is reasonable, because the paper is already quite long at this point, and I am aware that such tuning is time consuming and opaque. But it does make the paper feel a little unfinished. Have the authors considered making this part 1 of a two-part paper, or at least spelling out in more detail the implied follow up study?

We added a new paragraph to describe the ideas for the implied follow-up study (line 476):

“Although the new parameterization does not improve the simulated dependency of SID on WS and sea-ice conditions compared to observations/reanalysis, the sensitivity study clearly shows that the new parameterization does increase the SID due to the added form drag. In a follow-up study, we are going to put efforts therefore on several aspects to improve the simulations. First, tunable parameters of the new parameterization, such as z_0, z_t, $Ce_{10,i}$, $Ce_{10,k}$ and β represent an opportunity to better adapt the form drag parameterization itself to the observations. A first step could be the use of values found by Elvidge et al. (2016). A large effect can be expected by a modification of the skin drag coefficient, since a large region would be affected, and large variations in the drag due to pressure ridges allow a wide range of values. Second, model parameters outside the new parameterization, which have direct impact on SID, like ice strength and ocean-ice drag coefficient, need to be harmonized with the new parameterization, since their values were chosen empirically in terms of adequately balanced performance of the model. A key is probably the oceanic form drag. Its effect is accounted for in the present study only indirectly via the constant oceanic drag coefficient. Such a parametrization is probably too simple, especially when atmospheric form drag is included (see also Tsamados et al., 2014). Birnbaum (2002) as well as Lüpkes et al. (2012b) found in a mesoscale modelling study that oceanic form drag can have a strong decelerating effect on SID especially when the sea ice concentration is low so that the discussed drawbacks for small sea ice fraction would be reduced or even removed. This effect of form drag on SID was discussed also by Steele et al. (1989). The parametrizations are evidently not balanced anymore after improving one key process of the SID-related atmosphere-ocean-ice interaction. A previous study on the surface-albedo feedback by Dorn et al. (2009) showed that an improved simulation can only be achieved by a harmonized combination of more sophisticated parameterizations of the related sub-processes. It can be assumed that this holds true for the SID-related sub-processes.”

Birnbaum, G., and Lüpkes, C.: A new parameterization of surface drag in the marginal sea ice zone, Tellus A: Dynamic Meteorology and Oceanography, 54, 107-123, 10.3402/tellusa.v54i1.12121, 2002.

Steele M., Morison, J.H., Untersteiner N. (1989) The partition of air-ice ocean momedntum exchange as a function of sea ice concentration, floe size, and draft. J. Geophys. Res. 94: 12739-12750.

We also revised the discussion of the new parametrization at line 530:

“The inclusion of the melt pond effect on the atmospheric form drag in the model might be beneficial. In the current version, form drag was only considered at the edges of ice floes, mainly in the marginal sea-ice zone but not on top of the ice where, melt ponds cause form drag also during summer (Andreas et al., 2010; Lüpkes et al., 2012a). Additional form drag at the ice-ocean interface may further improve the simulated SID-

WS relation, because the oceanic form drag has normally the opposite effect on the ice motion as the atmospheric form drag (Steele et al., 1989; Lüpkes et al., 2012b). Systematic biases in the reanalysis used for the calculation of the 'observed' wind factor cannot be excluded, since form drag is not taken into account in the underlying atmospheric model. Therefore, the increased deviation of the simulated SID-WS relation from the observations/reanalysis does not necessarily mean that the implemented new parameterization worsens the SID-WS relation. "

Specific Comments

1. The paper's title is long and a bit clumsy (three "ands"). I'd maybe try to reword.

We agree and modified the title to

"Evaluation of Arctic sea-ice drift and its dependency on near-surface wind and sea-ice conditions in the coupled regional climate model HIRHAM-NAOSIM"

2. In the Introduction I would recommend a short discussion on the quality of the surface exchange parameterization you've introduced. Around L65 you point out that parameterizations without a form drag element for momentum exchange are "poorly constrained" and that a recent observations-based form-drag parameterization has been implemented in a model by Renfrew et al. Here I think you need a few sentences pointing out that the mathematical parameterizations by Lüpkes et al. 2012 and Lüpkes and Gryanik 2015 were constrained by summertime observations over the sea-ice pack (from Andreas et al. 2010) and by limited aircraft observations over the MIZ (marginal ice zone). Then more comprehensively validated and tuned over the MIZ by a larger set of aircraft observations in Elvidge et al. 2016 [Note, this paper is not in the reference list, but there is a citation for Elvidge et al. 2018 in the manuscript, but no reference, so I think you mean the 2016 paper]. Importantly, I think you also need to point out that most of the validation and tuning has been done for momentum exchange (i.e. C_{DNi}), very little validation has been done for heat or moisture exchange (i.e. C_{HNi}). The validation and tuning for scalar fluxes is, I think, still something of an open question.

We corrected the citation and added a short discussion on the quality of the surface exchange parameterization following the Referee's suggestions (line 72):

"The physical parameterizations suggested by Lüpkes and Gryanik (2015) were constrained by summertime observations over the sea-ice pack and by aircraft observations over the marginal ice zone (MIZ) during winter. Later the parameterizations were once more validated using a larger and independent set of aircraft data obtained from campaigns during different seasons (Elvidge et al., 2016). This validation work concerned the momentum fluxes. The assumptions of Lüpkes and Gryanik (2015) about heat and moisture fluxes over the MIZ could not yet be evaluated by measurements. Thus, further research is necessary on this issue."

3. Page 4 contains a mathematical description of the new surface exchange parameterization for over sea ice, based on Lüpkes et al. 2012 and Lüpkes and Gryanik 2015. I am familiar with these two papers and I think you are right to leave most of the mathematical details out of this article and refer the reader to these previous articles for details. However, what is tricky is that both of these previous articles are long and technical, with more than 60 and 70 equations in them respectively, and both contain several sets of parameterizations in a hierarchy of complexity. This makes checking the summary you have here difficult, especially as the notation used here is slightly different to the previous papers. I think you need to be more specific and say which equations from the two above papers are implemented and try to use notation that is as close as possible to what is already published (I appreciate this can be difficult). To give one example, equations (3), (4) & (7) all have a '+1', in "$z_{0,i}$+1" – this isn't explained and I don't know what it means. Also equation (8) does not seem to match equation (63) in Lüpkes and Gryanik 2015 – should it? Finally there are a number of parameters set on page 4: C_{e10}, $z_{o,f}$, b, then later on a and $z_{0,i}$. It is not clear where the values for these parameters have come from and I found it difficult to relate them to parameters in the previous studies or in Elvidge et al. 2016. I think this section (2.1.3) could be vastly improved without much additional length or detail. Finally, you don't comment on exchange of moisture, is this changed?

We added the source of equations (1) to (4) and the explanation of adding '+1' in equations (3) and (4) at line 141:

"Equations (1) to (4) are common descriptions of air-ice momentum and heat transfer coefficients except that '+1' was added to both $z_L/z_{0,i}$ and $z_L/z_{t,i}$ in equations (3) and (4). This is done in the model to avoid that the argument of the logarithm can go to zero, for which $C_{d,i}$ ($C_{h,i}$) would go to infinity (see also Giorgetta et al., 2013)."

Giorgetta, M. A., Roeckner, E., Mauritsen, T., Bader, J., Crueger, T., Esch, M., Rast, S., Kornblueh, L., Schmidt, H., and Kinne, S.: The atmospheric general circulation model ECHAM6-model description, 2013.

The source of equations (5) to (7) were added at line 151:

"Equations (5) is obtained by combining the equations (6), (52) and (70) by Lüpkes and Gryanik (2015). Equations (6) is obtained by combining the equations (9), (64) and (74) by Lüpkes and Gryanik (2015). After adding '+1' both to $10/z_0$ and z_L/z_0 and replacing z_0 with $z_{0,f}$ in equation (65) by Lüpkes and Gryanik (2015), $C_{dn,f}$ is calculated as

$$C_{dn,f} = C_{e10}\left[\frac{\ln(10/z_{0,f}+1)}{\ln(z_L/z_{0,f}+1)}\right]^2 A(1-A)^{\beta} \qquad (7)”$$

Equation (8) represents a simple algebraic transformation of equation (60) by Lüpkes and Gryanik (2015) making use of their equations (59) and (61). We added one sentence to clarify how we got the equation (8) at line 166:

“Equation (8) represents a simple algebraic transformation of equation (60) by Lüpkes and Gryanik (2015) making use of their equations (59) and (61) with $\alpha_f = \alpha$.”

We added the source of the values for C_{e10} , $z_{0,f}$ and β at line 158:

“The value of C_{e10} is the average given in equations (48) and (49) by Lüpkes and Gryanik (2015). The value of $z_{0,f}$ is an average resulting from measured roughness lengths by various campaigns considered by Andreas et al. (2010), Lüpkes et al. (2012a) and Castellani et al. (2014). Note that this value is not critical for the parametrization. The value of β comes from equation (59) by Lüpkes et al. (2012a).”

The exchange of moisture is treated in the same way as the exchange of heat, meaning that the same coefficients are used.

4. In the summary (L440) you state that the SENS simulation is not any better than the CTRL simulations, in terms of sea-ice drift etc. However, you don’t really provide evidence for this statement. I think there is evidence in your paper, but you need to discuss it and demonstrate this is the case. Consequently, I would recommend adding another paragraph or two to Section 4, where you discuss the quality of the SENS and CTRL simulations. For example, is it possible to compare the gradients in Fig 6a to Fig 10 and demonstrate whether the CTRL or SENS is better? Could you add some observational data to Fig 10 to show this fact? I appreciate that ‘not any better yet’ is a bit of a negative result and could be changed by tuning the model, so perhaps you don’t want to spend too much time and effort on this aspect. But I think you need to provide a small amount of evidence for this statement.

We agree that it is helpful to support the statement that SENS is not better than CTRL in term of SID and SID-WS relation. We followed the Referee’s suggestions and modified the original Figure 10 to include the boxplot of sea-ice drift speed against different sea-ice concentration and wind speed from observation and reanalysis. We added a new Figure 11 that compares wind factor, 10-m wind speed and 2-m air temperature from observation/reanalysis and from the CTRL and SENS simulations for summer 2007. We also added a new Figure 12 that compares the seasonal cycle of Arctic basin-wide averaged sea-ice drift speed and 10-m wind speed from observation/reanalysis and from CTRL and SENS. The modified and new figures show that the new parameterization both slightly reduces and increases the wind factor and 10-m wind bias over the Arctic dependent on location. The discussions based on these figures are added as a new subsection "4.2 Model versus observation":

"**4.2 Model versus observation**

The increased dependency of SID on WS and SIC in SENS compared to CTRL does not reduce the deviation to the observation/reanalysis. In contrast, Figure 10 shows that the overestimation of the dependency of SID on WS and SIC in SENS is larger than in CTRL.

Figure 11 shows the spatial distribution of the summer 2007 wind factor, WS and near-surface air temperature from observation/reanalysis data, and the deviations of these three variables in CTRL and SENS from observation/reanalysis. It is obvious that both the bias patterns and the bias magnitudes in CTRL and in SENS are quite similar. Considering the ensemble mean bias and taking the internal model variability into account, it is hard to detect significant changes in SENS, compared to CTRL, as discussed in Section 4.1.

Although the ensemble mean of Arctic basin-wide mean SID from July to September in SENS is larger than in CTRL, the differences are not statistically significant due to a large ensemble spread (Figure 12). Actually, there are no statistically significant differences in the Arctic basin-wide mean SID between CTRL and SENS in all months. From January to May, the simulated Arctic basin-wide mean SID (both in CTRL and in SENS) are higher than that in KIMURA. With respect to the summer months (June to September), the August SID in CTRL is lower than in KIMURA, while the July and September SID in SENS are higher than in KIMURA. For the Arctic basin-wide mean WS, there is no significant difference between CTRL and SENS as well as between model and reanalysis, except for May, when both model simulations significantly overestimate the WS."

The modified Figure 10 is as follow:

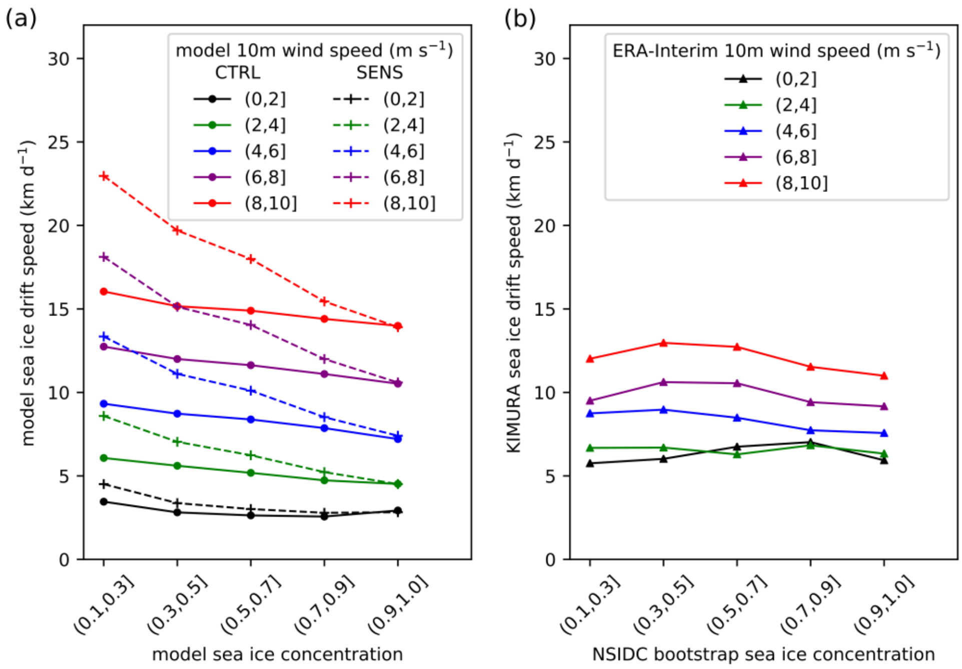

Figure 10: The (a) simulated relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors) for 2007 summer (JJAS) in CTRL (circle marker and solid line) and SENS (cross marker and dashed line) experiment. The relationship based on KIMUAR sea-ice drift speed, NSIDC bootstrap sea-ice concentration and ERA-interim 10-m wind speed is shown in (b). The points in the plot is the median value of all the daily data and on all grid points within the study domain indicated in Figure 1 under certain wind speed and sea-ice concentration classes. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

The added Figure 11 and 12 are as follows:

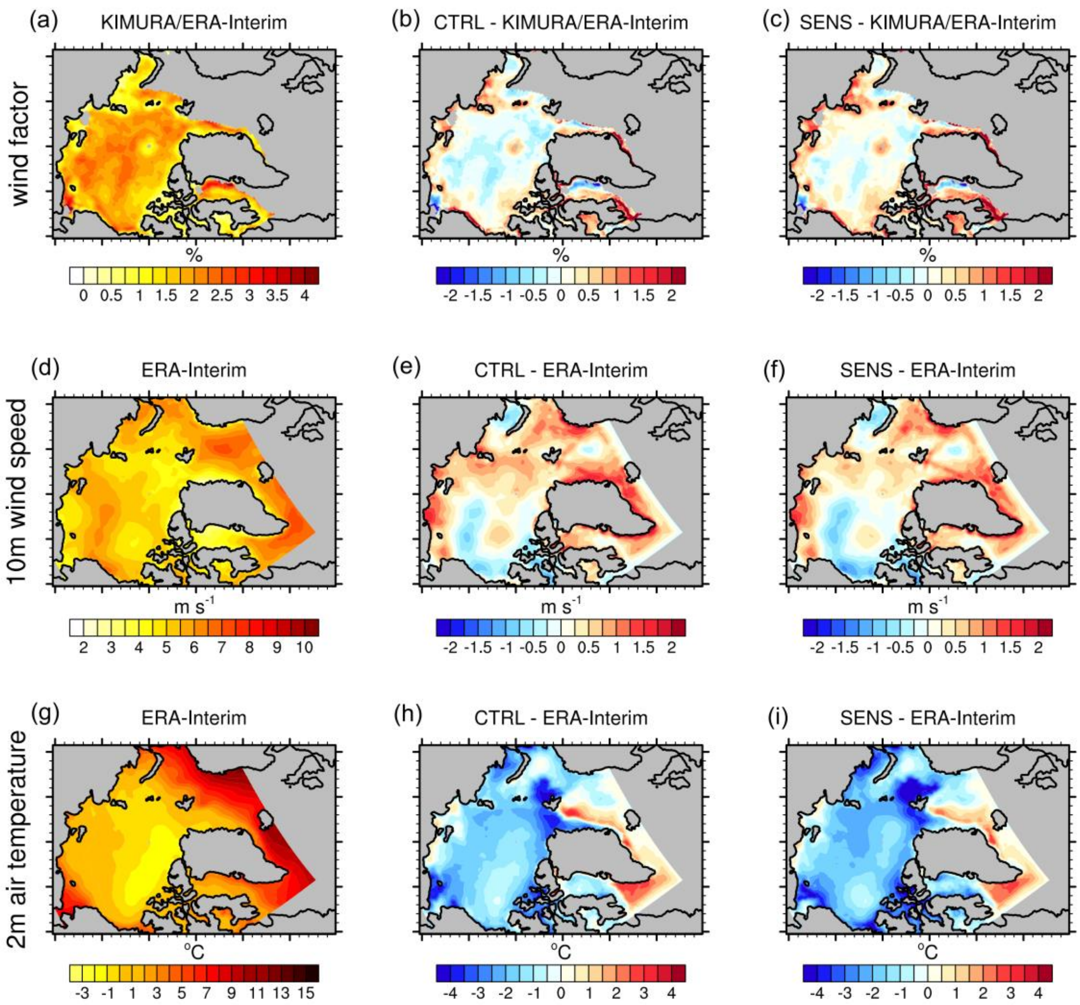

Figure 11: The 2007 summer (JJAS) (a) wind factor, (d) 10-m wind speed and (g) 2-m air temperature from ERA-Interim (KIMURA sea-ice drift is used for wind factor calculation). (b) wind factor, (e) 10-m wind speed and (h) 2-m air temperature differences between CTRL experiment and ERA-Interim (KIMURA and ERA-interim for wind factor). (c), (f) and (i) are the same as that for (b), (e) and (h), but show the differences between SENS experiment and ERA-Interim (KIMURA and ERA-interim for wind factor).

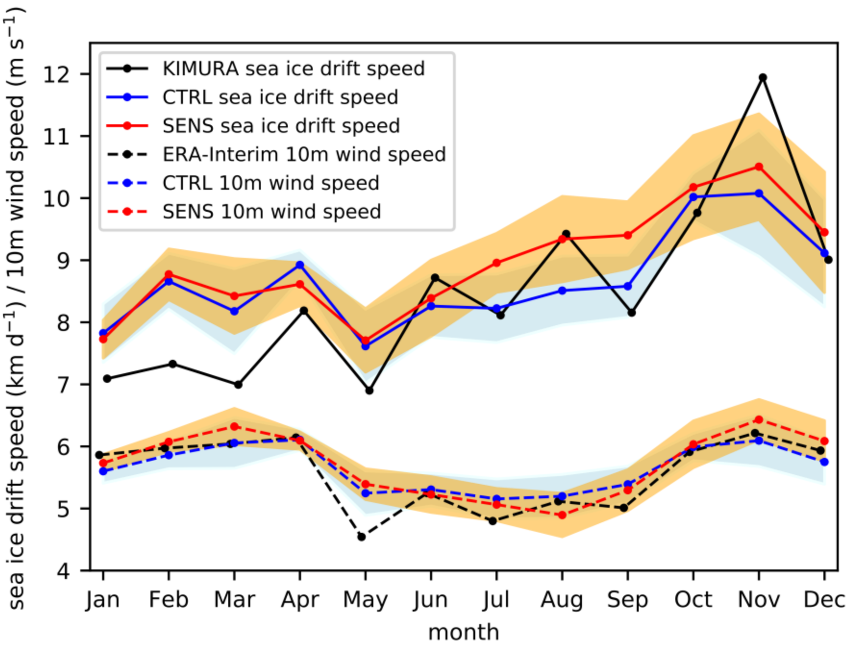

Figure 12: Mean annual cycle of sea-ice drift speed [km d^{-1}] (solid lines) and 10-m wind speed [m s^{-1}] (dashed lines), based on CTRL experiment (ensemble mean; blue lines), SENS experiment (ensemble mean; red lines) and the observation/reanalysis (KIMURA ice drift, ERA-I wind; black lines) for 2007 over the study domain (indicated in Figure 1). The across-ensemble scatters (standard deviation) of the simulations are included as shaded area (light blue for CTRL, orange for SENS).

Minor Points

L14 – "…of the Arctic basin" [insert the]

Changed as suggested.

L28 – "sea ice has experienced…"

Changed as suggested.

L66 You categorise Tsamados et al. 2014 as an ice-ocean model, but that study was actually using only a sea-ice model.

We agree and modified the introduction of the study of Tsamados et al. (2014) and other studies that also include sea-ice form drag in the model simulation as follows (line 61):

"Several model studies that include the sea-ice form drag were carried out (e.g. Castellani et al., 2018; Renfrew et al., 2019; Tsamados et al., 2014). Tsamados et al. (2014) implemented a complex sea-ice form drag parameterization based on many sea-ice cover properties (e.g. sea-ice concentration, vertical extent and area of ridges, freeboard and floe draft, and the size of floes and melt ponds) into the stand-alone sea-ice model CICE. Castellani et al. (2018) implemented a simpler sea-ice form drag parameterization that only relies on sea-ice deformation energy and concentration into the coupled ocean-sea ice model MITgcm. Both studies showed improvement in sea-ice drift after the form drag had been included. Recently, Renfrew et al. (2019) implemented an observation-based parameterization of atmospheric form drag caused by floe edges based on suggestions by Lüpkes et al. (2012a), Lüpkes and Gryanik (2015), and Elvidge et al. (2016) into a stand-alone atmosphere model. The simulation results show an improved agreement of mean atmospheric variables and turbulent fluxes with measurements in cold-air outbreak situations over the Fram Strait when form drag is included."

L175 – Have you considered a Cryosat product for sea-ice thickness – probably not worth the effort now, but might be interesting for any follow up studies.

We have considered to use Cryosat2, but Cryosat2 is only available from 2010 onwards and from October to next April. Therefore, Cryosat2 does not cover the whole period of 2003-2014 and does not provide the summer data. Nevertheless, we decided to add the comparison of sea-ice thickness from Cryosat2 and from the model simulations during winter 2010-2014 in supplementary Figure S2. It shows that the sea-ice thickness difference between Cryosat2 and the model is qualitatively similar to the difference between PIOMAS and the model.

We added according sentence in section 3.1:

"Analysis of the SIT differences between HIRHAM-NAOSIM 2.0 and CryoSat-2 during winter 2010-2014 (Figure S2; see Hendricks and Ricker, 2019, for details about the CryoSat-2 SIT data used here) confirms that HIRHAM-NAOSIM 2.0 underestimates the SIT over the central Arctic and north of the Canada Archipelago and Greenland, at least in winter."

L180 – The description of ERAI resolution is misleading. The resolution of the atmospheric model is T255 equivalent to about 80 km resolution, and you have downloaded it on 0.25 degree grid. So please rephrase.

We added more information to the description of the ERA-Interim data at line 208:

"For the near-surface wind speed (WS), daily 10-m wind speed from ERA-I is used. The ERA-I data were downloaded from the MARS archive at ECMWF and interpolated to the same 0.25° x 0.25° grid as used in the model's atmosphere component HIRHAM5."

L185 – "resolutions, a bilinear…"

Changed as suggested.

L191 – “as the study…”

Changed as suggested.

L250 – Maybe swap order to winter then summer to match the order earlier in the sentence, i.e. rephrase sentence.

The sentence was rephrased as suggested (line 298):

“Averaged over the study domain, the simulated wind factor is 1.77% in winter and 1.87% in summer, which agrees with the observations/reanalysis (KIMURA ice drift/ERA-I wind) in the sense that the averaged wind factor is smaller in winter (1.42%) than in summer (1.96%).”

L258 and L262 – Maybe rephrase to state ‘in winter…” and “in summer, …” clearly at the beginning of the statement, rather than hidden in the middle of the sentence.

The sentences were rephrased as suggested (line 309):

“In winter, however, the simulated wind factor is overestimated compared to the KIMURA/ERA-I data almost everywhere over the study domain, with the maximum bias reaching 1% over the thick ice north of the Canadian Archipelago (Figure 3). In summer, the modelled wind factor peaks (~3%) along the marginal ice zone, such as in the coastal Beaufort Sea.

…and (line 315):

In contrast to winter, the modeled wind factor in summer is underestimated over the study domain.”

L335-340 – Can you cite some evidence that PIOMAS is wrong here – I think it is incorrect and it is certainly inconsistent with the model.

We don’t have a reference yet, but we think one possible explanation that PIOMAS gives a SID-SIC relation inconsistent with the observed relation is a violation of physical consistency in the modeling system by the data assimilation. We added the following sentences in paragraph 3 of section 3.3.2 to elaborate our explanation:

“PIOMAS shows a SID-SIC relation inconsistent with the observed relation. Thus, the PIOMAS relation might violate physical consistency due to the used optimal interpolation method to obtain realistic sea-ice field (concentration). This assimilation method contains addition/subtraction of sea ice into the system at every assimilation time step, when the modeled sea ice concentration differs from the observed one. Due to the addition/subtraction of sea ice (called increment or innovation in the terminology of data assimilation), PIOMAS does not necessarily preserve the physical relations described in the underlying sea ice-ocean model. Such an inconsistency is one of the drawbacks of the optimal interpolation method. Therefore, relations to assimilated physical variables should be examined with caution."

L345 – You don't discuss Fig 6a at all. Is it needed? Perhaps it should be discussed later.

Actually, we already discuss Figure 6a at the beginning of Section 3.3.1. We agree that it is easy to overlook Figure 6a or 6b because they are not discussed together. We start Section 3.3.1 now with the sentence 'Figure 6a shows…'

Figures

Figures 1, 3, 8, S1, S2, S3, S4
These all use the same colormap which is a blue-white-red (diverging colormap). Such colormaps are ideal for difference plots, e.g. Fig 1b,d, but are an odd choice for non-diverging fields, such as Fig 1a,c. I wonder if you are better changing colormap for the left-hand columns in all of these plots.

We understand the reviewer's concern about using blue-white-red color map for non-diverging fields. Therefore, we replaced the blue-white-red color map in Figures 1, 3, S1, S2, S3 and S4 with a yellow-red color map for all non-diverging fields. The color map in Figure 8 was not changed because there is no non-diverging field.

Figure 4
Unfortunately, this is really hard to read at this size (printed A4). I also think it has too much unnecessary detail in it. You have 10 wind speed classes. Do you really need this many classes? I think you'd get the same result with 2 m/s bins and it would be much clearer. Also do you include winds >10 m/s in the (9,10] bin? Note I have taken (1,2] to mean winds between 1 and 2 (inclusive) m/s – you should explain this in first caption. Secondly you have 9 SIC bins – again this is a lot and there seems very little difference in the results between adjacent bins. I'd perhaps recommend fewer bins, perhaps (0,0.1], (0.1,0.3], (0.3,0.5], (0.5,0.7], (0.7,0.9], (0.9,1.0]. This keeps the 'end' bins separate as these are more interesting. At present this Fig 4 and also 9 has so much detail and numbers, that the main message is a bit hidden. Finally, it may be worth noting how much data is in these bins. Although the bins are the same size (0.2 in ice fraction for example), the distributions mean there could be relatively few points in some bins.

For wind class bin (9,10], the wind speed greater than 10 m/s is not included. We agree that it is helpful to explain that "(" means exclusive and "]" means inclusive. We added this to the caption of Figure 4:

"In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive."

We agree that the boxplot figures in Figure 4 are complex, now we followed the suggestion of the Referee that change the wind class bin size to 2 m/s and rearranged the sea-ice fraction classes to (0,0.1], (0.1,0.3], (0.3,0.5], (0.5,0.7], (0.7,0.9], (0.9,1.0]. Also, we stress that we additionally provide Figures 5, 7, 10, where we display the median values only for an easier visualization of the relationships. The modified Figure 4 is as follow:

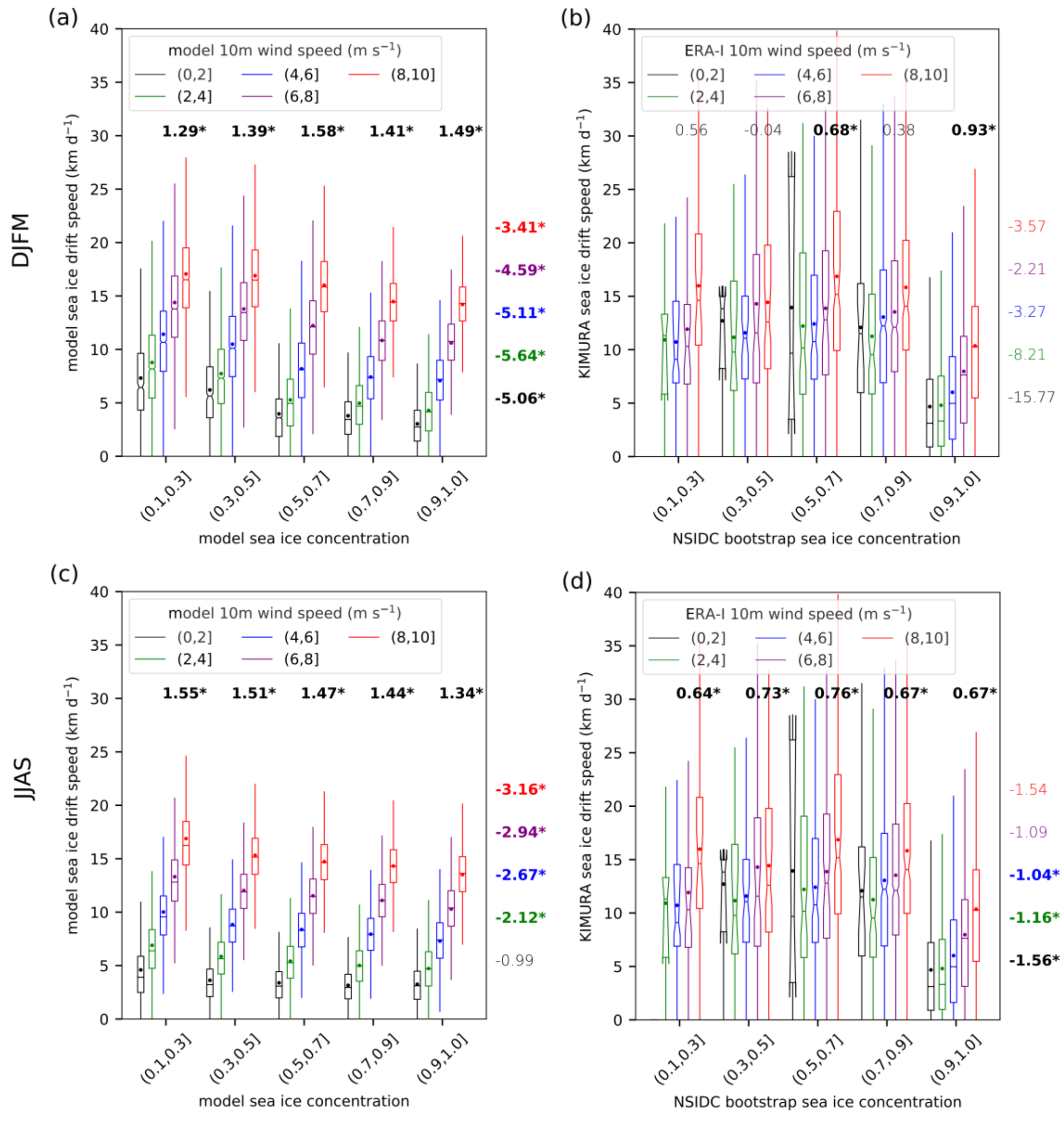

Figure 4: Box-whisker plots of the relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors) for 2003-2014 (a) winter (DJFM) and (c) summer (JJAS) in the model (HIRHAM-NAOSIM 2.0). (b) and (d) are the same as that for (a) and (c) respectively, but based on the observation/reanalysis data. For the model, all 10 ensemble members are included. The plot is based on daily data and on all grid points within the study domain indicated in Figure 1. The horizontal bar represents the median, the notch represents the 95% confidence interval of the median, the dot represents the mean, the top and bottom of the

box represent the 75th and 25th percentiles, the upper/lower whiskers represent the maximum/minimum value within 1.5 times interquartile range (IQR) to 75/25 percentiles. The numbers above the boxplots represent the slopes of near-surface wind and sea-ice drift speed fit lines (unit: km d^{-1} per 1 m s^{-1} wind speed change; font colors as for the wind speed classes). The numbers right of the boxplots represent the slopes of sea-ice concentration and sea-ice drift speed fit lines (unit: km d^{-1} per 10% sea-ice concentration change). A bold and asterisked number indicates that the slope of the fit line is significant at the 95 % level. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

We understand the Referee's concern about the sample size in each bin. Instead of giving the sample size of each bin directly in Figure 4, we provide therein the 95% confidence range of the median value for each bin (represented by the height of the notch in the boxplot). The confidence range includes the influence of the sample size. We provide the sample size for each bin in the new Table 1 as follow:

Table 1 The sample sizes of sea-ice drift speed data under different 10-m wind speed and sea-ice concentration classes in Figure 4. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

Season	Data source	Wind classes	Sea-ice concentration classes				
			(0.1,0.3]	**[0.3,0.5]**	**(0.5,0.7]**	**(0.7,0.9]**	**(0.9,1.0]**
DJFM	model	(0,2] m/s	494	864	3328	135516	45562216
DJFM	model	(2,4] m/s	2070	3716	12780	489893	183056161
DJFM	model	(4,6] m/s	3432	5766	17172	618383	239287363
DJFM	model	(6,8] m/s	5804	9402	17215	435238	181532612
DJFM	model	(8,10] m/s	7950	12511	18413	246921	102066710
DJFM	KIMURA/ERA-I/NSIDC	(0,2] m/s	0	7	7	40	102295
DJFM	KIMURA/ERA-I/NSIDC	(2,4] m/s	15	29	50	124	365803
DJFM	KIMURA/ERA-I/NSIDC	(4,6] m/s	32	66	117	279	499634
DJFM	KIMURA/ERA-I/NSIDC	(6,8] m/s	28	88	137	381	386667
DJFM	KIMURA/ERA-I/NSIDC	(8,10] m/s	53	83	145	288	218638
JJAS	model	(0,2] m/s	92547	2535519	17432992	25896542	9142130
JJAS	model	(2,4] m/s	322269	8521163	57295068	84426782	30714941
JJAS	model	(4,6] m/s	534300	12186383	81681898	113048227	40015962
JJAS	model	(6,8] m/s	549254	9864436	67161887	84920918	27346273
JJAS	model	(8,10] m/s	356102	4746320	34131702	38211228	11159363
JJAS	KIMURA/ERA-I/NSIDC	(0,2] m/s	1519	3439	5150	12096	100317
JJAS	KIMURA/ERA-I/NSIDC	(2,4] m/s	4727	10504	16204	39911	312814
JJAS	KIMURA/ERA-I/NSIDC	(4,6] m/s	6533	14571	22364	55418	385667
JJAS	KIMURA/ERA-I/NSIDC	(6,8] m/s	5261	11976	17587	40559	262251
JJAS	KIMURA/ERA-I/NSIDC	(8,10] m/s	2514	5249	7276	17272	107988

Figure 5

Same comments as above really and note some of the colours are very faint (7,8) class.

These plots are more readable but need to be consistent with Fig 4.

Agree and now we enhanced the visualization of Figure 5 by increasing the font, re-arranged into 3×2 panels, reduced the sea-ice concentration and wind speed classes as discussed before and discarded the faint color that previously used for wind class (7,8] m/s. The new Figure 5 is as follow:

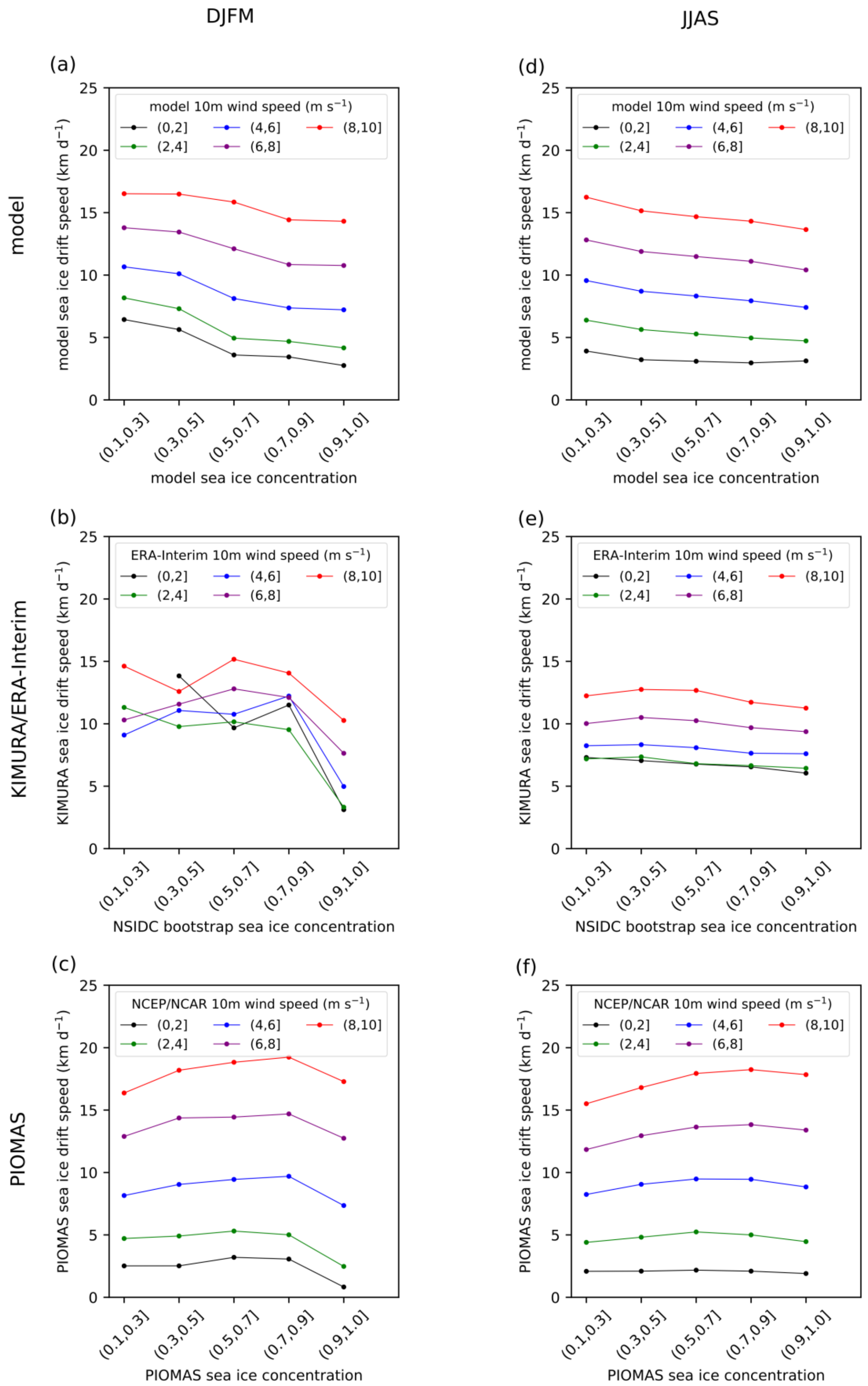

Figure 5: Relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors) for 2003-2014 (a) winter (DJFM) and (d) summer (JJAS) in the model (HIRHAM-

NAOSIM 2.0). (b) and (e) are the same as that for (a) and (d) respectively, but based on the observation/reanalysis data. (c) and (f) are the same as that for (a) and (d) respectively, but based on PIOMAS data. The points in the plot are the median value of all the daily data and on all grid points for certain wind speed and sea-ice concentration, within the study domain indicated in Figure 1. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

Missing Reference:

Elvidge, A.D., I.A. Renfrew, A.I. Weiss, I.M. Brooks, T.A. Lachlan-Cope, and J.C. King 2016:Observations of surface momentum exchange over the marginal-ice-zone and recommendations for its parameterization, *Atmospheric Chemistry and Physics,* **16,** 1545-1563. doi:10.5194/acp-16-1545-2016

We added the missing reference.

Answer to the comments of Referee #2

We would like to thank Referee #2 for his/her suggestions for improving our paper. All the comments have been addressed and point by point response is provided below each comment. The reviewer comments are written in black, our answer in blue, and the revisions in the paper are highlighted in red. The line numbers which are used in the answers correspond to the revised version of the manuscript (PDF file) unless otherwise indicated.

General description

The Manuscript validates a fully coupled ocean, sea ice and atmospheric circulation model (HIRHAM-NAOSIM). Main focus is on the correlation between the sea-ice drift, sea-ice conditions and the near surface wind speed. The model is validated towards remotely sensed data and another model (PIOMAS). The latter is more a comparison than a validation.

Comparisons has been made at two time scales. First the seasonal variation has been compared, then the daily variations and correlations between mainly ice drift and wind speed in different sea ice regimes.

Results are in general at the level of other model systems, however a few pointers are provided to places where HIRHAM-NAOSIM performs better than PIOMAS Introduction of sea-ice form drag influences the drift speed but this does not improve the overall performance.

Mayor revisions/concerns

A paper that validates a model is of relevance, however it seems like there are many references to the 2019 paper by Dorn et al. Without having read this I am a little puzzled whether this manuscript is more of the same of if it points to new findings. Especially when tuning of the form drag is postponed to a later paper.

The paper by Dorn et al. (2019) is cited as reference to the model description and to the long-term simulation setup (BASE run). The study in this paper evaluates sea-ice drift and its dependency on wind speed and sea-ice conditions, which was not addressed by Dorn et al. (2019). Therefore, this study is not a follow-up paper to Dorn et al. (2019), but presents exclusively new findings.

In addition, section 4 presents a sensitivity test for a new parameterization that added the sea-ice form drag from sea-ice edges. The focus is to investigate the sensitivity of simulated sea-ice drift to the new parameterization. We also added a new sub-section 4.2 and new figures to find whether the new parameterization improved the model simulations or not. Fine-tuning of the new parameterization is postponed, since it requires a lot of model simulations. Nevertheless, we added a new sub-section 4.3 that describes the ideas of which parameters could be tuned in the follow-up study to improve the model simulation.

My main concern with this manuscript is that it presents many numbers and correlations but there is a lack of introduction, perspective and discussion. A few lines is mentioned in the end of section 4 where ocean forcing is mentioned. I think that this should be the start of a discussion that discuss the reasons why for instance the seasonal cycle is poorly represented. How well is the internal ice pressure described? Are observations always the truth? For instance what are the uncertainties/biases of the KIMURA dataset.

We agree that there should be more discussion on our results. We followed the Referee's suggestions and added the uncertainty of KIMURA dataset at line 181:

"The uncertainty of the KIMURA data over the Arctic in summer is from 1.12 to 1.47 km d^{-1} and depends on the drift speed (Sumata et al., 2015a). In winter, the uncertainty is at least 50% smaller than in summer and depends on the drift speed too (Sumata et al., 2015b)"

We also included the discussion about the KIMURA sea-ice drift speed uncertainty and compared it with the model bias at line 253.

"Compared with the uncertainty in the KIMURA sea-ice drift speed provided by Sumata et al. (2015a, b), the model bias in summer is close to or slightly smaller than the uncertainty of the KIMURA data. This indicates that the sign of the model bias in summer SID is uncertain. In winter, however, the model clearly overestimates the SID over the central Arctic and north of the Canada Archipelago and Greenland, even if considering the uncertainty of the KIMURA data."

We added a new paragraph to discuss the reason for wintertime SID overestimation at line 306:

"The overestimation of winter SID could be related to the underestimation of winter SIT (Figure S2). Besides, the prescribed values of the ice-ocean drag coefficient and the ice strength parameter could also play a role. The ice-ocean drag coefficient in the base configuration of HIRHAM-NAOSIM (5.5×10^{-3}) is comparable to other CMIP5 models, even though a few models use 3-4 times higher coefficients (see Tandon et al., 2018). Higher ice-ocean drag might damp the SID and its strong dependency on the wind speed. Docquier et al., (2017) show that the higher the ice strength parameter, the lower the winter SID and the lower the SIT. The ice strength parameter in the base configuration of HIRHAM-NAOSIM (30,000 N m^{-2}) is already slightly higher than in all CMIP5 models (see Tandon et al., 2018). This value has been established for stand-alone ocean-ice simulations with daily wind forcing, but might still be too low considering the hourly wind forcing from the interactively coupled atmosphere."

References:

Sumata, H., Kwok, R., Gerdes, R., Kauker, F., and Karcher, M.: Uncertainty of Arctic summer ice drift assessed by high-resolution SAR data, Journal of Geophysical Research: Oceans, 120, 5285-5301, 2015a.

Sumata, H., Gerdes, R., Kauker, F., and Karcher, M.: Empirical error functions for monthly mean Arctic sea-ice drift, Journal of Geophysical Research: Oceans, 120, 7450-7475, 10.1002/2015jc011151, 2015b.

The article points to the lack of a seasonal cycle and a bad timing of the minimum. My opinion would be that the minimum is more a matter of lack of a seasonal cycle and that this is a random minimum that is irrelevant as long as the seasonal cycle is not present.

A seasonal cycle in the simulated SID is present, even if its amplitude is much weaker than in the KIMURA data due to the model's overestimation of winter SID. We agree that one may argue that it is irrelevant to discuss the minimum as long as the model systematically overestimates the SID just in the season where the observed minimum occurs. On the other hand, the simulated (bad) timing of the minimum is certainly not a random feature, since it appears in all ensemble members and in many other coupled climate models as well. Therefore, we think that it is relevant to point to this model deficit when discussing the seasonal cycle.

From line 52 and the next few lines a method for validation is mentioned. I would recommend to move this into section 2 and describe what this validation method do.

We agree that the previous introduction of the validation method was insufficient and should be located in section 2. We added the following description about the validation method to Section 2.3 at line 227:

"Following Olason and Notz (2014) and Docquier et al. (2017), we use scatter plots showing Arctic basin-wide and multi-year averaged monthly mean sea-ice drift speed against sea-ice conditions (sea-ice concentration and thickness) to evaluate the relationships between sea-ice drift speed and sea-ice conditions. The linear fit-lines are added in the scatter plots to assist the comparison of the relationship in the model and in the observation/reanalysis."

Further, we modified the sentence at line 52:

"We first evaluate the simulated Arctic basin-wide monthly mean drift, then we evaluate the relationship between sea-ice drift speed and sea-ice conditions/wind speed both on Arctic basin-wide, multi-year monthly mean scale and on daily grid scale."

Some of the findings are close related. Higher ice drift will lead to lower ice thickness and again higher ice drift. Therefore a comparison with for instance PIOMAS tells you more about the current state of the model than a direct bias (at least that would be my opinion). The comparisons are valid but I will be hesitant to say that for instance the internal strength of the model is too weak. A relevant discussion related to PIOMAS would be to discuss the difference between a forced ocean-sea ice model and a fully coupled model ocean-sea ice-atm model. Are there features that could be described by this?

We agree that the comparison with PIOMAS sea-ice thickness only tells us something about the current state of the model. In order to clarify this, we added one sentence in section 2.2.3 at line 202:

"Therefore, the comparison with PIOMAS informs us rather about the current state of the model than about a direct model bias."

We also agree that a discussion of the difference between PIOMAS, a forced ocean-sea ice model, and HIRHAM-NAOSIM, a fully coupled atmosphere-ocean-sea ice model, and the possible contribution of this difference to the sea-ice thickness differences between PIOMAS and HIRHAM-NAOSIM should be provided. Therefore, we added the following discussion at line 258:

"The SIT differences between HIRHAM-NAOSIM 2.0 and PIOMAS can partly be attributed to the feedback between atmosphere and ocean-sea ice in the fully coupled atmosphere-ocean-sea ice model, which is not present in an ocean-sea ice model like PIOMAS."

In addition to PIOMAS, we have considered to use Cryosat2 product for sea-ice thickness, but Cryosat2 is only available from 2010 onwards and does not cover the whole period 2003-2014. Nevertheless, we decided to add the comparison of sea-ice thickness from Cryosat2 and from the model simulations during winter 2010-2014 in supplementary Figure S2. It shows that the sea-ice thickness difference between Cryosat2 and the model is qualitatively similar to the difference between PIOMAS and the model. Therefore, we added the following discussion at line 261:

"Analysis of the SIT differences between HIRHAM-NAOSIM 2.0 and CryoSat-2 during winter 2010-2014 (Figure S2; see Hendricks and Ricker, 2019, for details about the CryoSat-2 SIT data used here) confirms that HIRHAM-NAOSIM 2.0 underestimates the SIT over the central Arctic and north of the Canada Archipelago and Greenland, at least in winter."

Minor corrections

Line 44: In my opinion the comparison of CMIP 3 models is outdated. The reference provided afterwards is more relevant (Tandon et al 2018).

We agree that the CMIP3 results from Rampal et al. (2011) are not up to date anymore. Therefore, we removed the corresponding statement in Section 1.

Line 50: Please don't start the section with Thus. For instance change to: This paper/manuscript has two aims.

We follow your suggestion, and deleted "Thus" at the beginning of that paragraph.

Line 54. Stating that an observation is rare seems a bit short and subjective. They do exist (RGPS buoys, SAR drift), however these are not present for the entire period. Choosing not to use them is valid but again a few more lines on why would be nice.

We agree and removed the phrase: "Since both model evaluations and observational studies based on the daily grid scale are rare"

Line 75: Replace with: The organization of this paper is as follows: Section 2.

We changed the text as suggested.

Line 84 to 95: A map of the domain and the where the boundaries extend to would improve the understanding of the model domain.

We understand the concern of the Referee about the model domain. However, as the model domain and the study area of interest (shown by the purple line) are already shown in Figure 1, we think there is no need to provide an additional figure. The domain of the ocean-sea ice component is exactly the domain shown in Figures 1, 3, 8, and 11. In the revised version, we added corresponding information to the respective figure captions. Further, we added the following sentence at the end of the model description section 2.1.1 (line 105):

"The ocean-sea ice domain corresponds to the domain shown in Figure 1."

Line 92 reference a dynamic-thermodynamic model described by Harder is an upgrade? What is upgraded. Dynamics are referenced to 1979 and thermodynamics to 1976. Maybe "update" should be removed or explicitly explained what is the update.

We agree that the expression 'upgrade' is confusing. Therefore, we deleted the phrase "and represents an upgrade of the original Hibler (1979) model" in line 101 of the discussion paper and keep the sea-ice model reference of Harder et al. (1998). Compared to Hibler (1979), the sea-ice dynamics include an upstream advection scheme (to avoid negative ice thicknesses), no explicit diffusion, and drag coefficients optimized by comparison with observed buoy drift (Harder and Lemke, 1994; Fischer, 1995; Drinkwater et al., 1995; Harder, 1996; Kreyscher et al., 1997). As these improvements were already mentioned by Harder et al. (1998), we abstained from repeating it again in this paper.

References:

Drinkwater, M. R., Fischer, H., Kreyscher, M., & Harder, M. (1995, July). Comparison of seasonal sea-ice model results with satellite microwave data in the Weddell Sea. In 1995 International Geoscience and Remote Sensing Symposium, IGARSS'95. Quantitative Remote Sensing for Science and Applications (Vol. 1, pp. 357-359). IEEE.

Fischer, H. (1995). Vergleichende Untersuchungen eines optimierten dynamisch-thermodynamischen Meereismodells mit Beobachtungen im Weddellmeer= Comparison of an optimized dynamic-thermodynamic sea ice model with observations in the Weddell Sea. Berichte zur Polarforschung (Reports on Polar Research), 166.

Harder, M. (1994). Erweiterung eines dynamisch-thermodynamischen Meereismodells zur Erfassung deformierten Eises. Berichte aus dem Fachbereich Physik, Report, 50.

Harder, M. (1996). Dynamik, Rauhigkeit und Alter des Meereises in der Arktis-numerische Untersuchungen mit einem großskaligen Modell= Dynamics, roughness, and age of Arctic sea ice-numerical investigations with a large-scale model (Doctoral dissertation, Universität Bremen).

Kreyscher, M., Harder, M., & Lemke, P. (1997). First results of the Sea-Ice Model Intercomparison Project (SIMIP). Annals of Glaciology, 25, 8-11.

Line 104: How is the spinup designed? Running one year 22 times? Has the model bin spun up properly or is the ensemble a representation of the spinup? A bit more elaboration of the choices would be nice. Is Levitus data near the area of interest good enough? Does this imply that the variations seen only originates from the atmosphere?

The BASE ensemble simulations were already carried out for the study by Dorn et al. (2019). The design of the preceding spin-up simulation was described in detail by Dorn et al. (2019): "initial ocean and sea-ice fields were taken from the Januaries 1991 to 2000 of a preceding coupled spin-up run for the period 1979–2000. The coupled spin-up run already reached a quasi-stationary seasonal-cyclic state of equilibrium for the mid-1980s. Consequently, all ensemble members were initialized with ocean and sea-ice fields that represent the diversity of ocean–ice conditions within the steady state of the specific model configuration".

To better emphasize that the BASE ensemble simulations, including the preceding spin-up simulation, were carried out for the study by Dorn et al. (2019), we reformulated the beginning of the paragraph at line 108:

"A 10-member ensemble of multi-decadal climate simulations for the period 1979–2016 were carried out by Dorn et al. (2019) with the base configuration of HIRHAM-NAOSIM 2.0. These multi-decadal ensemble simulations represent the basis for the present study and are referred to as BASE hereafter. The individual BASE ensemble members used the same atmospheric initialization, but applied different ice-ocean initial conditions, which were taken from January 1 of the last 10 years of a preceding 22-year-long coupled spin-up run (see Dorn et al., 2019, for more details)."

We also modified the description of the initial condition for CTRL and SENS simulations at line 174:

"The ice-ocean initial conditions for CTRL and SENS were produced in exactly the same way as for BASE (see Section 2.1.2)."

The Levitus climatology is only used at the open boundary in the northern North Atlantic (at approx. 50°N). Since this boundary is far away from the area of interest (our study domain in this paper), the Levitus data are not an issue for the present study. Even though there are no externally forced variations at the lateral ocean boundary, there are variations between the ensemble members as well as year-to-year variations. Variations between the ensemble members are by definition a result of internally generated variability in the model. This comprises both atmosphere and ice-ocean variability. In contrast, year-to-year variations in the ensemble mean can be attributed to the external forcing at the lateral atmospheric boundaries (and the surface boundary conditions outside the coupling domain).

Line 157: Validation towards AMSRE. Is the ice drift It would be interesting to see how the model performed vs RGPS buoys and Sentinel 1 SAR icedrift data.

Alternatively an evaluation of the uncertainty of the chosen drift product versus the bias/uncertainty of the model results.

It is beyond of the scope of our study to evaluate KIMURA drift data against buoy and SAR drift data. Intercomparison studies of Arctic ice drift exist in literature. For example, Sumata et al. (2014) intercompared four remotely sensed ice-drift products (incl. KIMURA) and compared them also with available buoy data. Also, there is a whole international activity to validate sea-ice drift products (http://esa-cci.nersc.no/, http://esa-cci.nersc.no/?q=webfm_send/195). It is also beyond the scope of our study to evaluate the model with other data sets such as buoys and SAR data. We have justified in section 2.2.1 why we have selected the KIMURA data set. It is because it has a much wider spatial and temporal coverage than buoys data and is therefore appropriate for regional model evaluation (Sumata et al., 2015a). Another advantage of the KIMURA product is that it provides ice drift data both in winter and summer. More details are given by Kimura et al. (2013) and Sumata et al. (2015a).

Sumata, H., Lavergne, T., Girard-Ardhuin, F., Kimura, N., Tschudi, M. A., Kauker, F., Karcher, M., and Gerdes, R. (2014), An intercomparison of Arctic ice drift products to deduce uncertainty estimates, J. Geophys. Res. Oceans, 119, 4887– 4921, doi:10.1002/2013JC009724

According to the Referee’s suggestion, we include information about the uncertainty of the KIMURA product and link that with the identified model bias.

We included at line 181:

“The uncertainty of the KIMURA data over the Arctic in summer is from 1.12 to 1.47 km d-1 and depends on the drift speed (Sumata et al., 2015a). In winter, the uncertainty is at least 50% smaller than in summer and depends on the drift speed too (Sumata et al., 2015b).”

And, we included at line 253:

“Compared with the uncertainty in KIMURA sea-ice drift speed provided by Sumata et al. (2015a, b), the model bias in summer is close to or slightly smaller than the uncertainty of the KIMURA data. This indicates that the sign of the model bias in summer SID is uncertain. In winter, however, the model clearly overestimates the SID over the central Arctic and north of the Canada Archipelago and Greenland, even if considering the uncertainty of the KIMURA data.”

Line 162: As partly mentioned the comparison with PIOMAS just shows whether NAOSIM provides the same as PIOMAS. Why not use Icesat as mentioned in the discussion about PIOMAS. Admitted there are relatively high uncertaintes on ice thickness products like IceSat, however reference a model and motivate this choice by its skill vs another product seems weird. Other data sets that can be used are operation ice bridge and Cryosat. They do not cover the full period and domain but they can do as Ground Truth.

We followed the Referee’s suggestions and added the comparison of sea-ice thickness from the model and from Cryosat2 during 2010-2014 by extending supplementary Figure 2 and Section 3.1 (line 261):

"Analysis of the SIT differences between HIRHAM-NAOSIM 2.0 and CryoSat-2 during winter 2010-2014 (Figure S2; see Hendricks and Ricker, 2019, for details about the CryoSat-2 SIT data used here) confirms that HIRHAM-NAOSIM 2.0 underestimates the SIT over the central Arctic and north of the Canada Archipelago and Greenland, at least in winter."

The modified supplementary Figure 2 is as follow:

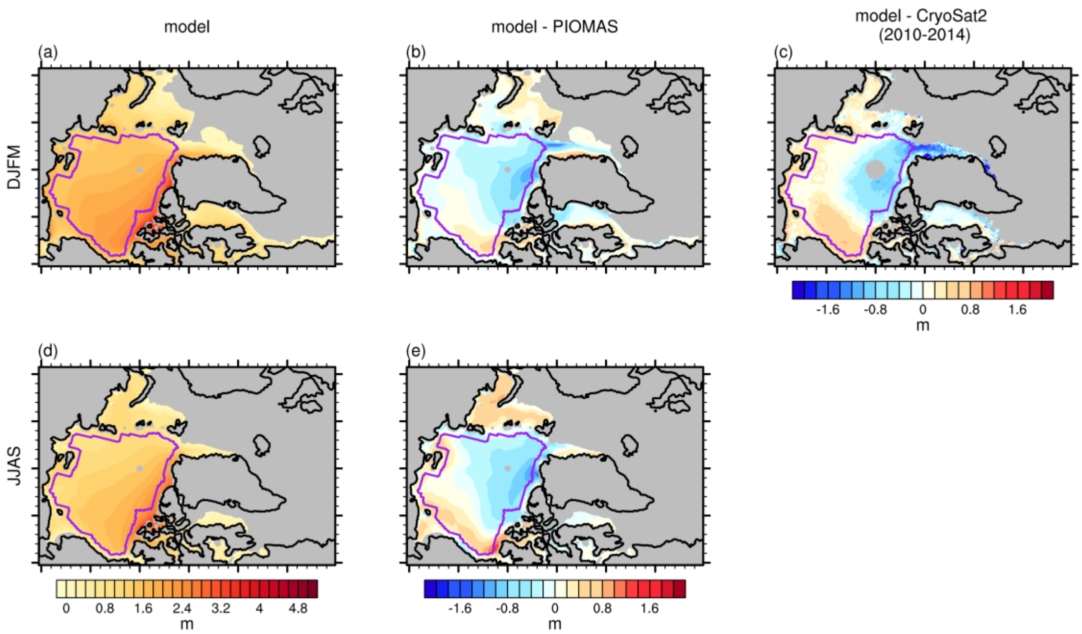

Figure S2: Mean spatial pattern of sea-ice thickness [m] in the model (ensemble mean of HIRHAM-NAOSIM 2.0) for 2003-2014 (a) winter (DJFM) and (d) summer (JJAS). (b) and (e) are the model differences to the PIOMAS ("Model - PIOMAS") for 2003-2014 winter and summer respectively. (c) are the model differences to the CryoSat-2 sea-ice thickness for 2010-2014 winter. The CryoSat-2 monthly mean gridded sea-ice thickness data are download from ftp.awi.de/sea_ice/product/cryosat2/v2p2/nh/l3c_grid/monthly. The purple line in each panel indicates the study domain used for the basin-wide analysis.

Line 187 - 189. Is there a reason for excluding spring and fall?.

The reason for not showing the spring and fall is that we focused our study on the extreme seasons to emphasize the contrast between warm and cold conditions. Figures for spring and fall show intermediate results and do not provide additional insights.

Line 211-216 Not sure why it is required to include such a long description of why sea ice drift is influenced by thickness, concentration and wind speed. This is stated in several articles. Just state that the drift is governed mainly by ice conditions, wind speed and ocean currents (less important).

We agree that the previous description was unnecessarily long. We shorted the sentences at line 244 as follows:

"SID is mainly governed by near-surface wind, sea-ice conditions, and ocean currents."

Line 240 - Small variation of wind don't explain variation of ice drift. The modelled ice drift seems to be controlled mostly by the wind, however this is in contrast to obs.

We agree that the previous wording was misleading. We reworded the paragraph (lines 288) as follows:

"As shown in previous studies (Docquier et al., 2017; Kushner et al., 2018; Olason &and Notz, 2014; Tandon et al., 2018), the observed distinct mean seasonal cycle of SID (maximum in autumn, minimum in spring) is obviously not solely controlled by the wind speed, which is strongest in winter and weakest in summer (Figure 2). The phase lag between the seasonal cycle of SID and WS is about 3-4 months in observations/reanalysis (KIMURA ice drift/ERA-I wind). The modeled seasonal cycle and magnitude of the WS agrees well with the ERA-I reanalysis. Therefore, according According to the delayed SID minimum (Ssection 3.1), the phase lag between the simulated seasonal cycle of SID and WS is reduced to about one month, like in many CMIP3 and CMIP5 models (Rampal et al., 2011; Tandon et al., 2018), leading to a higher correlation between SID and WS. This indicates that the modeled SID is much stronger controlled by the wind speed than the observed SID."

245 - 250 Again too high correlated wind and ice drift speed in winter. Other factors/forcing of the dynamics of the sea-ice must impact. A discussion of these would be relevant in a discussion section.

We added a discussion of potential causes for the model bias to Section 3.1 and refer at the end of this paragraph to this discussion (line 300):

"As mentioned in Section 3.1, too high sensitivity of the SID to the wind in winter may be related to the underestimated SIT and model parameters governing the sea-ice dynamics."

Line 260. I thought that there is a dynamical forcing between ocean and sea ice everywhere. This should be more specific.

From a model perspective, ocean and sea ice are coupled throughout the model domain. Here we refer to a specific physical coupling process between ocean and sea ice. We agree that more information is helpful and modified the sentences at line 312:

"This could be the result of a dynamical coupling between sea ice and the coastal ocean as suggested by Nakayama et al. (2012): In a coastal ocean covered with sea ice, wind-forced sea-ice drift excites coastal trapped waves and generates fluctuating ocean currents. These ocean currents can enhance the sea-ice drift when the current direction is the same as the wind-driven drift direction."

Line 300 what is the method? Short description please. Same reference is made in introduction

A description of the method was added to Section 2.3 at line 227 (see above). In this paragraph, we removed the citations and the introduction of the method. The remaining text at line 351 reads:

"Figure 6a shows the relationship between SID and SIC in terms of the mean seasonal cycle."

Line 350 Abrupt end to line.

Thank you very much! The corrected sentence reads now:

"As pointed out by Olason and Notz (2014), the inverse correlation between drift speed and thickness in winter, when the ice concentration is high, is physically plausible, but the inverse correlation in summer, when the ice concentration is lower, is probably only of statistical nature."

Figure 4 and 5 are hard to read. Please increase font size

We agree that Figures 4 and 5 are hard to read. We enhanced the visibility of the two figures by rearrange the panels and increased the font size as suggested. Besides, we changed the wind class bin size to 2 m/s and the sea-ice fraction classes to (0,0.1], (0.1,0.3], (0.3,0.5], (0.5,0.7], (0.7,0.9], (0.9,1.0]. The modified Figure 4 and 5 are as follows:

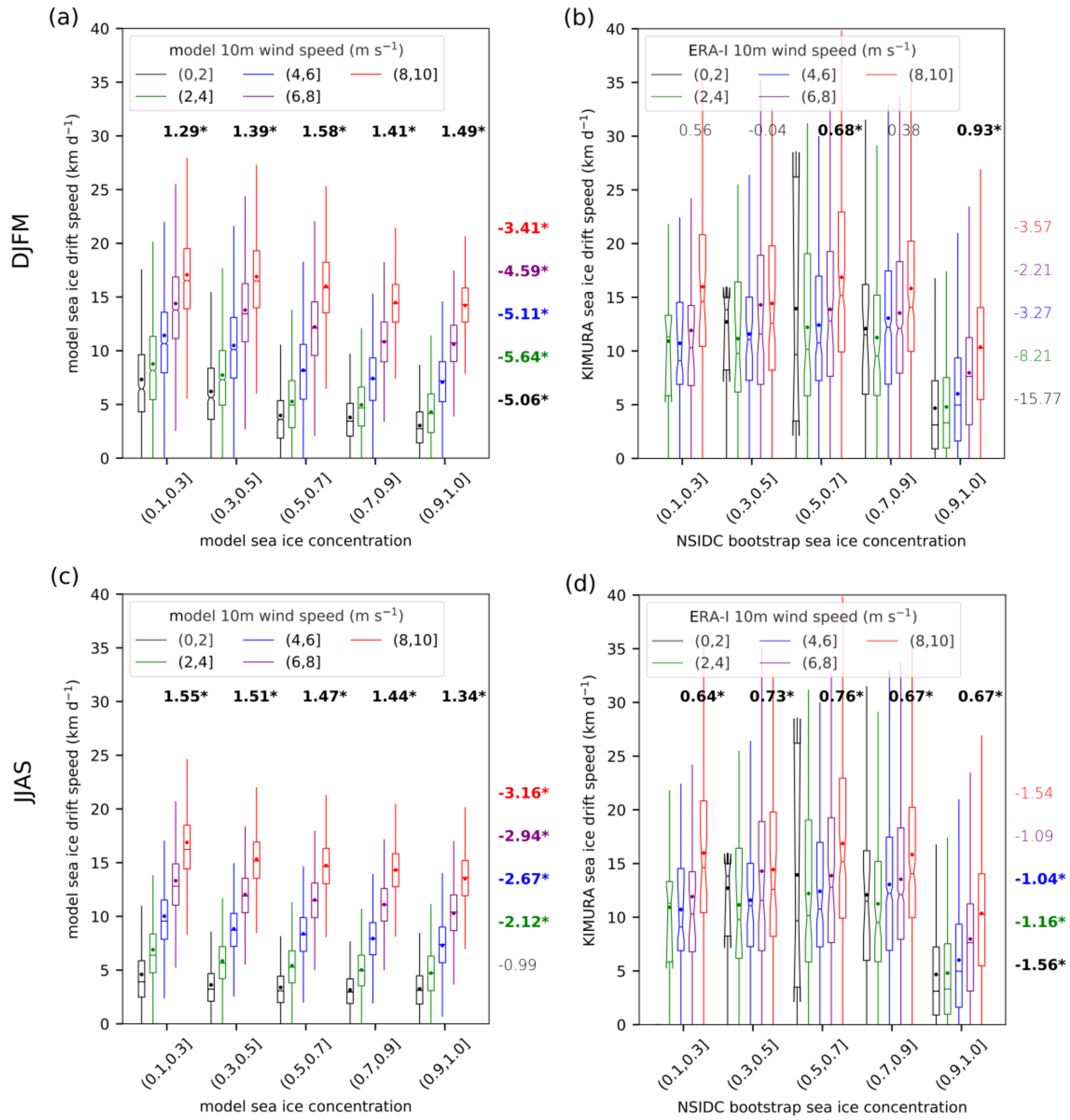

Figure 4: Box-whisker plots of the relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors) in the model duringfor 2003-2014 (a) winter (DJFM) and (c) summer (JJAS) in the model (HIRHAM-NAOSIM 2.0). (b) and (d) are the same as that for (a) and (c) respectively, the relationshipbut based on the observation/reanalysis data during 2003-2014 winter and summer respectively. For the model, all 10 ensemble members are included. The plot is based on daily data and on all grid points within the study domain indicated in Figure 1. The horizontal bar represents the median, the notch represents the 95% confidence interval of the median, the dot represents the mean, the top and bottom of the box represent the 75th and 25th percentiles, the upper/lower whiskers represent the maximum/minimum value within 1.5 times interquartile range (IQR) to 75/25 percentiles. The numbers above the boxplots represent the slopes of near-surface wind and sea-ice drift speed fit lines (unit: km d-1 per 1 m s-1 wind speed change; font colors as for the wind speed classes). The numbers right of the boxplots represent the slopes of sea-ice concentration and sea-ice drift speed fit lines (unit: km d-1 per 10% sea-ice concentration change). A bold and asterisked number indicates that the slope of the fit line is significant at the 95 % level. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

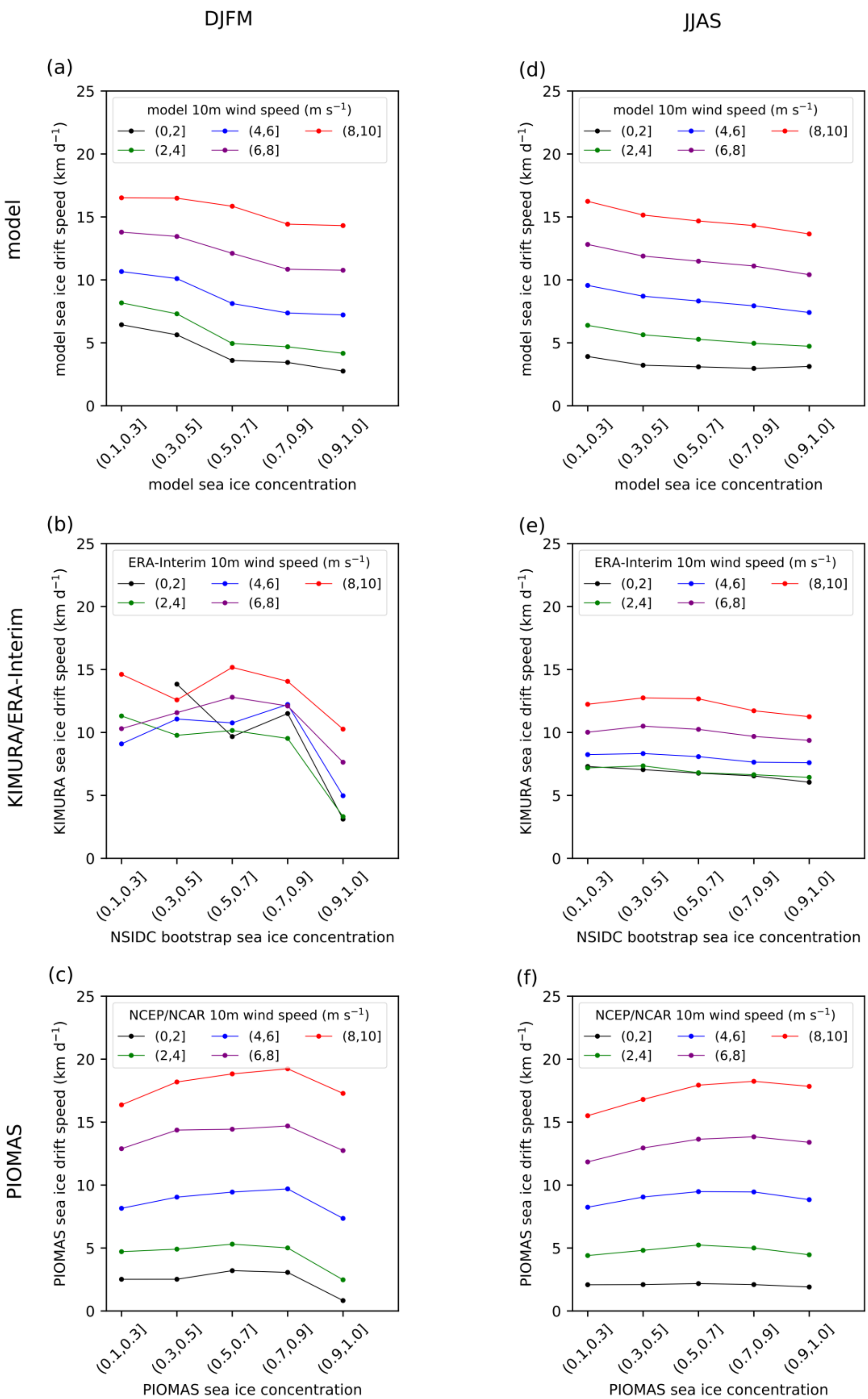

Figure 5: Relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors) in the model during for 2003-2014 (a) winter (DJFM) and (d) summer (JJAS) in the model (HIRHAM-NAOSIM 2.0). (b) and (e) are the same as that for (a) and (d) respectively, but based on the observation/reanalysis data. (c) and (f) are the same as that for (a) and (d) respectively, but based on PIOMAS data. The points in the plot are the median value of all the daily data and on all grid points for certain wind speed and sea-

ice concentration, within the study domain indicated in Figure 1. In the labels of different sea-ice concentration and 10-m wind speed classes, “(” means exclusive and “]” means inclusive.

Evaluation of Arctic sea-ice drift and its dependency on near-surface wind and sea-ice conditions~~concentration and thickness~~ in the coupled regional climate model HIRHAM-NAOSIM

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Abstract. We examine the simulated Arctic sea-ice drift speed for the period 2003-2014 in the coupled Arctic regional climate model HIRHAM-NAOSIM 2.0. In particular, we evaluate the dependency of the drift speed on the near-surface wind speed and sea-ice conditions. Considering the seasonal cycle of the Arctic basin averaged drift speed, the model reproduces the summer-autumn drift speed well, but significantly overestimates the winter-spring drift speed, compared to satellite-derived observations. Also, the model does not capture the observed seasonal phase lag between drift and wind speed, but the simulated drift speed is more in phase with the near-surface wind. The model calculates a realistic negative ~~relationship~~ correlation between drift speed and ice thickness and between drift speed and ice concentration during summer-autumn when the ice concentration is relatively low, but the correlation is weaker than observed. A daily grid-scale diagnostic indicates that the model reproduces the observed positive ~~relationship~~ correlation between drift and wind speed. The strongest impact of wind changes on drift speed occurs for high and moderate wind speeds, with a low impact for rather calm conditions. The correlation under low-wind conditions is overestimated in the simulations~~,~~ compared to observation/reanalysis data. A sensitivity experiment demonstrates the significant effects of sea-ice form drag from floe edges included by an improved parameterization of the transfer coefficients for momentum and heat over sea ice. However, this does not improve the agreement of the model~~l~~ed drift speed/wind speed ratio with observations based on reanalysis data for wind and remote sensing data for sea ice drift. An improvement might be achieved~~possible, among others,~~ by tuning parameters that are not well established by observations~~the open parameters of the parameterization in future~~.

1 Introduction

Arctic sea ice has experienced a rapid decrease in recent decades (e.g. Serreze ~~&~~and Stroeve, 2015; Stroeve et al., 2012). On the one hand, the observed Arctic sea-ice decline is caused by thermodynamic processes, such as increasing air and ocean temperatures, e.g. due to ocean heat transports into the Arctic (Serreze et al., 2007). On the other hand, dynamical processes, such as a changed sea-ice drift in response to changing wind, ocean currents and sea-ice conditions (e.g., reduction of sea-ice concentration and thickness), play an important role in the redistribution of sea ice (Rampal et al., 2011; Serreze et al., 2007; Spreen et al., 2011). Except for the fast-ice and shear zones, sea ice moves largely in response to local winds and ocean currents. More than 70% of the variance of the central Arctic pack ice motion is explained by the geostrophic wind alone on the time scale of days to months (Thorndike ~~&~~and Colony, 1982). For compact sea ice in the inner Arctic or sea ice near the coasts, the internal friction can be as large as the forces due to the winds and ocean currents (Leppäranta, 2011). The seasonal Arctic basin-wide sea-ice drift speed, however, is mainly correlated with the sea-ice concentration and thickness, other than with near-surface wind: Sea-ice drift speed decreases with increasing ice concentration when ice concentration is low, and sea-ice drift speed decreases with increasing ice thickness when ice concentration is high (Docquier et al., 2017; Olason ~~&~~and Notz, 2014). In order to understand and project Arctic sea-ice changes, it is vital for climate models that they can realistically capture the observed sea-ice drift and its dependency on the atmospheric and oceanic forcing and on the sea-ice conditions at different time scales.

~~Rampal et al. (2011) suggested that the underestimated thinning of Arctic sea ice in the CMIP3 models is related to their failure of capturing the observed acceleration of Arctic sea-ice drift in recent decades. Based on the CMIP5 models and consistent temporal sampling of modeled and observational data,~~ Tandon et al. (2018) showed that only few CMIP5 models capture the observed seasonal cycle of sea-ice drift speed and that some models show a seasonal cycle of sea-ice drift in phase with the near-surface wind speed.

~~Thus, the~~The first aim of this paper is to evaluate the simulated sea-ice drift speed and its relation with sea-ice concentration, thickness and near-surface wind speed in the coupled Arctic regional climate model HIRHAM-NAOSIM 2.0 (Dorn et al., 2019). We ~~use a methodology presented by Olason and Notz (2014) and Docquier et al. (2017) which is appropriate to~~first evaluate the simulated Arctic basin-wide monthly mean drift, then we evaluate the relationship between sea-ice drift speed and ~~its relation to the~~ sea-ice ~~and~~ conditions/wind speed ~~conditions. Since both model evaluations and observational studies based on the daily grid scale are rare, we also present relationship-based diagnostics~~ both on Arctic basin-wide, multi-year monthly mean scale and on daily grid scale.

The second aim of this paper is to explore the sensitivity of the simulated ice drift to the parameterization of the atmospheric near-surface transfer coefficients for heat and momentum over sea ice, in which the effect of sea-ice form drag is included. The air-ice drag controls the sea-ice drift under the influence of the wind forcing. It can be separated into the frictional skin drag due to microscale roughness elements on the sea-ice surface and the form drag caused by large structures like pressure ice ridges and floe edges (Arya, 1973, 1975). Most climate models account for the sea-ice skin drag and consider the form drag only by tuning the spatially and temporally invariant air-ice drag coefficient (Castellani et al., 2018; Tsamados et al., 2014). This approach is poorly constrained by the observations and fails to describe the variability of the air-ice drag processes correctly (Andreas et al., 2010; Lüpkes et al., 2012a; Lüpkes ~~&~~and Gryanik, 2015; Tsamados et al., 2014).

Several model studies that include the sea-ice form drag were carried out (e.g. Castellani et al., 2018; Renfrew et al., 2019; Tsamados et al., 2014). Tsamados et al. (2014) implemented a complex sea-ice form drag parameterization based on many sea-ice cover properties (e.g. sea-ice concentration, vertical extent and area of ridges, freeboard and floe draft, and the size of floes and melt ponds) into the stand-alone sea-ice model CICE. Castellani et al. (2018) implemented a simpler sea-ice form drag parameterization that only relies on sea-ice deformation energy and concentration into the coupled ocean-sea ice model MITgcm. Both studies showed improvement in sea-ice drift after the form drag had been included. Recently, Renfrew et al. (2019) implemented an observation-based parameterization of atmospheric form drag caused by floe edges based on suggestions by Lüpkes et al. (2012a), Lüpkes and Gryanik (2015), and Elvidge et al. (2016) into a stand-alone atmosphere model. The simulation results show an improved agreement of mean atmospheric variables and turbulent fluxes with measurements in cold-air outbreak situations over the Fram Strait when form drag is included.

~~Recently, a modern observation-based sea-ice form drag description (Lüpkes & Gryanik, 2015) was implemented into a stand-alone atmospheric model (Renfrew et al., 2019) and a similar parameterization was used by Castellani et al. (2018) as well as by Tsamados et al. (2014) in studies with coupled ice-ocean models. The study of Renfrew et al. (2019) showed an improved~~

agreement of mean atmospheric variables and turbulent fluxes in cold-air outbreak situations over the Fram Strait with measurements when the parameterization including form drag was used. The ice-ocean modelling studies revealed an improvement of the sea-ice drift pattern when form drag was included.

The physical parameterizations suggested by Lüpkes and Gryanik (2015) were constrained by summertime observations over the sea-ice pack and by aircraft observations over the marginal ice zone (MIZ) during winter. Later the parameterizations were once more validated using a larger and independent set of aircraft data obtained from campaigns during different seasons (Elvidge et al., 2016). This validation work concerned the momentum fluxes. The assumptions of Lüpkes and Gryanik (2015) about heat and moisture fluxes over the MIZ could not yet be evaluated by measurements. Thus, further research is necessary on this issue.

Despite the potential uncertainties in terms of the heat and moisture fluxes, the strategy of the present study is to investigate the performance of the parametrization by Lüpkes and Gryanik (2015) without further modification in a coupled atmosphere-ocean-sea ice model. The parametrization by Lüpkes and Gryanik (2015) contains constants that could be fine-tuned in the future to eventually improve the model results. We leave this optimization, however, to future work since it requires a large number of model runs and extensive analysis work that is beyond the scope of this paper focusing on the principal impact of sea-ice form drag on the model results. We explore within a coupled atmosphere-sea ice-ocean model the impact of the sea-ice form drag caused by ice floe and lead edges on the sea-ice drift. Although the new parameterization contains several parameters which might be tuned for an improvement of model results, we leave optimization of these parameters as future work, and focus on the principal behavior of the model system when form drag is included in the parameterization of atmospheric stress in this study.

The organization of this paper is as follows: Section 2This paper is organized in the following way. In Section 2, we describes the model simulations and the observational data as well as the analysis methods used. In Section 3, we present the simulated long-term average Arctic sea-ice drift speed and its dependency on near-surface wind and sea-ice conditions based on both multiyear, Arctic basin-wide scale and daily grid scale. In Section 4, we discuss the sea-ice form drag impact on the atmospheric near-surface turbulent fluxes and on the sea-ice drift speed. Finally, a summary and conclusions are provided in Section 5.

2 Data and Analysis

2.1 Model and simulations

2.1.1 Coupled atmosphere-ice-ocean regional model

The model used in this study is HIRHAM-NAOSIM 2.0 (Dorn et al., 2019), which consists of the regional atmospheric model HIRHAM5 and the regional ocean-sea ice model NAOSIM (North Atlantic/Arctic Ocean Sea-Ice Model). HIRHAM5 is based on the numerical weather forecast model HIRLAM-7.0 (Undén et al., 2002) and applies the physical parameterizations of the atmospheric general circulation model ECHAM-5.4.00 (Roeckner et al., 2003). Köberle and Gerdes (2003) give a basic description of NAOSIM, while Fieg et al. (2010) describe NAOSIM's fine-resolution model version, which is used in HIRHAM-NAOSIM 2.0. NAOSIM's ocean component is based on the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model MOM-2 (Pacanowski, 1996). The sea-ice component is based on the dynamic–thermodynamic sea-ice model described by Harder et al. (1998) and represents an upgrade of the original Hibler (1979) model. The internal ice stress is described by a viscous-plastic rheology according to Hibler (1979). Thermodynamic snow-ice processes are handled using the zero-layer approach by Semtner (1976). Detailed information about HIRHAM-NAOSIM 2.0 is given by Dorn et al. (2019). The model is applied over a circum-Arctic domain at a horizontal resolution of 1/4° (~27 km) in the atmosphere (HIRHAM5) and 1/12° (~9 km) in the ocean (NAOSIM). The ocean-sea ice domain corresponds to the domain shown in Figure 1.

2.1.2 Long-term simulations of the base configuration

A 10-member ensemble of multi-decadal climate simulations~~, covering the 38 years from~~ for the period 1979 to 2016~~,~~ were carried out by Dorn et al. (2019) with the base configuration of HIRHAM-NAOSIM 2.0~~, as described by Dorn et al. (2019)~~. These ensemble simulations represent the basis for the present study and are referred to as BASE hereafter. The individual ensemble members used the same atmospheric initialization, but applied different ice-ocean initial conditions, which were taken from January 1 of the last 10 years of a preceding 22-year-long coupled spin-up run for the period 1979-2000 (see Dorn et al., 2019, for more details). The regional model simulations were driven by ERA-Interim reanalysis data (Dee et al., 2011; referred to as ERA-I hereafter). ERA-I provided 6-hourly lateral atmospheric boundary conditions as well as daily surface boundary conditions where required (outside the coupling domain). The lateral ocean boundary conditions in the northern North Atlantic were taken from the Levitus climatology (Levitus and Boyer, 1994; Levitus et al., 1994).

2.1.3 Sensitivity experiments

To investigate the model's sensitivity to the momentum ~~heat~~ and heat ~~momentum~~ transfer coefficients which explicitly include sea-ice form drag contributions, both a control run (CTRL) and a sensitivity experiment (SENS) for one year (year 2007) were performed. CTRL applies the default atmospheric boundary layer parameterization of ECHAM 5.4 (Roeckner et al., 2003) with air-ice momentum and heat transfer coefficients depending only on atmospheric stability. The sea-ice form drag effect is not included. SENS includes the improved parameterization of air-ice momentum and heat transfer coefficients ~~by~~ adapted based on Lüpkes and Gryanik (2015). There, the transfer coefficients depend on sea-ice concentration and include both the sea-ice skin drag and form drag effects caused by the edges of~~-~~ ice floes in the marginal sea ice zone and ~~at~~ of leads in the inner Arctic. The parameterization could also account ~~also~~ for the effect by melt pond edges, but this additional effect would require the knowledge of the pond fraction on top of the ice~~concentration~~, which is not available in HIRHAM-NAOSIM 2.0. The model applies a flux averaging method, which means that the total flux over a surface covered with sea ice of concentration *A* and with open water (1-*A*), is the concentration-weighted mean of both contributions. We describe here only the fluxes over sea ice, in which form drag is included in SENS and refer to Roeckner et al. (2003) for the parameterization of fluxes over open water. In ~~the~~ CTRL ~~run~~ (as in ~~the~~ BASE ~~run~~), however, the air-ice momentum transfer coefficient $C_{d,i}$ and the heat transfer coefficient $C_{h,i}$ include only the sea-ice skin drag effect~~s~~. They are calculated as

$$C_{d,i} = C_{dn,i}\, f_{m,i} \tag{1}$$

$$C_{h,i} = C_{hn,i}\, f_{h,i} \tag{2}$$

where $C_{dn,i}$ ($C_{hn,i}$) are the drag (heat transfer) coefficients under neutral atmospheric stratification over ice and $f_{m,i}$ ($f_{h,i}$) are the stability correction functions over ice to adjust $C_{dn,i}$ ($C_{hn,i}$) based on atmosphere stability. $C_{dn,i}$ is calculated as

$$C_{dn,i} = \frac{k^2}{\left[\ln(z_L/z_{0,i}+1)\right]^2} \tag{3}$$

where k=0.4 represents the von~~-~~ Karman~~'s~~ constant, z_L is the height of the lowest atmospheric model level, and $z_{0,i}$ represents the skin drag roughness length over sea ice. $C_{hn,i}$ is calculated as

$$C_{hn,i} = \frac{k^2}{\ln(z_L/z_{0,i}+1)\,\ln(z_L/z_{t,i}+1)} \tag{4}$$

where $z_{t,i}$ represents the scalar roughness length over ice. Equations (1) to (4) are common descriptions of air-ice momentum and heat transfer coefficients except that '+1' was added to both $z_L/z_{0,i}$ and $z_L/z_{t,i}$ in equations (3) and (4). This is done in the model to avoid that the argument of the logarithm can go to zero, for which $C_{d,i}$ ($C_{h,i}$) would go to infinity (see also Giorgetta et al., 2013).

In the SENS run, the new momentum transfer coefficient $\hat{C}_{d,i}$ and the new heat transfer coefficient $\hat{C}_{h,i}$ over ice, which both include skin drag and form drag effects, are calculated as

$$\hat{C}_{d,i} = C_{dn,i}\, f_{m,i} + C_{dn,f}\left[f_{m,i}A + f_{m,w}(1-A)\right]/A \qquad (5)$$

$$\hat{C}_{h,i} = C_{hn,i}\, f_{m,i} + C_{hn,f}\left[f_{h,i}A + f_{h,w}(1-A)\right]/A \qquad (6)$$

where $C_{dn,f}$ ($C_{hn,f}$) represent the form drag (heat transfer) coefficients related to neutral conditions over ice, $f_{m,w}$ ($f_{h,w}$) are the stability correction functions over water to adjust $C_{dn,f}$ as well asand $C_{hn,f}$ to atmospheric stability. Equations (5) is obtained by combining the equations (6), (52) and (70) by Lüpkes and Gryanik (2015). Equations (6) is obtained by combining the equations (9), (64) and (74) by Lüpkes and Gryanik (2015). After adding '+1' both to $10/z_0$ and z_L/z_0 and replacing z_0 with $z_{0,f}$ in equation (65) by Lüpkes and Gryanik (2015), $C_{dn,f}$ is calculated as

$$C_{dn,f} = C_{e10}\left[\frac{\ln(10/z_{0,f}+1)}{\ln(z_L/z_{0,f}+1)}\right]^2 A(1-A)^{\beta} \qquad (7)$$

where C_{e10} represents the effective resistance coefficient (both the aerodynamic resistance coefficient of individual floes and the shape factor), $z_{0,f}$ represents the (form) roughness length, and β is a constant exponent describing the dependence of cross wind dimension of a floe on A. The values of C_{e10}, $z_{0,f}$ and β are $2.8\cdot10^{-3}$, $0.57\cdot10^{-3}$ m and 1.1 respectively. The value of C_{e10} is the average given in equations (48) and (49) by Lüpkes and Gryanik (2015). The value of $z_{0,f}$ is an average resulting from measured roughness lengths by various campaigns considered by Andreas et al. (2010), Lüpkes et al. (2012a) and Castellani et al. (2014). Note that this value is not critical for the parametrization. The value of β comes from equation (59) by Lüpkes et al. (2012a). $C_{hn,f}$ is calculated as

$$C_{hn,f} = \frac{C_{dn,f}}{1 + C_{a,f}\sqrt{C_{dn,f}}} \qquad (8)$$

where

$$C_{a,f} = \frac{1}{k}\ln\left(\frac{z_{0,i}}{z_{t,i}}\right) \quad C_{a,f} = \frac{1}{k}\ln\left(\frac{z_{0,t}}{z_{t,t}}\right) \qquad (9)$$

Equation (8) represents a simple algebraic transformation of equation (60) by Lüpkes and Gryanik (2015) making use of their equations (59) and (61) with $\alpha_f = \alpha$. The skin drag roughness length over sea ice is set to

$$z_{0,i} = 0.69\cdot10^{-3}\ \text{m} \qquad (10)$$

and the scalar roughness length over sea ice is parameterized as mostly done in the literature as

$$z_{t,i} = \alpha z_{0,i} \qquad (11)$$

with

$$\alpha = \exp\left[3.0 - 29.53 {z_{0,i}}^{0.25}\right] \qquad (12)$$

CTRL and SENS simulations comprise each an ensemble of 10 members, which only differ in their ice-ocean initial state. The ice-ocean initial conditions for CTRL and SENS were produced in exactly the same way as for BASE (see Section 2.1.2). ERA-I provided the boundary forcing also as in the BASE simulations.

2.2 Datasets for evaluation

2.2.1 Sea-ice drift

For the evaluation of the sea-ice drift speed, satellite-based daily sea-ice drift observations from Kimura et al. (2013) (referred to as KIMURA hereafter) are used. There, the improved maximum cross-correlation method (Kimura ~~&~~and Wakatsuchi, 2000, 2004) were applied to detect ice motions based on AMSR-E brightness temperature. The horizontal resolution of the KIMURA dataset is 60 km x 60 km. The uncertainty of the KIMURA data over the Arctic in summer is from 1.12 to 1.47 km d^{-1} and depends on the drift speed (Sumata et al., 2015a). In winter, the uncertainty is at least 50% smaller than in summer and depends on the drift speed too (Sumata et al., 2015b). Although the accuracy of KIMURA drift speed ~~(1-2 cm s^{-1})~~ is lower than that of buoy data, it has a much wider spatial and temporal coverage and is therefore appropriate for regional model evaluation (Sumata et al., 2015a). Another advantage of the KIMURA product is that it provides ice drift data both in winter and summer. More details are given by Kimura et al. (2013) and Sumata et al. (2015a).

In addition, daily sea-ice drift speed from the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS; Zhang ~~&~~and Rothrock, 2003) is used. This enables a consistent and simultaneous evaluation of sea-ice drift speed, concentration and thickness, and near-surface wind speed. The PIOMAS data are downloaded from ftp://pscftp.apl.washington.edu/zhang/PIOMAS/data/v2.1/. The mean horizontal resolution in the Arctic is ca. 22 km (Docquier et al., 2017). Detailed information about the PIOMAS dataset is given by Schweiger et al. (2011).

2.2.2 Sea-ice concentration

For sea-ice concentration (SIC), the NSIDC bootstrap daily SIC over the Northern Hemisphere, Version 3 (https://nsidc.org/data/nsidc-0079) is used. This SIC dataset is based on Nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data and has been generated using a bootstrap algorithm with daily varying tie-points. It provides an accuracy of 5-10% and is gridded on the 25 x 25 km^2 polar stereographic grid (Comiso, 2017).

2.2.3 Sea-ice thickness

Since Arctic basin-wide long-term sea-ice thickness (SIT) observations are not available, SIT data from PIOMAS are used in this study as a substitute for observational SIT as done in previous studies (Docquier et al., 2017; Johnson et al., 2012; Shu et al., 2015; J. Stroeve et al., 2014). However, we have to recall that PIOMAS is based on a coupled ice-ocean model, even though constrained through the assimilation of observed sea-ice concentrations and sea surface temperatures. Therefore, the comparison with PIOMAS informs us rather about the current state of the model than about a direct model bias. Schweiger et al. (2011) showed that the PIOMAS ice thickness agrees with ICESat ice thickness retrievals (in the order of 0.1 m mean difference) and that the spatial thickness patterns agree with each other (pattern correlation coefficients > 0.8). However, PIOMAS appears to overestimate thin ice thickness and to underestimate thick ice (Schweiger et al., 2011).

2.2.4 Near-surface wind

For the near-surface wind speed (WS), daily 10-m wind speed from ERA-I is used. The ERA-I data were downloaded from the MARS archive at ECMWF and interpolated to the same ~~from ERA-I with~~ 0.25° x 0.25° ~~horizontal resolution~~grid ~~are~~ as used in the model's atmosphere component HIRHAM5. More information about this dataset is given by Berrisford et al. (2011). The NCEP/NCAR 10-m wind speed with 1.875° x 1.9° horizontal resolution is used to accompany the PIOMAS sea-ice data as this data were used as the wind forcing for PIOMAS. More information about the NCEP/NCAR dataset is given by Kalnay et al. (1996).

2.3 Analysis methods

As the different evaluation datasets for sea ice have different spatial resolution, ~~the~~ a bilinear interpolation method is used to remap them onto the NAOSIM grid. The common analysis period used in this study is the 12-year-long period 2003-2014 (only December is included for 2012). This limitation is related to~~because of~~ the KIMURA data, which are only available since October 2002, and January to November data are missing ~~in~~ for 2012 due to the transition from AMSR-E to AMSR-2. We focus on extended summer (JJAS) and winter (DJFM) in this study.

The domain for the basin-wide analysis covers the Arctic Ocean (referred to as the study domain hereafter; enclosed by the purple line in Figure 1). The study domain is defined following Tandon et al. (2018) and excludes the grid points within a distance of 150 km from each coastline.

The simulations are evaluated by means of the commonly used climatological approach. For this, we present multi-year seasonal mean spatial maps and results spatially averaged over the study domain. The model data represent an average of the 10 ensemble members, which were first spatially averaged ~~spatially~~ over the study domain and then ~~temporally~~ time averaged ~~from~~ over the period 2003-2014. Following Olason and Notz (2014) and Docquier et al. (2017), we use scatter plots showing Arctic basin-wide and multi-year averaged monthly mean sea-ice drift speed against sea-ice conditions (sea-ice concentration and thickness) to evaluate the relationships between sea-ice drift speed and sea-ice conditions. The linear fit-lines are added in the scatter plots to assist the comparison of the relationship in the model and in the observation/reanalysis. Furthermore, we present evaluation results based on daily data on the grid scale, i.e. for all grid points within the study domain. With this we aim to statistically evaluate the high spatial and temporal variability in the domain, and we represent this by means of box-whisker plots. Therein, the horizontal bar represents the median, the notch represents the 95% confidence interval of the median, the dot represents the mean, the top and bottom of the box represent the 75th and 25th percentiles, and the upper/lower whiskers represent the maximum/minimum values within the 1.5 times interquartile range (IQR) to 75/25 percentiles.

Normalized ensemble mean differences between SENS and CTRL ~~run~~ are used to investigate the influence of sea-ice form drag on atmosphere-ice momentum and heat fluxes, sea-ice states and motion and were calculated by dividing ensemble mean differences of SENS minus CTRL with ensemble standard deviations of these differences. Assuming that the differences between two random simulations are normally distributed around zero, the normalized differences enable a rough estimate of the statistical significance of the differences. Normalized differences greater than 2 (3) or lower than -2 (-3) indicate that the difference is significant on the 95 % (99.7 %) level.

3 Evaluation of simulated sea-ice drift speed

First, the skill of the BASE simulated mean sea-ice drift speed (SID) is quantified (Section 3.1). SID is mainly governed by near-surface wind, -sea-ice conditions, and ocean currents. ~~forced by the near-surface wind, but it is also influenced by sea-ice roughness and the internal friction. The former is influenced by SIC and the latter is influenced both by SIC and SIT. Therefore, t~~The ~~SID~~ dependency of SID on near-surface wind speed (WS) (~~section~~ Section 3.2) and on sea-ice conditions (Sections 3.3~~-~~ and 3.4) is evaluated ~~afterwards,~~ in each case in terms of both the climatological and the daily grid-scale views.

3.1 Multi-year mean sea-ice drift speed (SID)

The simulated mean SID shows a distinct spatial pattern with highest drift speed near the ice edges in the Barents Sea, Greenland Sea, and Labrador Sea in winter and over the Alaskan coast in summer (Figure 1a). Compared to the KIMURA dataset, the study-domain-mean bias (RMSE) is 1.72 km d^{-1} (2.12 km d^{-1}) in winter and -0.03 km d^{-1} (0.91 km d^{-1}) in summer.

The model generally overestimates SID in the ice edge zone and north of the Canadian archipelago, the region of thickest ice, with a maximum bias of ca. 6 km d^{-1} in winter and a smaller bias in summer (Figure 1b and 1d). Compared with the uncertainty in the KIMURA sea-ice drift speed provided by Sumata et al. (2015a, b), the model bias in summer is close to or slightly smaller than the uncertainty of the KIMURA data. This indicates that the sign of the model bias in summer SID is uncertain. In winter, however, the model clearly overestimates the SID over the central Arctic and north of the Canada Archipelago and Greenland, even if considering the uncertainty of the KIMURA data. This overestimation of SID in the thick-ice region may be linked to the underestimation of SIT and SIC and overestimation of WS ~~over~~ in that region (Suppl. Figures S1-S3). The SIT differences between HIRHAM-NAOSIM 2.0 and PIOMAS can partly be attributed to the feedback between atmosphere and ocean-sea ice in the fully coupled atmosphere-ocean-sea ice model, which is not present in an ocean-sea ice model like PIOMAS. Analysis of the SIT differences between HIRHAM-NAOSIM 2.0 and CryoSat-2 during winter 2010-2014 (Figure S2; see Hendricks and Ricker, 2019, for details about the CryoSat-2 SIT data used here) confirms that HIRHAM-NAOSIM 2.0 underestimates the SIT over the central Arctic and north of the Canada Archipelago and Greenland, at least in winter. The underestimation of SIT and sea-ice volume compared to PIOMAS has been discussed by Dorn et al. (2019) for the longer time period 1979-2016.

The model reproduces the basic mean seasonal cycle of SID ~~compared to~~of the KIMURA data (Figure 2) with respect to timing and absolute values between May and December. The average bias between June and November is almost zero (-0.0003 km d^{-1}) and the corresponding RMSE is 0.28 km d^{-1}. The maximum ice drift speed (10 km d^{-1}) occurs in October both in the model and in the KIMURA data. However, the model substantially overestimates the SID speed in winter and early spring. The averaged bias (RMSE) between December and May reaches 1.52 km d^{-1} (1.64 km d^{-1}). In addition, the modeled minimum SID occurs in May, two months delayed ~~in May,~~ compared to the KIMURA ~~data which shows the~~(minimum SID in March). This reflects a longer-lasting and much weaker SID reduction from autumn to ~~the~~ spring ~~season~~ in the model compared to the KIMURA data. Furthermore, the interannual variation of SID ~~is~~ in the model is lower than in the KIMURA data (Figure 2). For example, the interannual amplitude is 0.70 km d^{-1} (1.26 km d^{-1}) in the model (KIMURA data) in March and 0.36 km d^{-1} (0.74 km d^{-1}) in September, respectively.

The overestimation of winter SID could be related to the underestimation of winter SIT (Figure S2). Besides, the prescribed values of the ice-ocean drag coefficient and the ice strength parameter could also play a role. The ice-ocean drag coefficient in the base configuration of HIRHAM-NAOSIM 2.0 (5.5×10^{-3}) is comparable to other CMIP5 models, even though a few models use 3-4 times higher coefficients (see Tandon et al., 2018). Higher ice-ocean drag might damp the SID and its strong dependency on the wind speed. Docquier et al. (2017) showed that the higher the ice strength parameter, the lower the winter SID and the lower SIT. The ice strength parameter in the base configuration of HIRHAM-NAOSIM 2.0 (30,000 N m^{-2}) is already slightly higher than in all CMIP5 models (see Tandon et al., 2018). This value has been established for stand-alone ocean-ice simulations with daily wind forcing, but might still be too low considering the hourly wind forcing from the interactively coupled atmosphere.

3.2 Dependency of sea-ice drift speed (SID) on near-surface wind speed (WS)

3.2.1 Climatological view

As shown in previous studies (Docquier et al., 2017; Kushner et al., 2018; Olason ~~&~~and Notz, 2014; Tandon et al., 2018), the observed distinct mean seasonal cycle of SID (maximum in autumn, minimum in spring) is obviously not solely controlled by the wind speed, which is strongest in winter and weakest in summer (Figure 2). The phase lag between the seasonal cycle of SID and WS is about 3-4 months in observations/reanalysis (KIMURA ice drift/ERA-I wind). The modeled seasonal cycle and magnitude of the WS agrees well with the ERA-I reanalysis. Therefore, according According to the delayed SID minimum (Ssection 3.1), the phase lag between the simulated seasonal cycle of SID and WS is reduced to about one month, like in many CMIP3 and CMIP5 models (Rampal et al., 2011; Tandon et al., 2018), leading to a higher correlation between SID and WS. This indicates that the modeled SID is much stronger controlled by the wind speed than the observed SID.

Another metric to quantify the mean relationship between SID and WS is the wind factor, which is the ratio of SID to WS multiplied by 100. Averaged over the study domain, the simulated wind factor is 1.77% in winter and 1.87% in summer, which agrees with the observations/reanalysis (KIMURA ice drift/ERA-I wind) in the sense that the averaged wind factor is larger in summer (1.96%) than in winter (1.42%)smaller in winter (1.42%) than in summer (1.96%). However, compared to the observations, the simulated wind factor is too large in winter. As mentioned in Section 3.1, too high sensitivity of the SID to the wind in winter may be related to the underestimated SIT and model parameters governing the sea-ice dynamics.

Figure 3 shows the spatial patterns of the multi-year mean wind factor over the Arctic. In winter, the simulated wind factor has its maximum associated with the strong wind and low ice thickness in over the Baffin Bay and Greenland Sea. Within the study domain, it has athe maximum (~2%)occurs along the Transpolar Drift Stream (~2%) and the minimum values over north of Greenland and the Canadian Archipelago (<0.5%) where sea ice is thickest (<0.5%). This The simulated pattern roughly agrees is in general agreement with the corresponding pattern ofobservation/reanalysis according to KIMURA ice drift/ERA-I wind (Figure 3 and Suppl. Figure S4) and previous results using SSM/I ice drift/NCEP wind (Spreen et al., 2011). In winter, hHowever, the simulated wind factor is overestimated compared to the KIMURA/ERA-I data almost everywhere over the study domain in winter, with the maximum bias reaching 1% over the thick ice north of the Canadian Archipelago (Figure 3). In summer, the modelled wind factor peaks (~3%) along the marginal ice zone, such as in the coastal Beaufort Sea. This could be the result of a dynamical coupling between sea ice and the coastal ocean as suggested by Nakayama et al. (2012): In a coastal ocean covered with sea ice, wind-forced sea-ice drift excites coastal trapped waves and generates fluctuating ocean currents. These ocean currents can enhance the sea-ice drift when the current direction is the same as the wind-driven drift direction. This has been discussed as a result of an enhancement of SID caused by the dynamical coupling between sea ice and coastal ocean (e.g., Nakayama et al., 2012). In contrast to winter, the modelled wind factor in summer is underestimated over the study domain in summer. These seasonally different bias patterns in the wind factor are associated with those of the SID (Figures 1b and 1d).

3.2.2 Daily and grid-scale view

Previous studies reported on the ice drift's nearly linear increase with increasing wind for high and moderate WS (Thorndike &and Colony, 1982), but no clear relationshipconnection for low WS (Leppäranta, 2011; Rossby &and Montgomery, 1935). To investigate this in detail, Figures 4 and 5 present the analysis of the dependency of SID on WS based on daily data and on the grid scale. For the observation/reanalysis reference we use KIMURA ice drift and ERA-I wind.

During winter, the simulated SID significantly increases with increasing WS. According to the median values of SID and the associated best fit-line slope of SID vs. WS, the increase of SID varies from 1.31 29 km d^{-1} to 1.59 49 km d^{-1} per 1 m s^{-1} WS increase under different SIC classes (Figures 4a and 5a). The strongest SID increase per WS increase occurs for SIC of 50-70% (Figure 4a). In the observations/reanalysis, the SID only consistently increases with increasing WS when SIC is higher than 90% (Figures 4b and 5b). The corresponding slope indicates 0.94 93 km d^{-1} per 1 m s^{-1} WS increase, which is a ca. 40% smaller increase than the modeled onevalue. Both the model (for all SIC classes) and the observation/reanalysis (for SIC > 90%) show a linear increase of SID with increasing WS for strong winds (WS > 3 4 m s^{-1}), but a weak dependency of SID on WS for lower winds.

During summer, both the model and the observation/reanalysis ~~agree on~~show a consistent general increase of SID with increasing WS for all SIC classes when WS > ~~3~~ 4 m s^{-1} (Figures 4c, 4d, 5d and 5e). The simulated magnitude of SID increase per 1 m s^{-1} WS increase is similar as in winter. ~~And, a~~Again, the simulated SID increases faster with increasing WS than ~~in~~ the observed SID~~ation/reanalysis~~, by ~~about~~ a factor of about 2-2.5. Another striking difference between the simulations and the observation/reanalysis is that the simulated SID-WS relation ~~shows generally a~~is rather linear~~ functionality~~ (~~the relation is~~only slightly attenuated ~~weaker~~ when WS ≤ 2 m s^{-1}). In contrast, this relation is highly nonlinear in the observation/reanalysis (Figure 4d, 5e)~~; it is only linear for strong winds (WS > 4 m s^{-1})~~. The observed increase of ~~the~~ SID with increasing WS is much stronger when WS passes a threshold (of ca. 4 m s^{-1}), compared to lower WS. For weak winds (WS lower than 4 m s^{-1}), SID is not much affected by WS changes.

Generally, the observed SID (for a certain WS and SIC class) shows an about 2 times higher spatiotemporal variability (indicated by the larger IQR; Figure 4) than the modell~~l~~ed one. This discrepancy might be linked to a data source difference or inconsistency between the used KIMURA SID observations and ERA-I reanalysis WS data, but it might also hint to a model weakness.

The PIOMAS-based SID-WS based relation ~~based on PIOMAS~~ (PIOMAS ice drift, NCEP/NCAR wind) is very similar to that in the HIRHAM-NAOSIM 2.0 simulations: SID increases with increasing WS for all SIC classes, both in winter and summer (Figures 5c and 5f). However, the SID-WS relation~~s~~ in PIOMAS ~~are~~ is stronger than ~~those~~ in HIRHAM-NAOSIM 2.0 during winter and summer (Figure 5). This may reflect a higher air-ice drag in PIOMAS than in HIRHAM-NAOSIM 2.0.

3.3 Dependency of sea-ice drift speed (SID) on sea-ice concentration (SIC)

3.3.1 Climatological view

~~Previous studies (Docquier et al., 2017; Olason & Notz, 2014) introduced a metric to evaluate~~Figure 6a shows the relationship between SID and SIC in terms of the mean seasonal cycle~~, which we follow here (Figure 6a)~~. An inverse correlation between SID and SIC is expected because a reduction in SIC reduces the internal friction, brings the SID closer to free drift conditions and increases SID. We find such an inverse correlation between SID and SIC both in the model and in the observations (KIMURA ice drift, NSIDC bootstrap ice concentration), as well as in PIOMAS from June to September when SIC is low. The corresponding fit line slope in the model is 4.04 km d^{-1} SID increase per 10% SIC decrease, which agrees with the slopes in the observations and in PIOMAS. During the winter months (January to May) when SIC > 95%, ~~no~~ such a relationship is not found ~~neither~~ both in the observations ~~nor~~ and in the models. The SID of the 12 months can be categorized into two groups based on SIC values. Group one for SIC smaller than 95% and group two for SIC larger than 95%. The observed mean SID value in group one (9.23 km d^{-1}) is obviously larger than in group two (7.28 km d^{-1}). This is also found in PIOMAS. The model reproduces the SID in group one, but largely overestimates the SID in group two. Therefore, the simulated mean SID values in group one (9.24 km d^{-1}) and two (8.95 km d^{-1}) are quite close to each other. This model deficit may result from the too strong coupling between the SID and the WS in the model (Figure 2; Section 3.2.1). Following Docquier et al. (2017), we also calculate the slope of the SID-SIC best fit line based on data from 12 months, even though there is no clear SID-SIC linear relation over the full year data. The slope ~~based on~~in the model (0.66 km d^{-1} SID increase per 10% SIC decrease) is much weaker than in the observations (6.93 km d^{-1} SID increase per 10% SIC decrease) and in PIOMAS (3.16 km d^{-1} SID increase per 10% SIC decrease). The simulated relationship is also much weaker than in the ocean model NEMO-LIM3.6~~,~~ as reported by Docquier et al. (2017). The underestimated relationship in the model can be explained by the overestimated SID in winter (Figure 2).

3.3.2 Daily and grid-scale view

On daily grid scale, the model shows an inverse correlation of SID with SIC during winter (Figures 4a, 5a), differently to the climatological view (section 3.3.1). SID increases with decreasing SIC when SIC is larger than ca. 30%. The slopes of the simulated SID-SIC relation across all the SIC and WS classes vary from 2.893.41 km d^{-1} to 5.975.64 km d^{-1} SID increase per 10% SIC decrease. In the observation, there is no clear SID-SIC the relation is not clear because the median SID uncertainty is very high when SIC is lower than 90% (Figures 4b, 5b). The small sample size is one of the reasons for the high uncertainty (Table 1). However, the statistically (considering the uncertainty of the median value, (represented by the notch), the statistically lower SID for high SIC (> 90%), compared to the SID for lower SIC, stands out both in the observations and in the simulations. The observations indicate an abrupt drop of SID at 90% SIC. This is in accordance with observations by Shirokov (1977) who showed that SID starts to decrease linearly with increasing SIC, but drops abruptly at a SIC of 90% when internal friction forcing starts its significant influence on SID. This is not reproduced by the simulations and indicates too low internal friction in the model.

The model also shows an inverse correlation of SID with SIC for SIC > 20% and WS ≥ > 2 m s^{-1} during summer (Figures 4c and 5d). Under different WS classes, the modelled SID-SIC relation varies from 1.402.12 km d^{-1} to 3.273.16 km d^{-1} SID increase per 10% SIC decrease. The higher WS is, the stronger is the SID-SIC relation. However, these findings from the simulations are not confirmed by the observations. The observations (KIMURA drift/NSIDC bootstrap ice concentration) do not show an inverse correlation between SID and SIC for all SIC and WS classes in summer (Figures 4d and 5e). Below wind speed of 4 m s^{-1}, the observations show a significant relation, but with smaller magnitudes than the model.

The SID-SIC relation in PIOMAS is just the opposite compared to HIRHAM-NAOSIM 2.0, are reversed both in winter and in summer when compared to HIRHAM-NAOSIM 2.0: SID increases with increasing SIC when SIC less is lower than 90% (Figures 5c and 5f). PIOMAS shows a SID-SIC relation inconsistent with the observed relation. Thus, the PIOMAS relation might violate physical consistency due to the usedThis striking feature in PIOMAS suggests that investigations are needed to explain the physically implausible SID-SIC relation in PIOMAS. optimal interpolation method to obtain realistic sea-ice field (concentration). This assimilation method contains addition/subtraction of sea ice into the system at every assimilation time step, when the modeled sea ice concentration differs from the observed one. Due to the addition/subtraction of sea ice (called increment or innovation in the terminology of data assimilation), PIOMAS does not necessarily preserve the physical relations described in the underlying sea ice-ocean model. Such an inconsistency is one of the drawbacks of the optimal interpolation method. Therefore, relations to assimilated physical variables should be examined with caution.

Generally, the obvious difference between the SID-SIC relation on multi-year Arctic mean scale and on daily grid scale emphasizes its strong dependency on the temporal and spatial scale.

3.4 Dependency of sea-ice drift speed (SID) on sea-ice thickness (SIT)

3.4.1 Climatological view

All datasets (HIRHAM-NAOSIM 2.0 simulations, KIMURA drift/PIOMAS thickness, and PIOMAS drift/PIOMAS thickness) show that SID decreases with increasing SIT (Figure 6b). The SID-SIT fit-line slope calculated based on HIRHAM-NAOSIM 2.0 is 1.10 km d^{-1} SID decrease per 1 m SIT increase. The observed SID-SIT relation is stronger. Data of KIMURA drift/PIOMAS thickness and PIOMAS drift/PIOMAS thickness indicate 2.17 km d^{-1} and 1.83 km d^{-1} SID decrease per 1 m SIT increase, respectively. The weaker simulated weaker dependency of SID on SIT changes is mainly due to the overestimated SID during winter and spring (December to May), when the ice is thick. As pointed out by Olason and& Notz (2014), the inverse correlation between drift speed and thickness in winter, when the ice concentration is high, is physically plausible, but the inverse correlation in summer, when the ice concentration is lower, is probably only of statistical nature.

3.4.2 Daily and grid-scale view

As in the climatological view, the simulations show generally that SID decreases with increasing SIT (Figures 7a and 7c and Suppl. Figure S5a and S5c), both in winter and in summer. In winter, this relation occurs only for SIT smaller than ca. ~~3.5~~4 m. The simulated SID-SIT relation that calculated based on all thickness categories varies from ~~0.57~~0.38 km d^{-1} to ~~1.08~~0.95 km d^{-1} SID decrease per 1 m SIT increase across different wind categories (Suppl. Figure S5a). PIOMAS simulates a stronger SID-SIT relation (Suppl. Figure ~~S5c~~S5b); the slope of the SID-SIT fit-line varies from ~~0.71~~0.65 km d^{-1} to ~~2.77~~2.64 km d^{-1} SID decrease per 1 m SIT increase, which is larger by a factor of up to 3.5 compared to the simulations.

In summer, the simulated inverse SID-SIT correlation is stronger than in winter, particularly for high WS (Figures 7a and 7c and Suppl. Figures S5a and S5c). The SID-SIT slope varies from ~~0.49~~0.71 km d^{-1} to ~~1.94~~ 1.69 km d^{-1} per 1m SIT increase across different wind categories. ~~These values are up to 1.7 times greater than the corresponding values in PIOMAS. This implies that the modeled relation is generally stronger than in PIOMAS in summer, which is in marked contrast to winter.~~In PIOMAS, the SID-SIT slopes are not significant when WS > 4 m s^{-1}. This is mainly influenced by the increase of SID when SIC increased from (0.1,0.3] to (0.3, 0.5].

Furthermore, Figure 7 confirms the nonlinearity of the SID-WS relation, with a strong impact of WS changes on SID for high and moderate wind speeds, but with a lower impact for low wind speeds (~~about~~ WS ≤ ~~3~~ 4 m s^{-1}).

4 Sensitivity to the parameterization including ~~the~~ sea-ice form drag

4.1 Model results

In the previous section, we investigated the ~~SID~~ dependency of SID on WS and sea-ice conditions in the BASE simulations, which do not account for the sea-ice form drag. In this section, we analyze how an additional sea-ice form drag influences the near-surface atmospheric fluxes, SID and its dependency on WS and sea-ice condition. For this we compare the one-year ensemble simulations ~~of~~ CTRL (without sea-ice form drag) and SENS (with sea-ice form drag) (see Section 2.1.3 for details). Tsamados et al. (2014) showed that ~~the added~~ an additional form drag ~~mostly~~ mainly ~~improved~~ improves the sea-ice drift ~~over the~~in summer ~~time~~. Therefore, our analysis is focused on summer (JJAS).

Figure 8a indicates that the increased ice roughness due to the additional form drag leads to an increased surface momentum flux over most regions of the Arctic Ocean, even though this increase is not significant from a statistical point of view. In few regions the momentum flux does not increase, which indicates that either the neutral drag coefficient~~s~~ over ice is very low or the wind speed and/or the atmospheric stratification has changed. SID ~~is~~ mainly increases~~d~~ over the ~~marginal ice zone (~~MIZ~~)~~ along the Russian coasts (Figure 8b). The spatial pattern of SID changes is similar to that of the momentum flux, with pattern correlation of 0.66 (0.76) between their normalized (not normalized) differences. This reveals that the SID increase is mainly associated with an increased momentum flux from the atmosphere to the ice. Related with this, WS decreases over most parts of the Arctic Ocean when the sea ice becomes rougher ~~in SENS~~ (Figure 8c). Changes in turbulent heat fluxes, SIC, and 2-m air temperature are small and mixed with regional increases and decreases (Figures 8d-f). Overall, the ensemble mean differences between SENS and CTRL are statistically insignificant, indicating a large across- ensemble scatter due to high internally generated model variability.

Nonetheless, the increase of SID for low SIC in the MIZ and the smaller effect on the more consolidated ice in the central Arctic should imply a stronger Arctic-wide SID-SIC relation. Figures 9 and 10a confirm the stronger increase of SID with decreasing SIC in SENS.

The ~~effect of~~increased SIC-dependency of SID~~, i.e. that the SID change is larger for low SIC,~~ can be explained by the fact that the form drag contribution to the air-ice drag is effectively proportional to $(1-A)^{\beta}$ (see Equations (5) and (7))~~ the linear dependence of the form drag acting on the floe area on SIC~~. ~~As~~ This means that the lower the SIC, ~~as~~ the higher the form drag and the higher the air-ice drag. When SIC is around 90%, the sum of form drag and skin drag in SENS is of the same order of magnitude as~~negligible and thus~~ the skin drag ~~coefficient~~ in ~~SENS is the same with~~ CTRL.

Furthermore, there is an increased WS-dependency, i.e. that the SID change is larger for high WS. For example, the SID-SIC relation for ~~calm~~ low wind conditions (WS of ~~1-2~~2-4 m s^{-1}) in SENS is ~~increase of 2.74~~5.26 km d^{-1} SID increase per 10% SIC decrease, which is about 2.~~4~~ 5 times ~~stronger~~ higher than in CTRL. The differences between SENS and CTRL increase~~s~~ even more for high wind speeds. For WS within ~~9~~8-10 m s^{-1}, the SID-SIC relation in SENS is ~~increase of 12.93~~11.79 km d^{-1} SID increase per 10% SIC decrease, which is about 4.~~8~~ 6 times ~~stronger~~ higher than in CTRL. The dependence of SID on wind is complex. Two external forces act on the flow, the ocean drag and atmospheric drag. When the ocean drag is much larger than the atmospheric drag (low wind speed), the drift is mainly governed by the ocean drag even ~~if the~~with doubled atmospheric drag ~~doubles~~coefficient. However, for high wind speeds,~~when both drags are of comparable size (strong wind)~~ a doubling of the atmospheric drag coefficient ~~by increased wind makes~~has a large effect on the drift speed~~. Another impact is~~, also due to proportionality of the air-ice stress ~~on~~ to the square of WS.

4.2 Model versus observation

The increased dependency of SID on WS and SIC in SENS compared to CTRL does not reduce the deviation to the observation/reanalysis. In contrast, Figure 10 shows that the overestimation of the dependency of SID on WS and SIC in SENS is larger than in CTRL.

Figure 11 shows the spatial distribution of the summer 2007 wind factor, WS and near-surface air temperature from observation/reanalysis data, and the deviations of these three variables in CTRL and SENS from observation/reanalysis. It is obvious that both the bias patterns and the bias magnitudes in CTRL and in SENS are quite similar. Considering the ensemble mean bias and taking the internal model variability into account, it is hard to detect significant changes in SENS, compared to CTRL, as discussed in Section 4.1.

Although the ensemble mean of Arctic basin-wide mean SID from July to September in SENS is larger than in CTRL, the differences are not statistically significant due to a large ensemble spread (Figure 12). Actually, there are no statistically significant differences in the Arctic basin-wide mean SID between CTRL and SENS in all months. From January to May, the simulated Arctic basin-wide mean SID (both in CTRL and in SENS) are higher than that in KIMURA. With respect to the summer months (June to September), the August SID in CTRL is lower than in KIMURA, while the July and September SID in SENS are higher than in KIMURA. For the Arctic basin-wide mean WS, there is no significant difference between CTRL and SENS as well as between model and reanalysis, except for May, when both model simulations significantly overestimate the WS.

4.3 Follow-up study

Although the new parameterization does not improve the simulated dependency of SID on WS and sea-ice conditions compared to observations/reanalysis, the sensitivity study clearly shows that the new parameterization does increase the SID due to the added form drag. In a follow-up study, we are going to put efforts therefore on several aspects to improve the simulations.

First, tunable parameters of the new parameterization, such as z_0, z_t, $Ce_{10,i}$, $Ce_{10,k}$ and β represent an opportunity to better adapt the form drag parameterization itself to the observations. A first step could be the use of values found by Elvidge et al. (2016). A large effect can be expected by a modification of the skin drag coefficient, since a large region would be affected, and large variations in the drag due to pressure ridges allow a wide range of values. Second, model parameters outside the new parameterization, which have direct impact on SID, like ice strength and ocean-ice drag coefficient, need to be harmonized with the new parameterization, since their values were chosen empirically in terms of adequately balanced performance of the model. A key is probably the oceanic form drag. Its effect is accounted for in the present study only indirectly via the constant oceanic drag coefficient. Such a parametrization is probably too simple, especially when atmospheric form drag is included (see also Tsamados et al., 2014). Birnbaum (2002) as well as Lüpkes et al. (2012b) found in a mesoscale modelling study that oceanic form drag can have a strong decelerating effect on SID especially when the sea ice concentration is low so that the discussed drawbacks for small sea ice fraction would be reduced or even removed. This effect of form drag on SID was discussed also by Steele et al. (1989). The parametrizations are evidently not balanced anymore after improving one key process of the SID-related atmosphere-ocean-ice interaction. A previous study on the surface-albedo feedback by Dorn et al. (2009) showed that an improved simulation can only be achieved by a harmonized combination of more sophisticated parameterizations of the related sub-processes. It can be assumed that this holds true for the SID-related sub-processes.

5 Summary and conclusions

We evaluated the sea-ice drift speed (SID) and its dependency on the near-surface wind and the sea-ice conditions (ice concentration and thickness) on multiyear, Arctic-wide mean scale during 2003-2014. Compared with observations, the model does not fully capture the observed SID seasonal cycle, but overestimates SID in winter-spring. Regardless, the model realistically describes the main drivers of the seasonal and long-term variations of Arctic SID: When the sea-ice concentration (SIC) is lower than 95% in summer-autumn, SID increases with decreasing SIC. However, when SIC is higher than 95% in winter, the sea-ice thickness (SIT) is the main factor for SID changes (higher SID for lower SIT). As the simulated SID is overestimated during the cold seasons, the modeled strength of the SID-SIC and SID-SIT relations is underestimated compared with observational data. The SID overestimation during winter in the model cannot simply be attributed to the underestimation of SIT or too strong coupling between SID and WS. Further in-depth analysis of the wintertime sea-ice dynamics and thermodynamics and the atmospheric and oceanic forcing are needed in the future to identify the possible cause of the SID overestimation.

The analysis on the daily and grid scale revealed that the SID relations with SIC and SIT are complex due to the large spatiotemporal variation of the sea ice. Based on observations, it is difficult to find a clear relation between SID and SIC. In the model, when SIC is larger than 30%, a higher SIC is accompanied by a significantly lower median SID compared to the SID for lower SIC ~~both in summer and winter~~. In agreement with the multi-year and Arctic wide findings, the SID decreases with increasing SIT, both in winter and in summer. However, in winter, this relation occurs only for high wind speeds. The simulated SID-SIT relation is stronger (weaker) in summer (winter) compared to PIOMAS.

We also evaluated the ~~SID~~ dependency of SID on near-surface wind speed (WS) on the daily and grid scale. The simulated increase of SID with increasing WS is consistent with the observation/reanalysis. Our analysis supports the earlier discussed strong nonlinearity of the SID-WS relation, with a strong impact of WS changes on SID for high and moderate wind speeds, but with only a low impact for lower wind speeds. The weak dependency of SID on WS, when WS is low, was also shown by Lund et al. (2018), based on shipboard marine radar sea-ice drift measurement over the MIZ. This changing relation in the low-wind regime may be caused by the increasing importance of upper-ocean currents for the drift compared to the wind (Lund et al., 2018). Another explanation was given by Leppäranta (2011) and Rossby ~~&~~and Montgomery (1935) who argued that the large-scale wind dominates over the local wind effect.

Finally, we investigated the impact of the changed parameterization of the transfer coefficients for heat and momentum over sea ice on the SID and its dependency on WS and sea-ice conditions. The consideration of sea-ice form drag effects increases the air-to-ice momentum flux and accordingly the SID over most of the Arctic. Largest effects appear for low SIC in the MIZ under high wind conditions. The reason is that in the new parameterization the lower SIC is associated with a potentially larger atmosphere-ice momentum flux, since the form drag contribution is completely transferred to the ice. As a consequence, the increases of SID with decreasing SIC is stronger when the form drag is included.

The implementation of this new parameterization does not improve the simulated SID dependency on WS and sea-ice conditions compared to observations/reanalysis. An improvement might be possible by tuning the open parameters of the parameterization, e.g., similarly as proposed by Renfrew et al. (2019) and Elvidge et al. (2018). A large effect can be expected by a modification of the skin drag coefficient since a large region would be affected and the large observed variability due to pressure ridges allows a test in a wide range of values. Also theThe inclusion of the melt pond effect on the atmospheric form drag in the model might be beneficial. since inIn the tested current version, form drag was only considered at the edges of ice floes, mainly accounted for only in the marginal sea sea-ice zones but not in on top of the inner ice areas. There where, melt ponds cause form drag also during summer (Andreas et al., 2010; Lüpkes et al., 2012a). Additionalng the form drag from at the ice-ocean interface may further improve the simulated SID-WS relation, because the oceanic form drag is has normally in the opposite effect on the ice motion as the of atmospheric form drag (Steele et al., 1989; Lüpkes et al., 2012b). We also cannot exclude sSystematic biases due toin the used reanalysis used for the calculation of the 'observed' wind factor cannot be excluded, since form drag is not taken into account in the underlying atmospheric model. Therefore, the increased deviation of the simulated SID-WS relation from the observations/reanalysis does not necessarily mean that the implemented new parameterization worsens the SID-WS relation.

Data availability. HIRHAM- – NAOSIM model data are available at the tape archive of the German Climate Computing Center (DKRZ; https://www.dkrz.de/up/systems/hpss/hpss); one needs to register at DKRZ to get a user account. We will also make the data available via Swift (https://www.dkrz.de/up/systems/swift) on request. KIMURA sea ice drift data are available at https://ads.nipr.ac.jp/vishop/. The ERA‐Interim data were obtained from the European Centre for Medium‐Range Weather Forecasts (ECMWF; http://apps.ecmwf.int/datasets/data/interim_full_moda/). The sea‐ice concentration data were obtained from the National Snow and Sea Ice Data Center (NSIDC; https://nsidc.org/data/NSIDC‐0051/).

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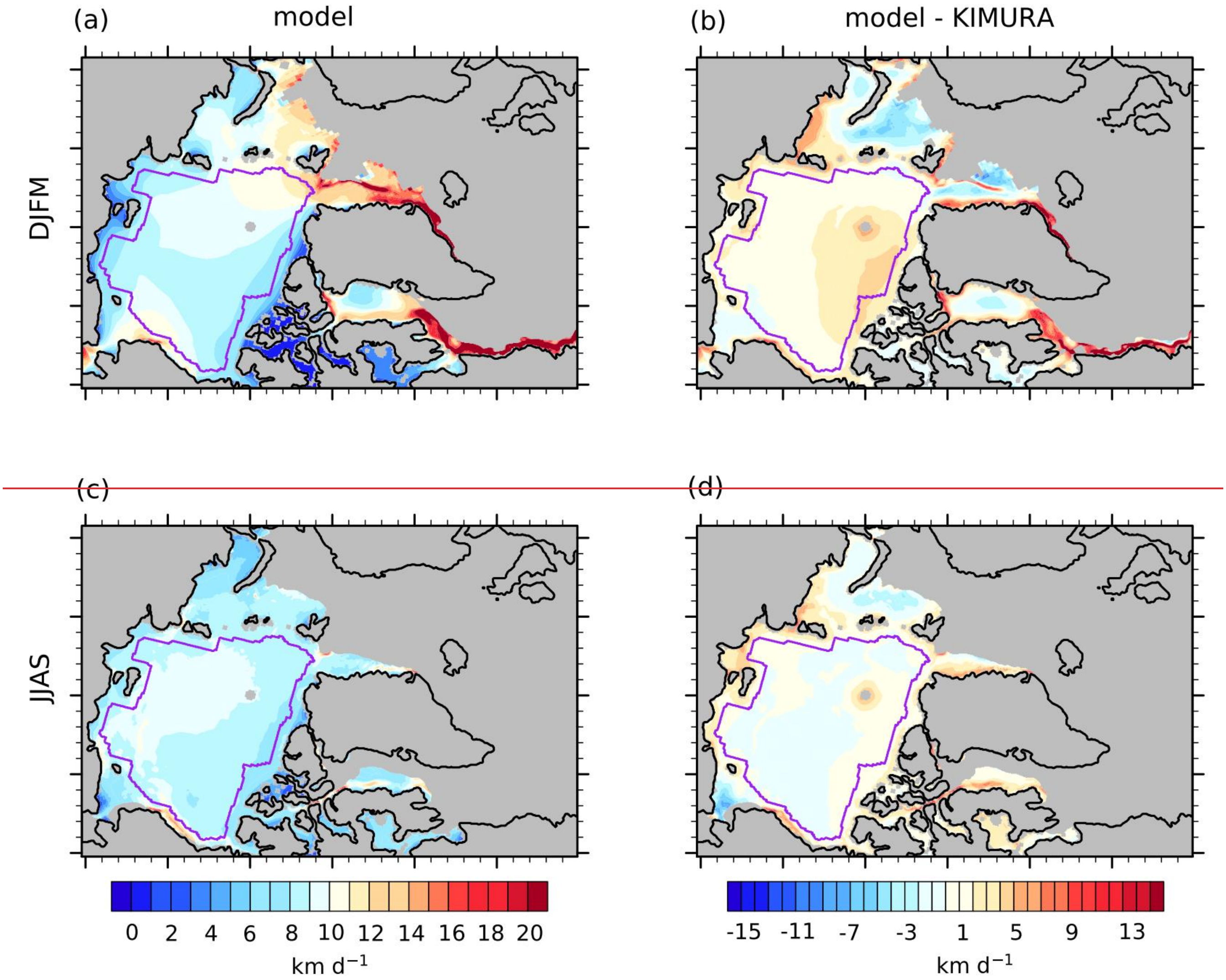
Table 1 The sample sizes of sea-ice drift speed data under different 10-m wind speed and sea-ice concentration classes in Figure 4. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

Season	**Data source**	**Wind classes**	**Sea-ice concentration classes**				
-	-	-	**(0.1,0.3]**	**[0.3,0.5]**	**(0.5,0.7]**	**(0.7,0.9]**	**(0.9,1.0]**
DJFM	**model**	**(0,2] m/s**	494	864	3328	135516	45562216
		(2,4] m/s	2070	3716	12780	489893	183056161
		(4,6] m/s	3432	5766	17172	618383	239287363
		(6,8] m/s	5804	9402	17215	435238	181532612
		(8,10] m/s	7950	12511	18413	246921	102066710
	KIMURA/ERA-I/NSIDC	**(0,2] m/s**	0	7	7	40	102295
		(2,4] m/s	15	29	50	124	365803
		(4,6] m/s	32	66	117	279	499634
		(6,8] m/s	28	88	137	381	386667
		(8,10] m/s	53	83	145	288	218638
JJAS	**model**	**(0,2] m/s**	92547	2535519	17432992	25896542	9142130
		(2,4] m/s	322269	8521163	57295068	84426782	30714941
		(4,6] m/s	534300	12186383	81681898	113048227	40015962
		(6,8] m/s	549254	9864436	67161887	84920918	27346273
		(8,10] m/s	356102	4746320	34131702	38211228	11159363
	KIMURA/ERA-I/NSIDC	**(0,2] m/s**	1519	3439	5150	12096	100317
		(2,4] m/s	4727	10504	16204	39911	312814
		(4,6] m/s	6533	14571	22364	55418	385667
		(6,8] m/s	5261	11976	17587	40559	262251
		(8,10] m/s	2514	5249	7276	17272	107988


(a)
model
(b)
model - KIMURA
DJFM
(c)
(d)
JJAS
0 2 4 6 8 10 12 14 16 18 20
km d^{-1}
-15 -11 -7 -3 1 5 9 13
km d^{-1}

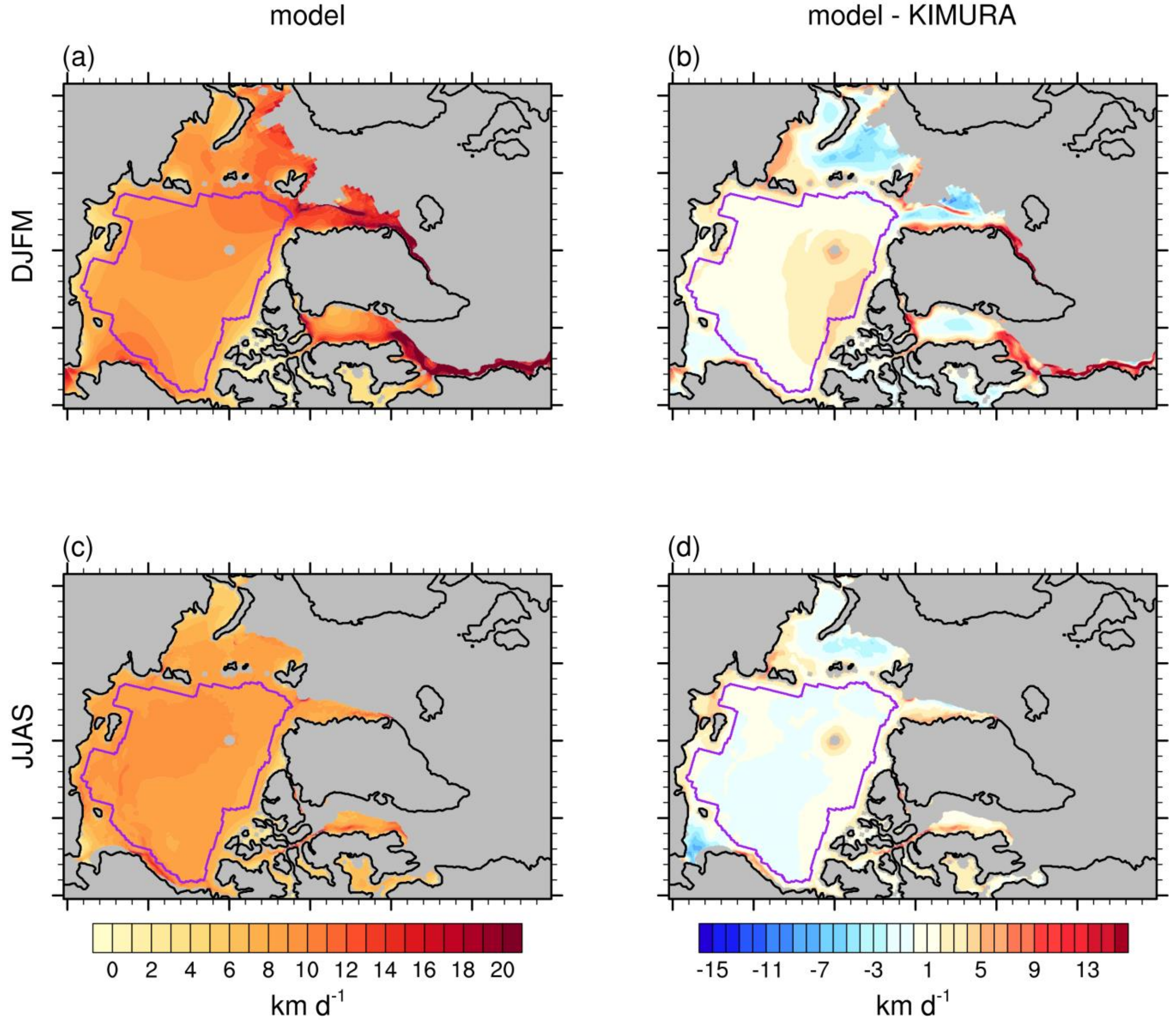


Figure 1: Mean spatial pattern of sea-ice drift speed [km d^{-1}] in the model (ensemble mean of HIRHAM-NAOSIM 2.0) ~~during~~ for 2003-2014 (a) winter (DJFM) and (c) summer (JJAS). (b) and (d) are the model differences to the observation ("Model - KIMURA") ~~during~~ for winter and summer respectively. The purple line in each panel indicates the study domain used for the basin-wide analysis.

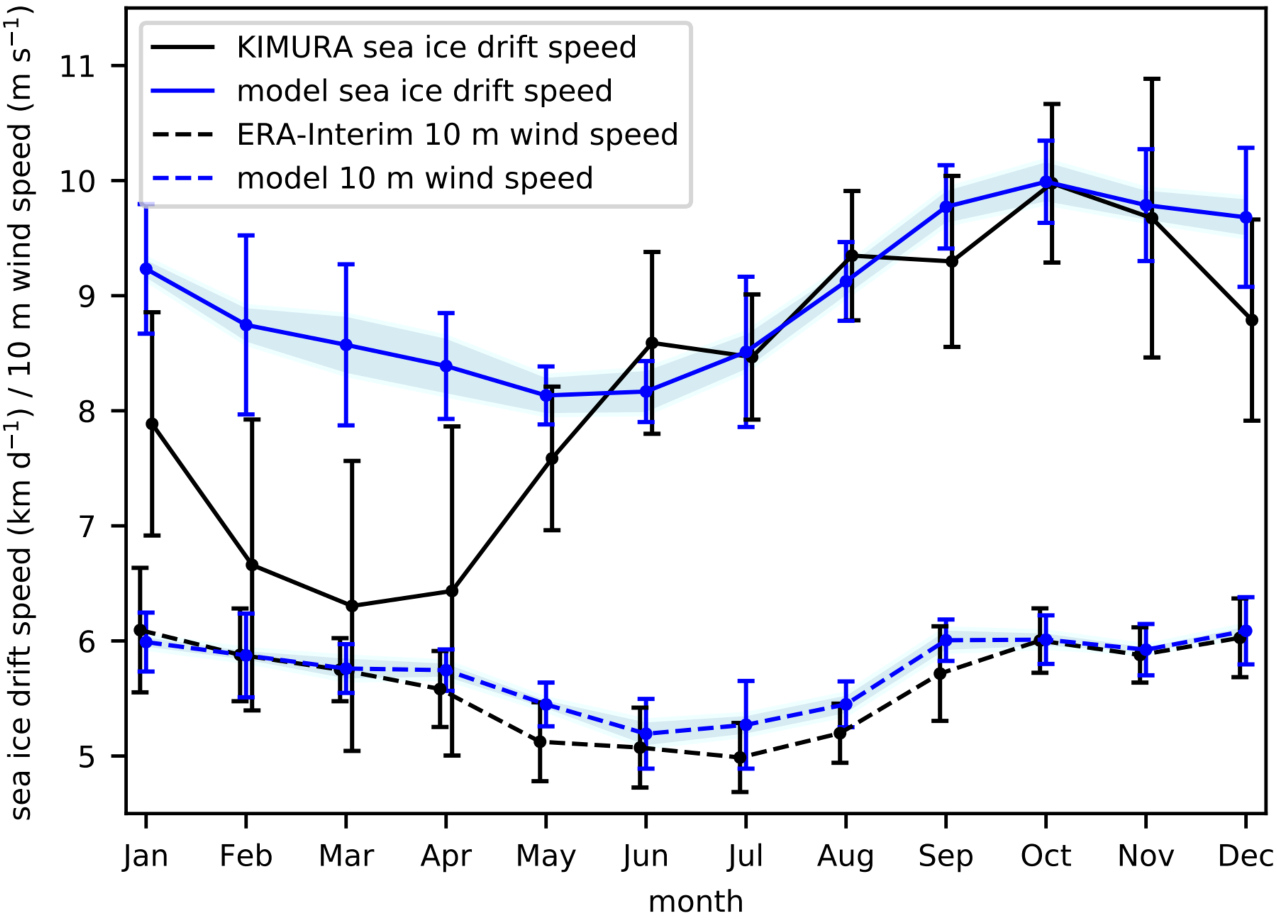
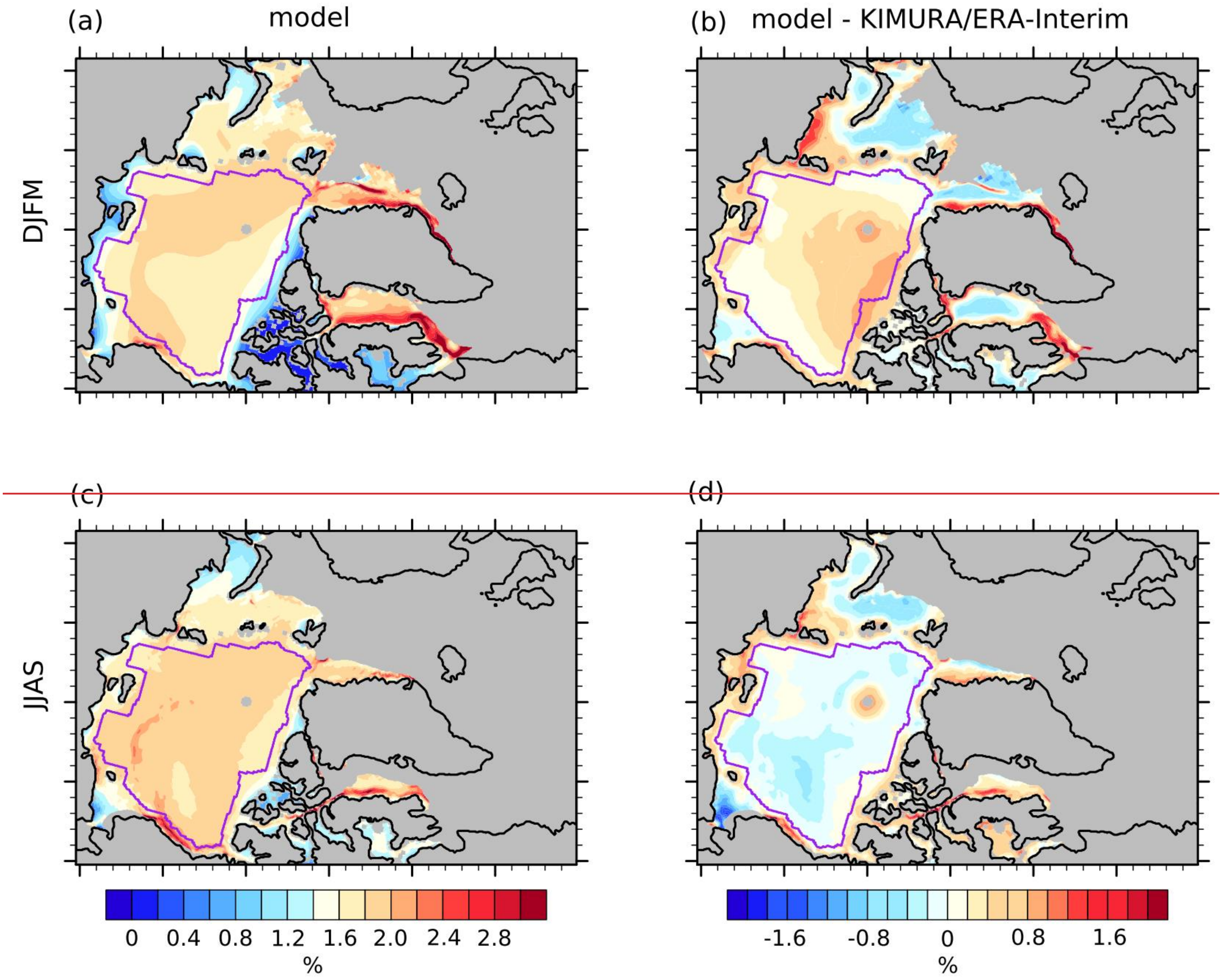


Figure 2: Mean annual cycle of sea-ice drift speed [km d^{-1}] (solid lines) and 10-m wind speed [m s^{-1}] (dashed lines), based on the model (ensemble mean of HIRHAM-NAOSIM 2.0; blue lines) and observation/reanalysis (KIMURA ice drift, ERA-I wind; black lines), for 2003-2014 over the study domain (indicated in Figure 1). The across-ensemble scatter (standard deviation) of the simulations is included as shaded area. The interannual variation is shown by error bars.



(a)
model
(b)
model - KIMURA/ERA-Interim
DJFM
(c)
(d)
JJAS
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
%
-1.6
-0.8
0
0.8
1.6
%

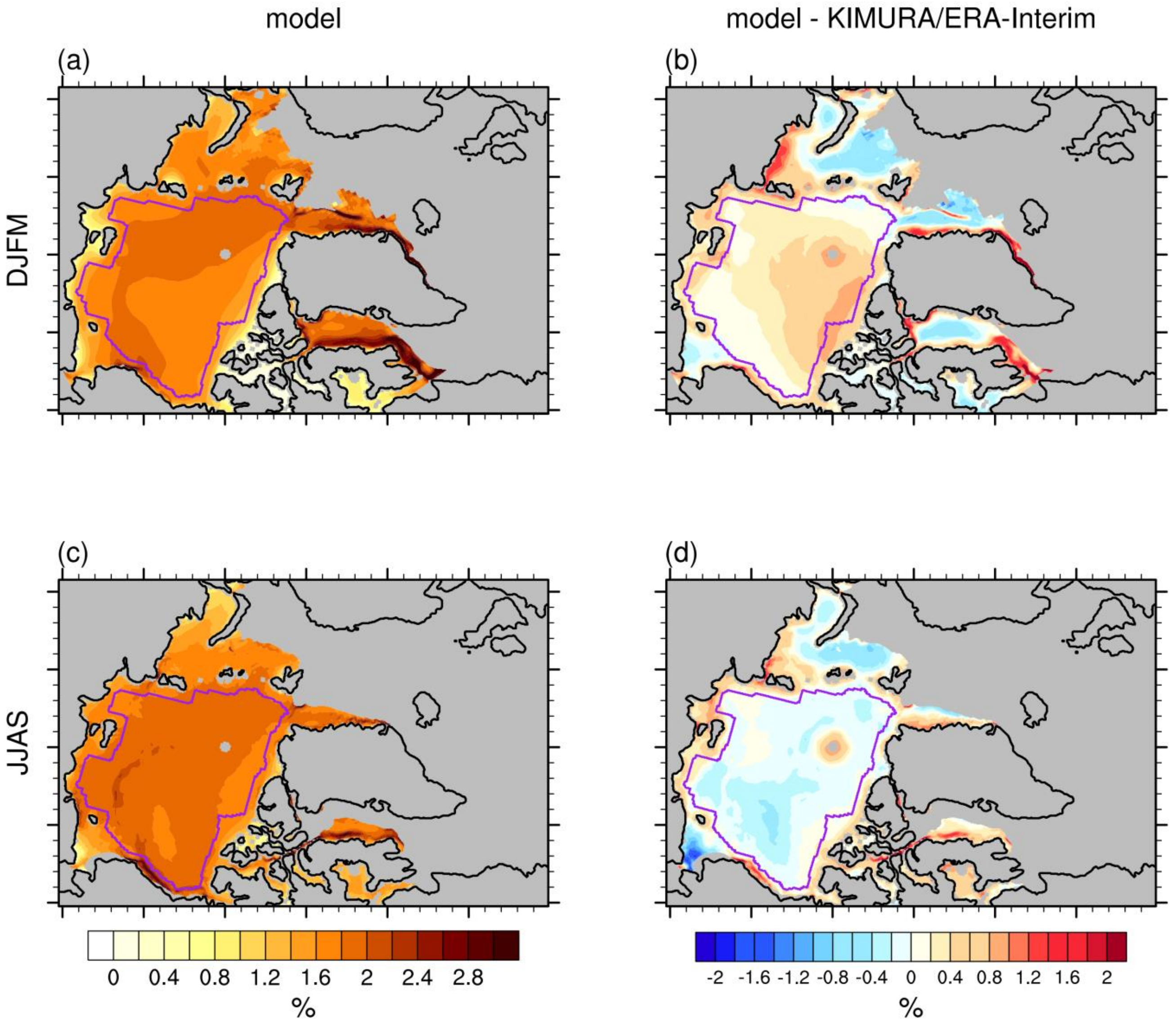
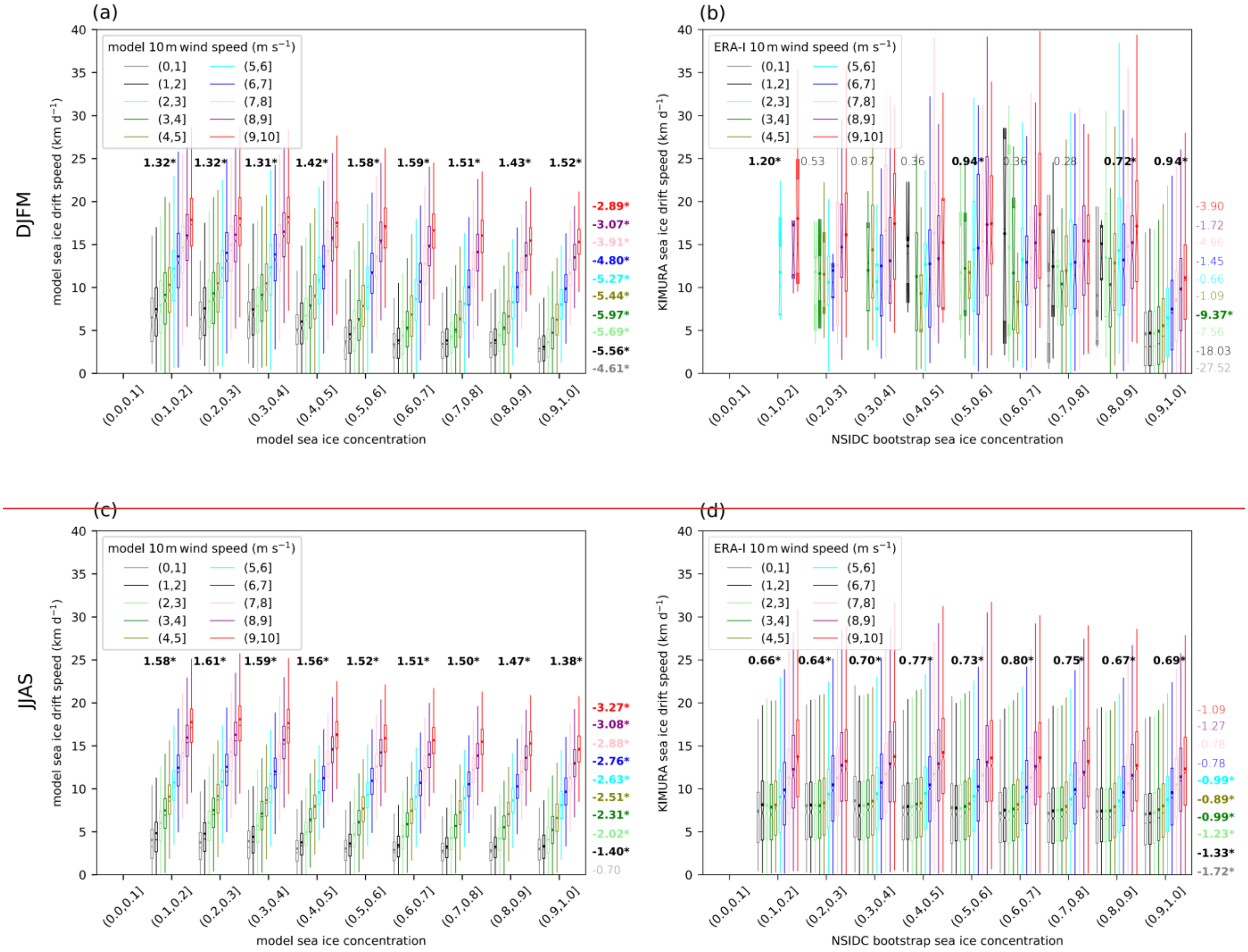


Figure 3: Mean spatial pattern of wind factor [%] in the model (ensemble mean of HIRHAM-NAOSIM 2.0) for 2003-2014 (a) winter (DJFM) and (c) summer (JJAS). (b) and (d) are the model differences to the observation/reanalysis ("Model - KIMURA/ERA-I") ~~during~~ for winter and summer respectively. The purple line indicates the study domain used for the basin-wide analysis.



(a)
(b)
(c)
(d)
DJFM
JJAS
model 10 m wind speed (m s^{-1})
ERA-I 10 m wind speed (m s^{-1})
model sea ice drift speed (km d^{-1})
KIMURA sea ice drift speed (km d^{-1})
model sea ice concentration
NSIDC bootstrap sea ice concentration

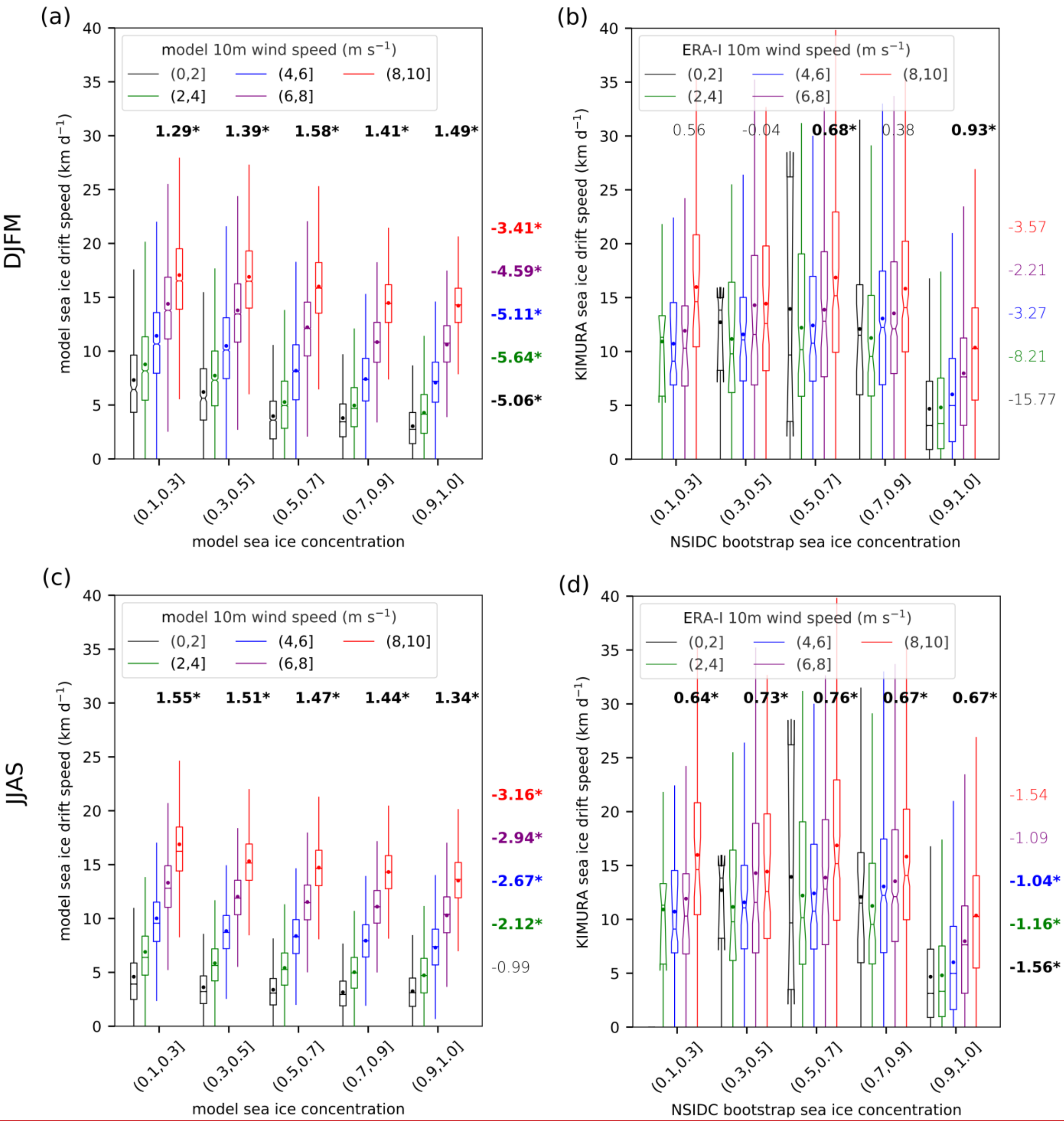
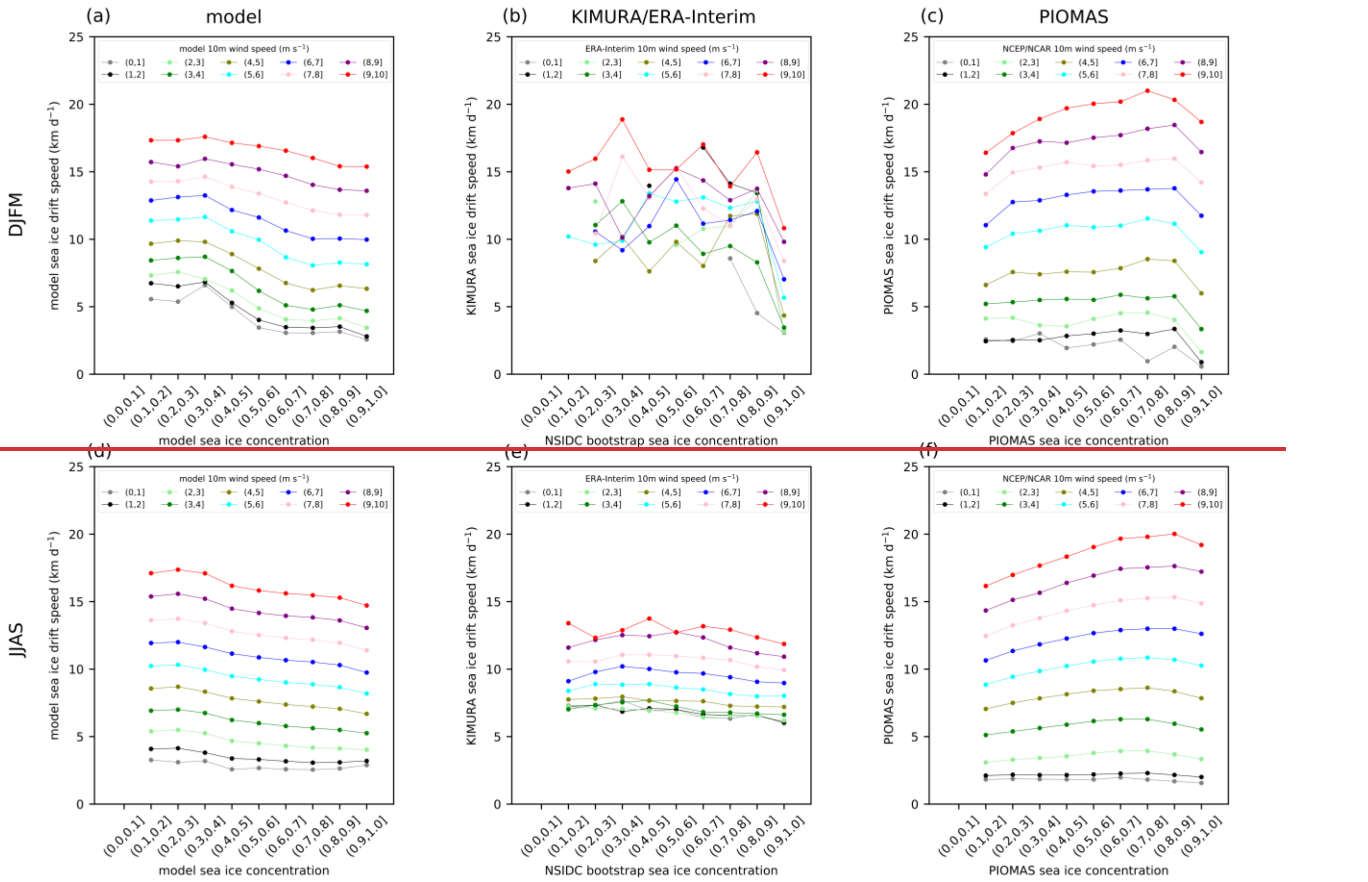


Figure 4: Box-whisker plots of the relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors) ~~in the model during~~for 2003-2014 (a) winter (DJFM) and (c) summer (JJAS) in the model (HIRHAM-NAOSIM 2.0). (b) and (d) are the same as that for (a) and (c) respectively, ~~the relationship~~but based on the observation/reanalysis data ~~during 2003-2014 winter and summer respectively~~. For the model, all 10 ensemble members are included. The plot is based on daily data and on all grid points within the study domain indicated in Figure 1. The horizontal bar represents the median, the notch represents the 95% confidence interval of the median, the dot represents the mean, the top and bottom of the box represent the 75th and 25th percentiles, the upper/lower whiskers represent the maximum/minimum value within 1.5 times interquartile range (IQR) to 75/25 percentiles. The numbers above the boxplots represent the slopes of near-surface wind and sea-ice drift speed fit lines (unit: km d^{-1} per 1 m s^{-1} wind speed change; font colors as for the wind speed classes). The numbers right of the boxplots represent the slopes of sea-ice concentration and sea-ice drift speed fit lines (unit: km d^{-1} per 10% sea-ice concentration change). A bold and asterisked number indicates that the slope of the fit line is significant at the 95 % level. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.


DJFM
JJAS
(a) model
(b) KIMURA/ERA-Interim
(c) PIOMAS
(d)
(e)
(f)
model 10m wind speed (m s−1)
ERA-Interim 10m wind speed (m s−1)
NCEP/NCAR 10m wind speed (m s−1)
model sea ice drift speed (km d−1)
KIMURA sea ice drift speed (km d−1)
PIOMAS sea ice drift speed (km d−1)
model sea ice concentration
NSIDC bootstrap sea ice concentration
PIOMAS sea ice concentration

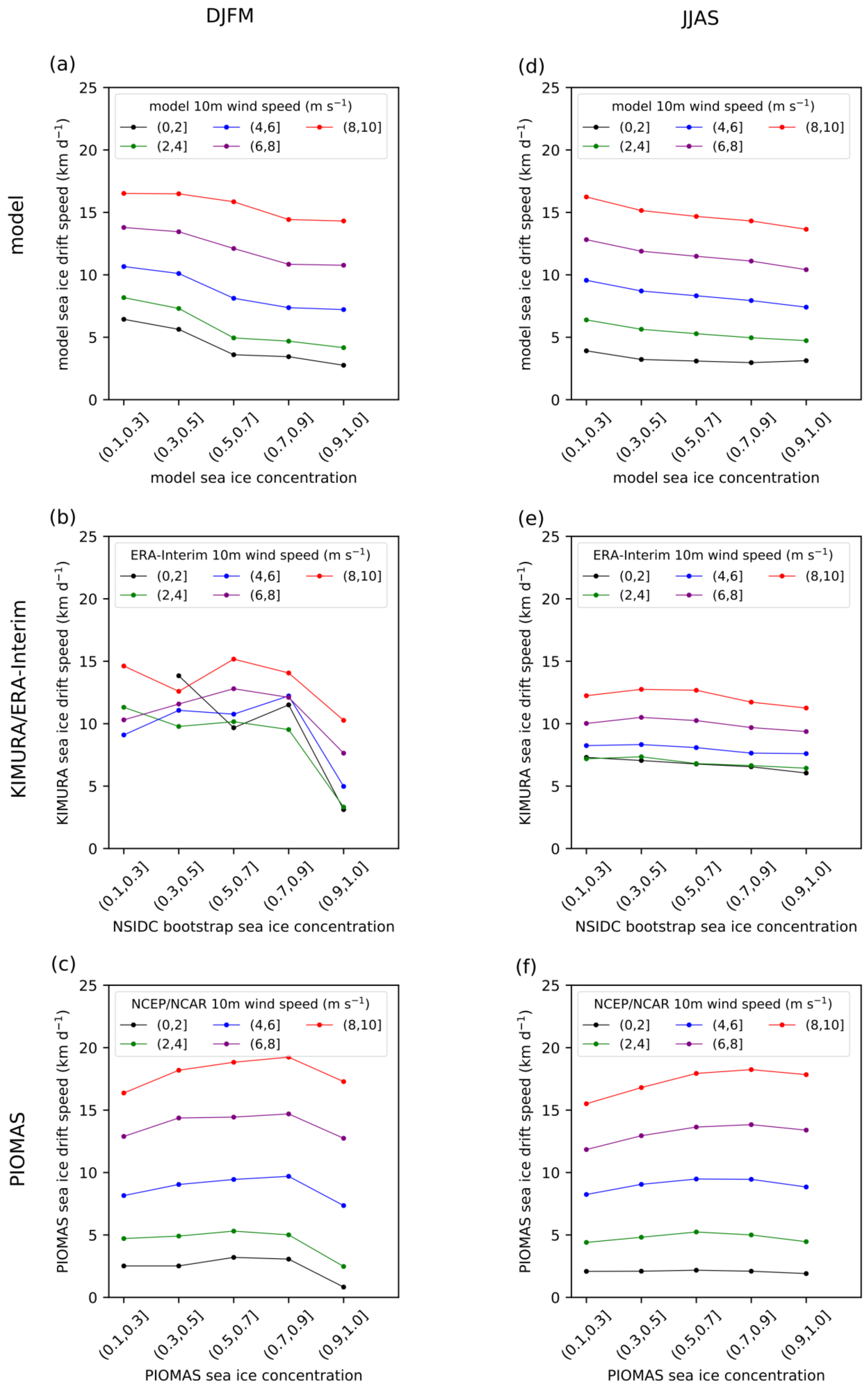


Figure 5: Relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors)

~~in the model during~~ for 2003-2014 (a) winter (DJFM) and (d) summer (JJAS) in the model (HIRHAM-NAOSIM 2.0). (b) and (e) are the same as that for (a) and (d) respectively, but based on the observation/reanalysis data. (c) and (f) are the same as that for (a) and (d) respectively, but based on PIOMAS data. The points in the plot are the median value of all the daily data and on all grid points for certain wind speed and sea-ice concentration, within the study domain indicated in Figure 1. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

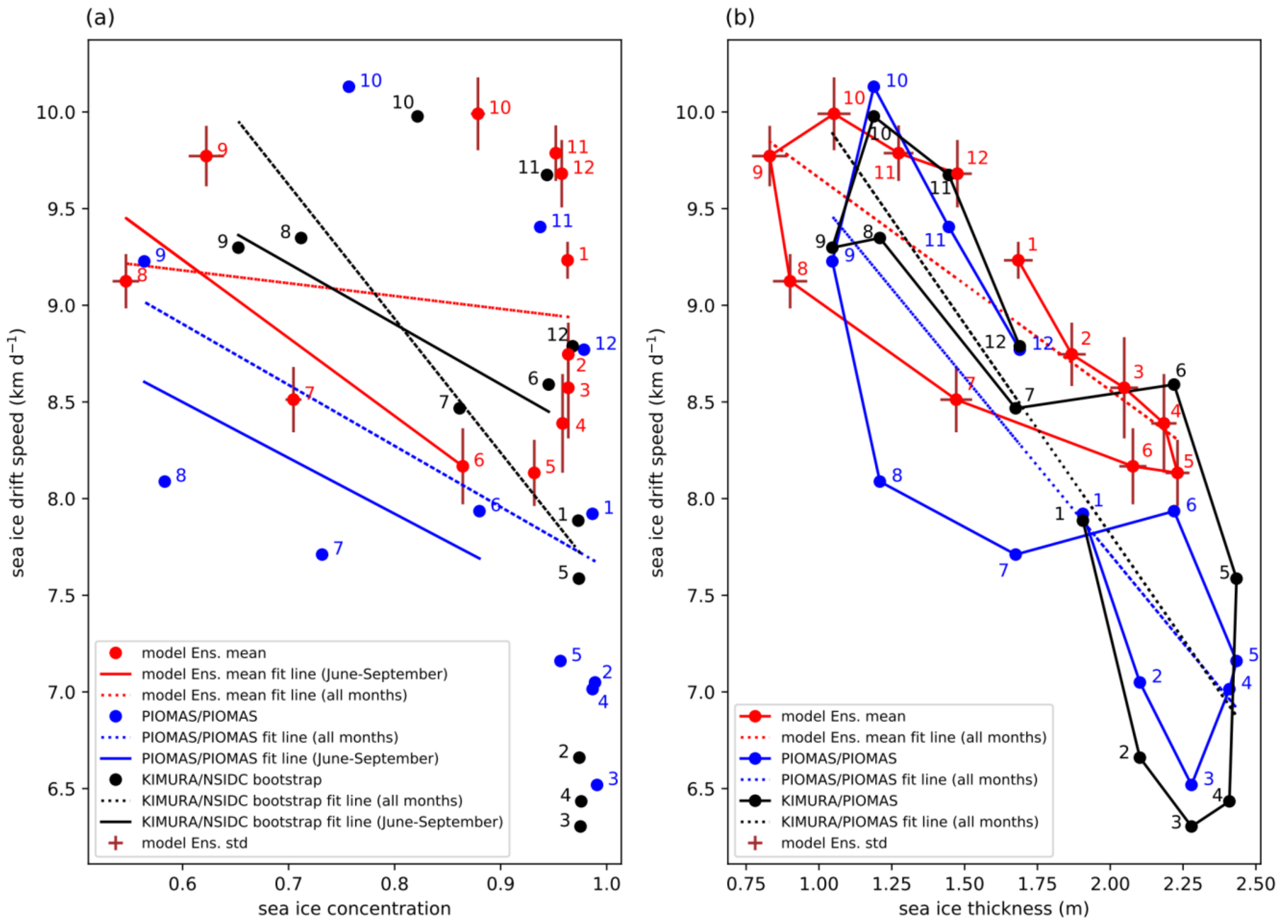
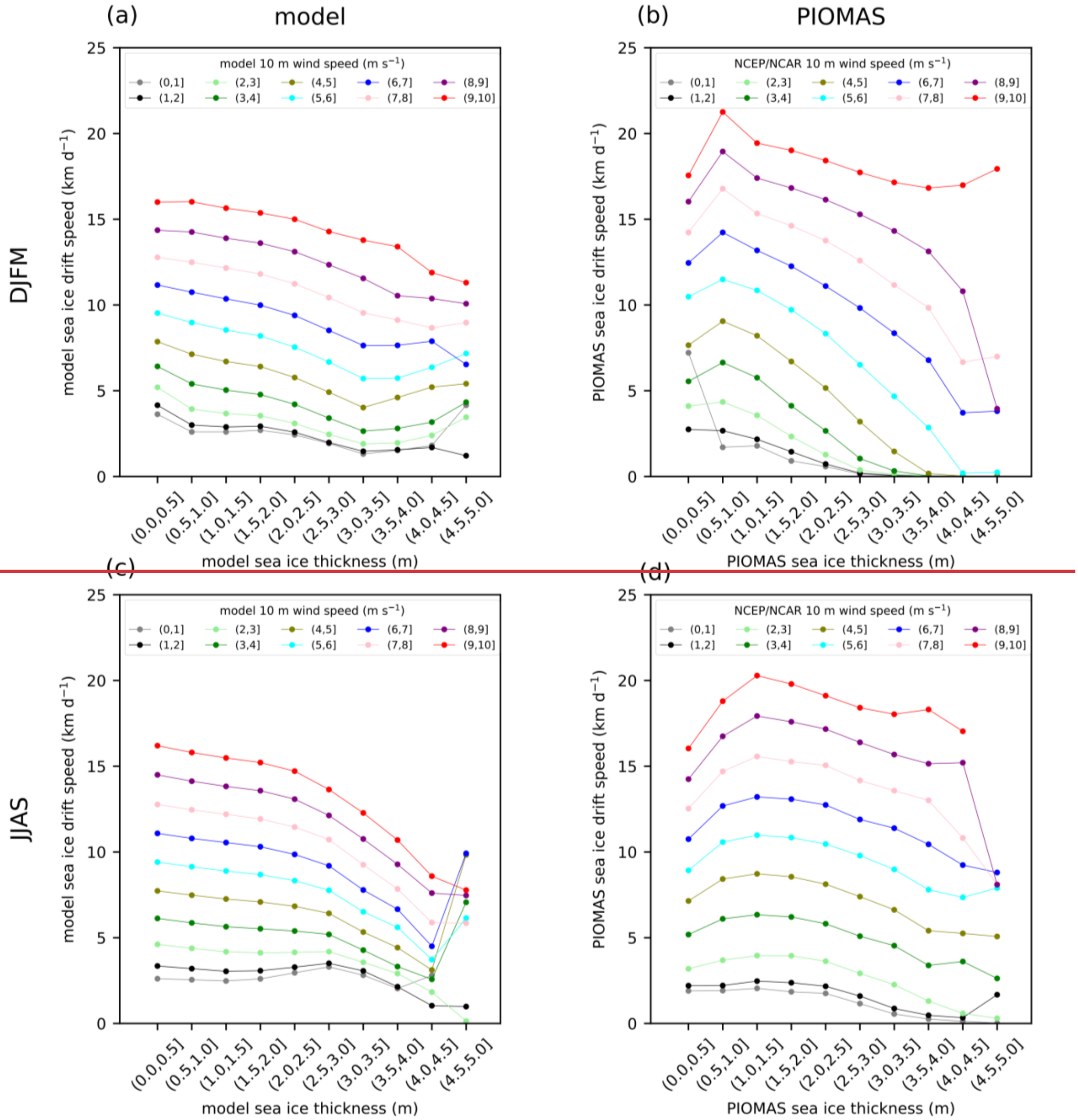


Figure 6: Scatter plots of monthly mean sea-ice drift speed against (a) sea-ice concentration and (b) sea-ice thickness, averaged over the period of 2003-2014 and the study domain (indicated in Figure 1). Numbers denote the months. Results are shown for the model (HIRHAM-NAOSIM 2.0) ensemble simulations (red), KIMURA for ice drift speed plus NSIDC bootstrap for ice concentration (black), and PIOMAS data (blue).


(a)
model
(b)
PIOMAS
(c)
(d)
DJFM
JJAS
model 10 m wind speed (m s⁻¹)
NCEP/NCAR 10 m wind speed (m s⁻¹)
(0,1]
(1,2]
(2,3]
(3,4]
(4,5]
(5,6]
(6,7]
(7,8]
(8,9]
(9,10]
model sea ice drift speed (km d⁻¹)
PIOMAS sea ice drift speed (km d⁻¹)
model sea ice thickness (m)
PIOMAS sea ice thickness (m)
(0.0,0.5]
(0.5,1.0]
(1.0,1.5]
(1.5,2.0]
(2.0,2.5]
(2.5,3.0]
(3.0,3.5]
(3.5,4.0]
(4.0,4.5]
(4.5,5.0]

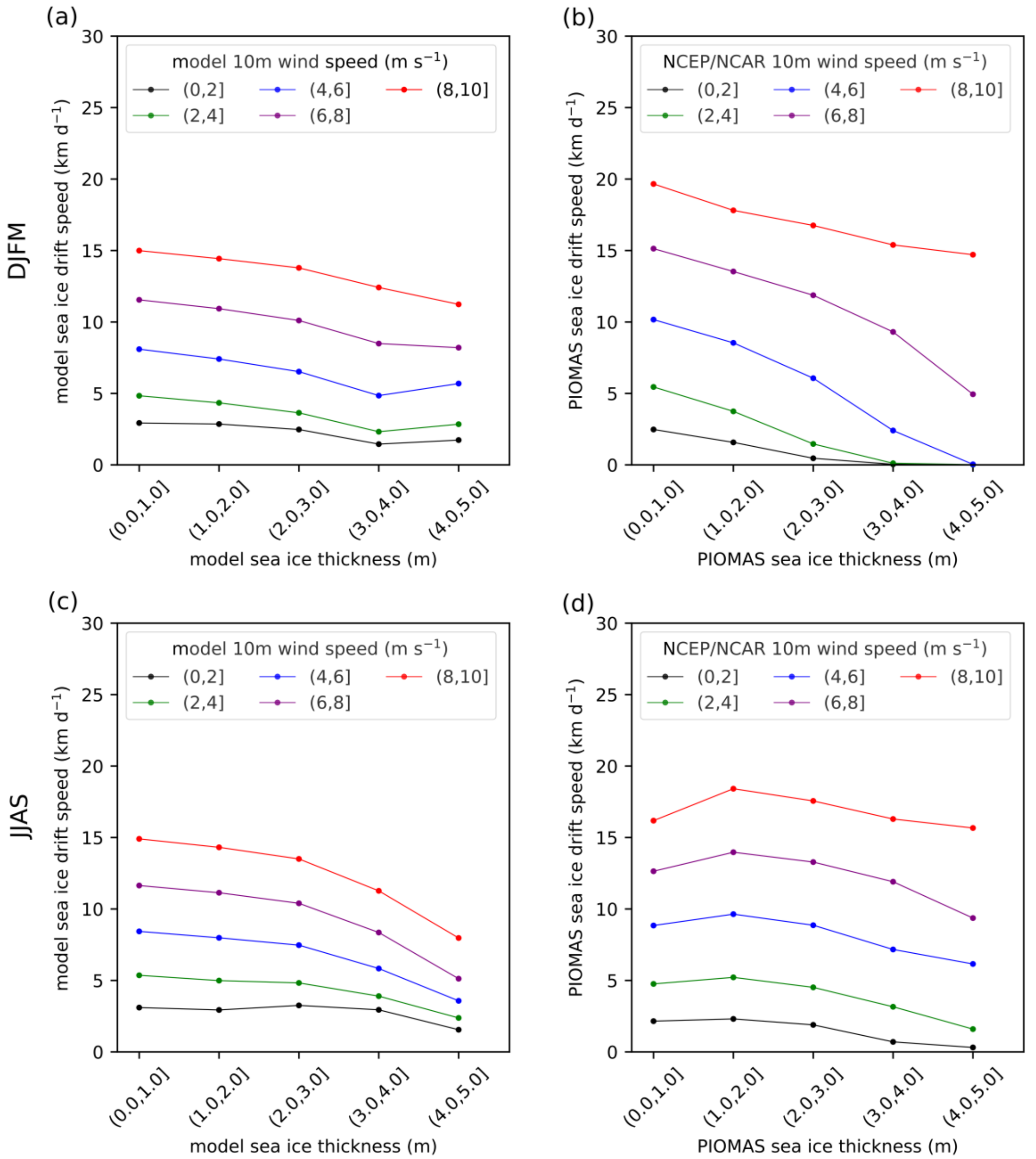


Figure 7: Relationship between sea-ice drift speed and sea-ice thickness for different near-surface wind speed classes (different colors) ~~in the model during~~ for 2003-2014 (a) winter (DJFM) and (d) summer (JJAS) in the model (HIRHAM-NAOSIM 2.0). (b) and (d) are the same as that for (a) and (d) respectively, but based on PIOMAS data. The points in the plot are the median value of all the daily data and on all grid points within the study domain based on Figure ~~S5~~1. In the labels of different sea-ice thickness and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

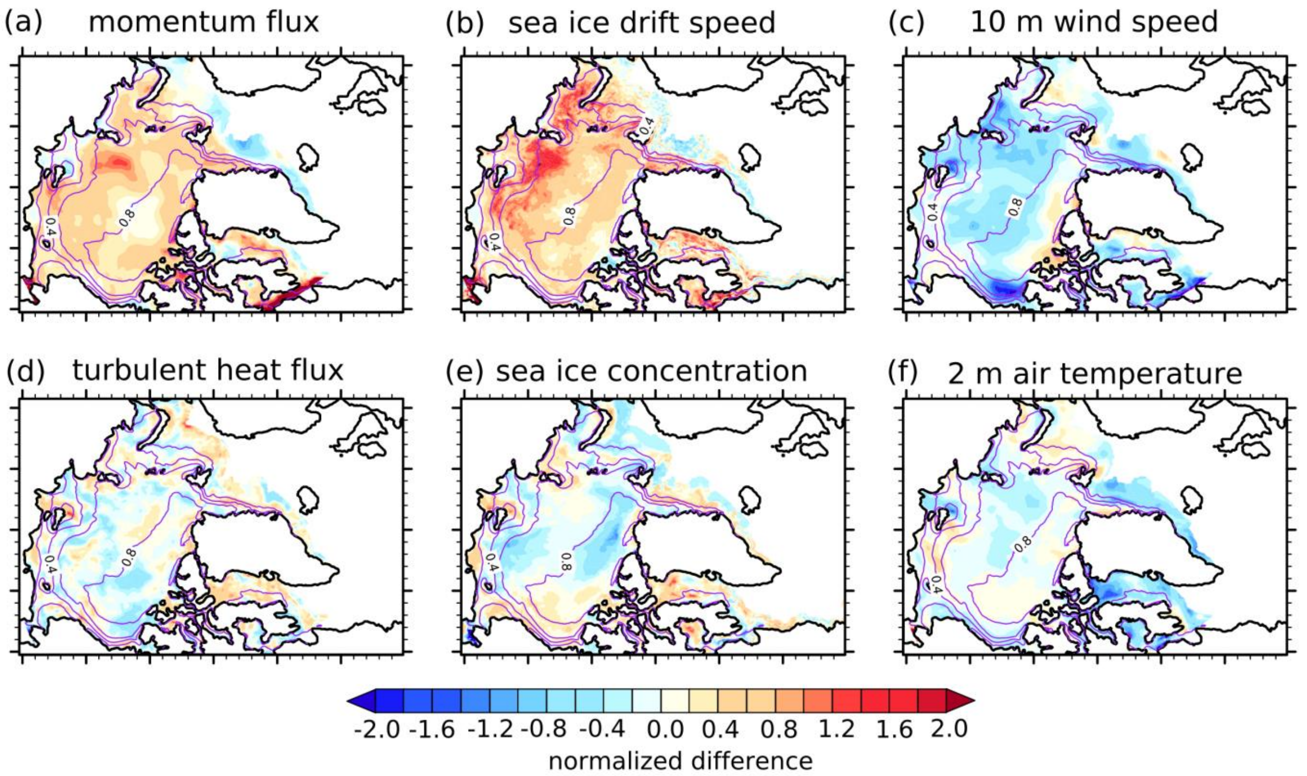
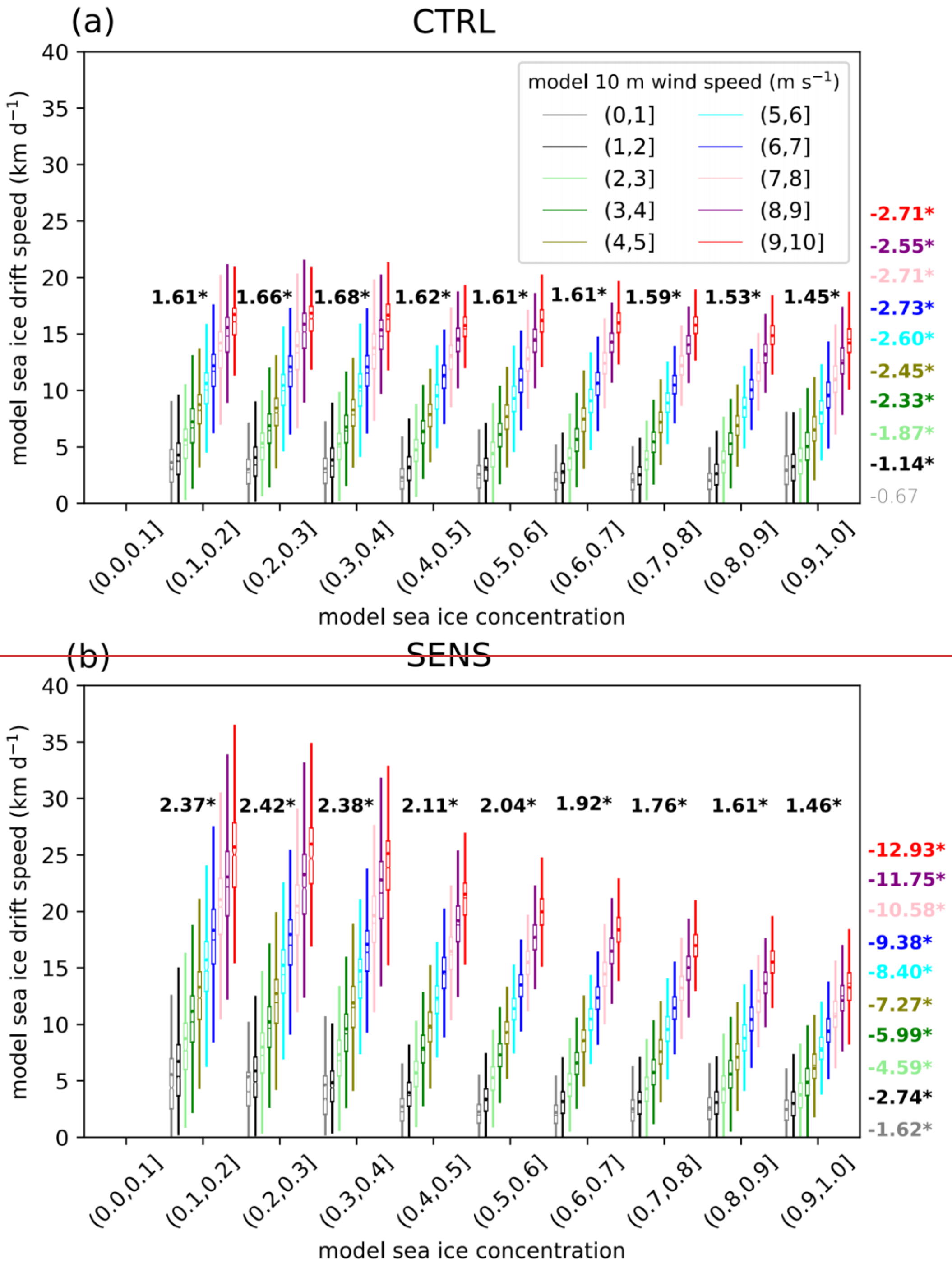


Figure 8: Normalized ensemble mean differences (SENS minus CTRL) of (a) momentum flux, (b) sea-ice drift speed, (c) 10-m wind speed, (d) turbulent heat flux, (e) sea-ice concentration, (f) 2--m air temperature during for 2007 summer (JJAS). The ensemble mean difference is normalized by the cross-ensemble standard deviation of the differences. The purple contours represent the ensemble mean sea-ice concentration in the CTRL experiment.


(a)
CTRL
model sea ice drift speed (km d^{-1})
model 10 m wind speed (m s^{-1})
(0,1] (1,2] (2,3] (3,4] (4,5] (5,6] (6,7] (7,8] (8,9] (9,10]
1.61* 1.66* 1.68* 1.62* 1.61* 1.61* 1.59* 1.53* 1.45*
-2.71* -2.55* -2.71* -2.73* -2.60* -2.45* -2.33* -1.87* -1.14* -0.67
(0.0,0.1] (0.1,0.2] (0.2,0.3] (0.3,0.4] (0.4,0.5] (0.5,0.6] (0.6,0.7] (0.7,0.8] (0.8,0.9] (0.9,1.0]
model sea ice concentration
(b)
SENS
model sea ice drift speed (km d^{-1})
2.37* 2.42* 2.38* 2.11* 2.04* 1.92* 1.76* 1.61* 1.46*
-12.93* -11.75* -10.58* -9.38* -8.40* -7.27* -5.99* -4.59* -2.74* -1.62*
(0.0,0.1] (0.1,0.2] (0.2,0.3] (0.3,0.4] (0.4,0.5] (0.5,0.6] (0.6,0.7] (0.7,0.8] (0.8,0.9] (0.9,1.0]
model sea ice concentration

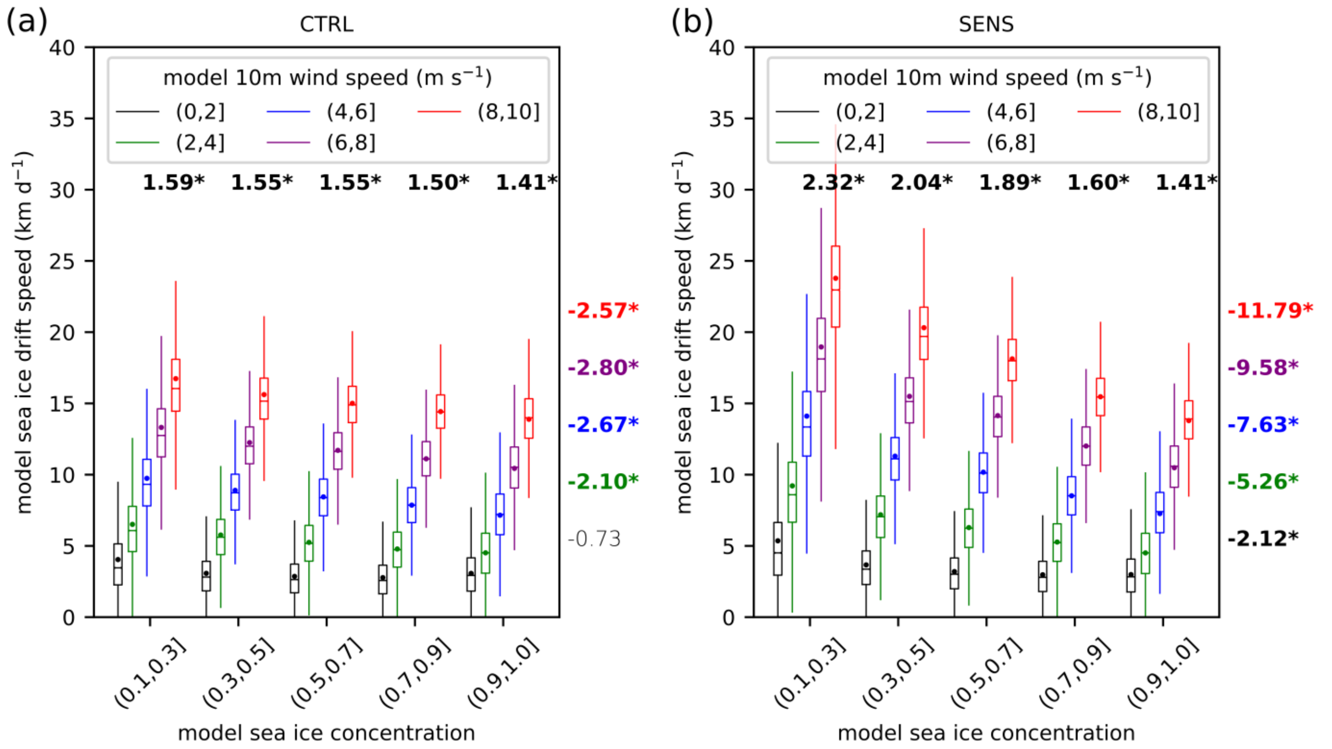
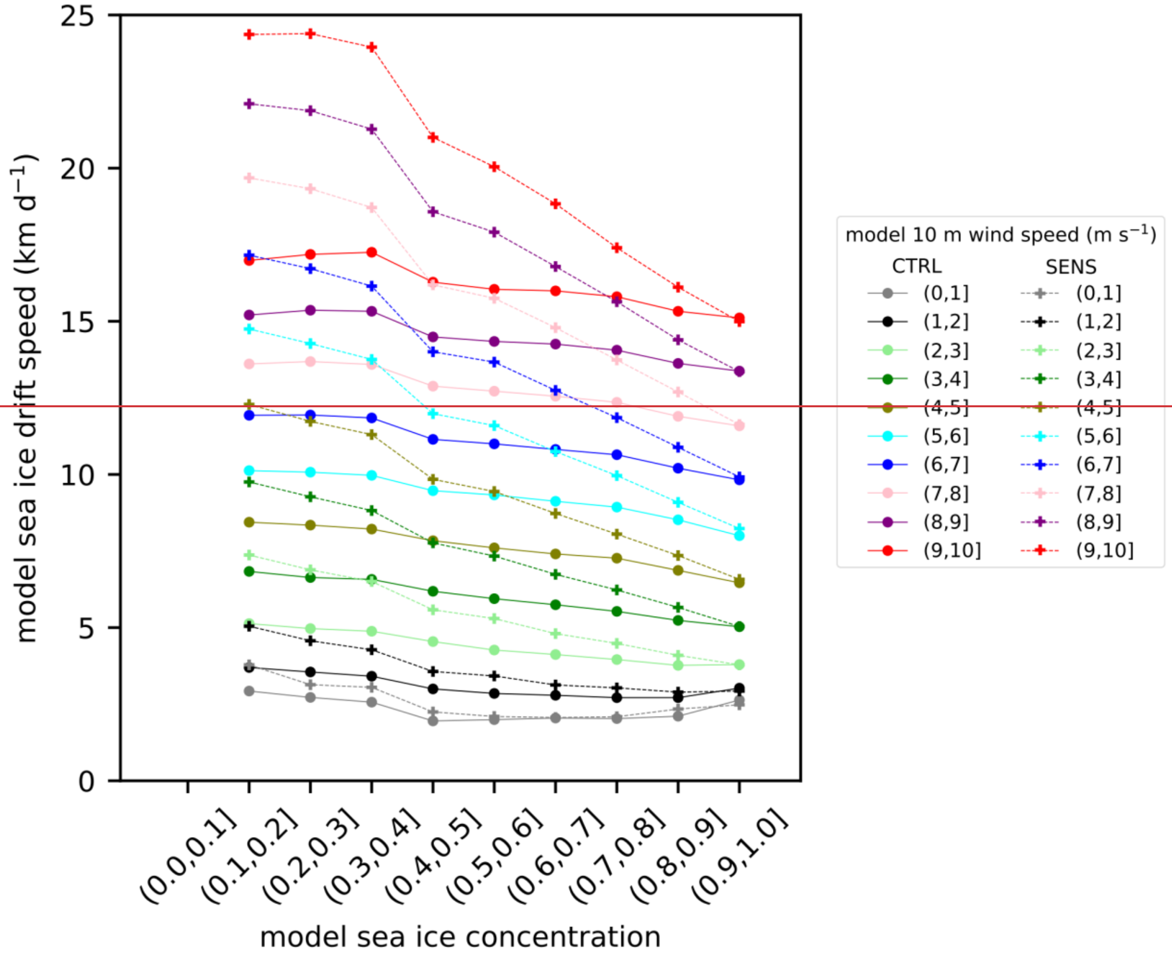


Figure 9: Box-whisker plots of the relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors) ~~during~~ for 2007 summer (JJAS) in (a) CTRL and (b) SENS experiment. The plot is based on daily data and on all grid points within the study domain indicated in Figure 1. The horizontal bar represents the median, the notch represents the 95% confidence interval of the median, the dot represents the mean, the top and bottom of the box represent the 75th and 25th percentiles, the upper/lower whiskers represent the maximum/minimum value within 1.5 times interquartile range (IQR) to 75/25 percentiles. The numbers above the boxplots represent the slopes of near-surface wind and sea-ice drift speed fit lines (unit: km d^{-1} per 1 m s^{-1} wind speed change; font colors as for the wind speed classes). The numbers right of the boxplots represent the slopes of sea-ice concentration and sea-ice drift speed fit lines (unit: km d^{-1} per 10% sea-ice concentration change). A bold and asterisked number indicates that the slope of the fit line is significant at the 95 % level. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.


model sea ice drift speed (km d^{-1})
model sea ice concentration
model 10 m wind speed (m s^{-1})
CTRL
SENS
(0,1]
(1,2]
(2,3]
(3,4]
(4,5]
(5,6]
(6,7]
(7,8]
(8,9]
(9,10]
(0.0,0.1]
(0.1,0.2]
(0.2,0.3]
(0.3,0.4]
(0.4,0.5]
(0.5,0.6]
(0.6,0.7]
(0.7,0.8]
(0.8,0.9]
(0.9,1.0]

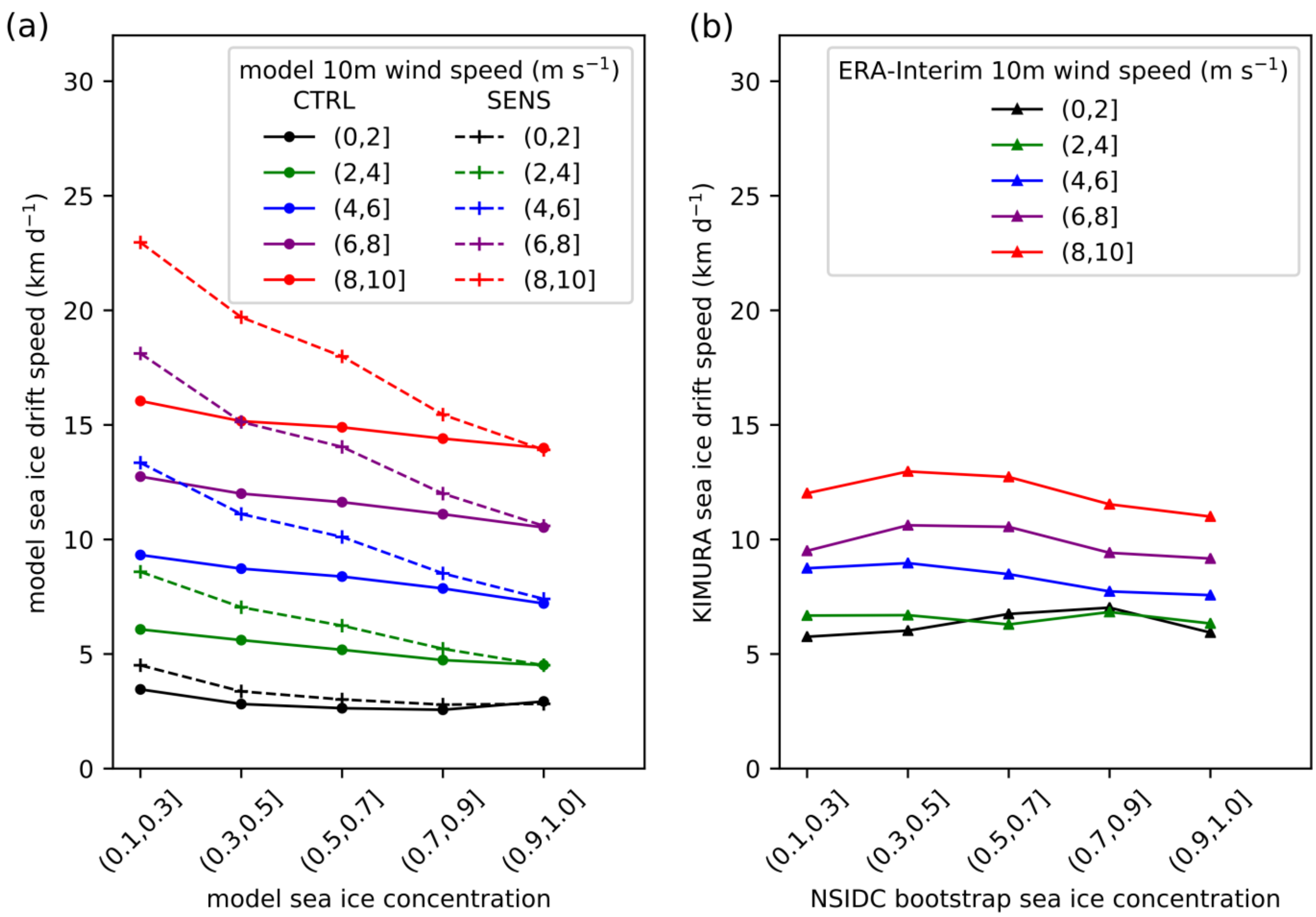

(a)
model sea ice drift speed (km d^{-1})
model 10m wind speed (m s^{-1})
CTRL
SENS
(0,2]
(2,4]
(4,6]
(6,8]
(8,10]
model sea ice concentration
(b)
KIMURA sea ice drift speed (km d^{-1})
ERA-Interim 10m wind speed (m s^{-1})
(0,2]
(2,4]
(4,6]
(6,8]
(8,10]
NSIDC bootstrap sea ice concentration
(0.1,0.3]
(0.3,0.5]
(0.5,0.7]
(0.7,0.9]
(0.9,1.0]

Figure 10: The (a) simulated ~~Relationship~~ relationship between sea-ice drift speed and sea-ice concentration for different near-surface wind speed classes (different colors) ~~during~~ for 2007 summer (JJAS) ~~for~~ in CTRL (circle marker and solid line) and SENS (cross marker and dashed line) experiment. The relationship based on KIMUAR sea-ice drift speed, NSIDC bootstrap sea-ice concentration and ERA-interim 10-m wind speed is shown in (b). The points in the plot is the median value of all the daily data and on all grid points within the study domain indicated in Figure 1 under certain wind speed and sea-ice concentration classes. In the labels of different sea-ice concentration and 10-m wind speed classes, "(" means exclusive and "]" means inclusive.

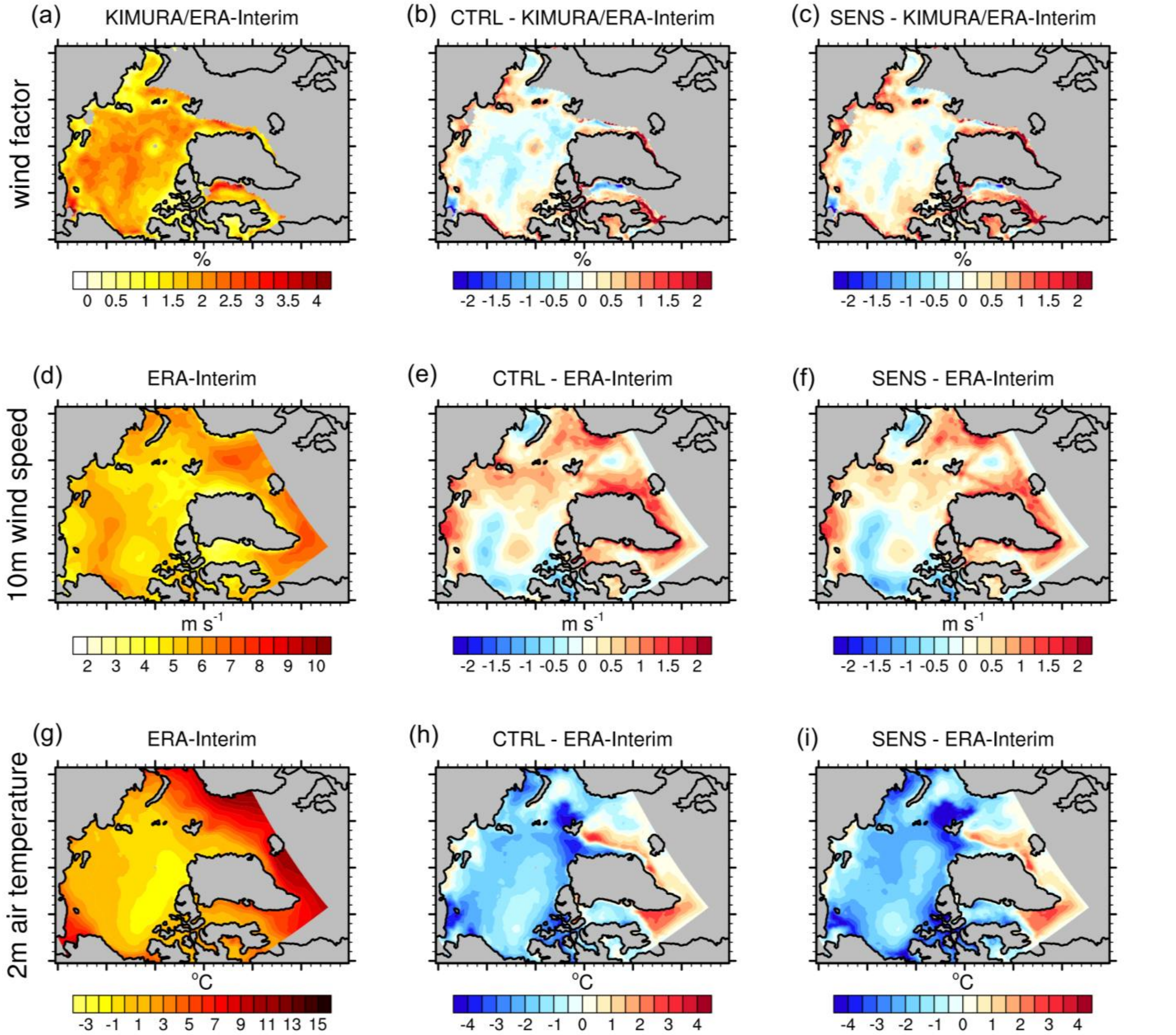


Figure 11: The 2007 summer (JJAS) (a) wind factor, (d) 10-m wind speed and (g) 2-m air temperature from ERA-Interim (KIMURA sea-ice drift is used for wind factor calculation). (b) wind factor, (e) 10-m wind speed and (h) 2-m air temperature differences between CTRL experiment and ERA-Interim (KIMURA and ERA-interim for wind factor). (c), (f) and (i) are the same as that for (b), (e) and (h), but show the differences between SENS experiment and ERA-Interim (KIMURA and ERA-interim for wind factor).

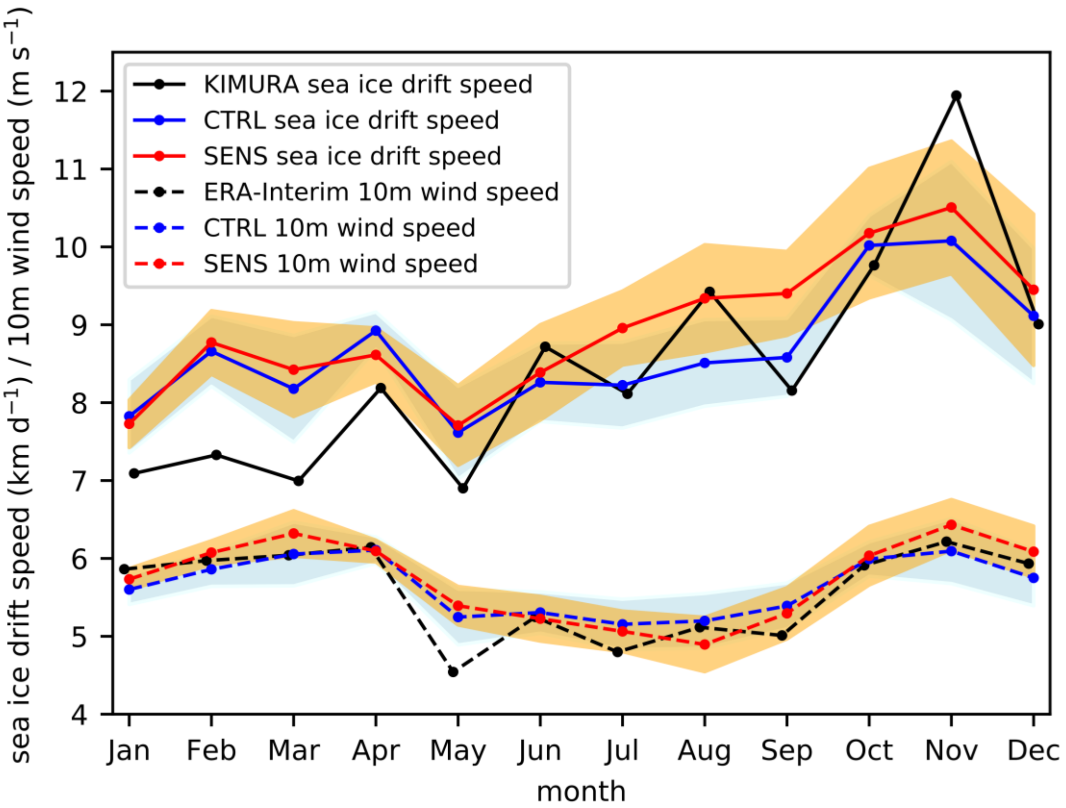


Figure 12: Mean annual cycle of sea-ice drift speed [km d^{-1}] (solid lines) and 10-m wind speed [m s^{-1}] (dashed lines), based on CTRL experiment (ensemble mean; blue lines), SENS experiment (ensemble mean; red lines) and the observation/reanalysis (KIMURA ice drift, ERA-I wind; black lines) for 2007 over the study domain (indicated in Figure 1). The across-ensemble scatters (standard deviation) of the simulations are included as shaded area (light blue for CTRL, orange for SENS).