Reviewer #2

Kageyama et al. present the results of CMIP6-PMIP4 LIG simulations from 12 models and analyse them in terms of Arctic sea ice changes. They also present a new compilation of LIG sea-ice proxy data which they compare the model results with. While the discrepancies between simulations and proxy data, as well as within proxy data and within simulations, prevent any unambiguous identification of LIG sea-ice changes, the author provide valuable insights into the parameters that may influence sea-ice dynamics through their analysis of inter-model differences.

I find the manuscript well-structured and written in a concise and convincing way, and I only have minor concerns about how the proxy reconstructions were transferred into values of sea-ice concentration and duration (as described below). I thus recommend this manuscript for publication with minor revisions.

We thank the reviewer for this careful review.

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Major comments about proxy data (mostly section 2.2):

I really like the author's cautious approach to provide common and clear definitions, based on sea-ice cover duration and sea-ice cover concentration, of ice-free / seasonal/ perennial sea ice that facilitate data-data and model-data comparison. However, it is not always clear for me how such values have been obtained for the proxy data:

- For dinocysts: the explanation is very clear, but I miss the info on how the min and max values have been obtained (are those the min and max values of the 5 (?) best analogues? The minimum and maximum monthly sea-ice cover durations? The range of variability within the LIG time slice? Other?).

The minimum and maximum values are given according to the range of estimates within the LIG time slice. This is added in section 2.2. in which the last sentence in the paragraph about dinocyst data now reads:

"The error of prediction for sea-ice concentration is ±12% and that of sea-ice cover duration through the year is ±1.5 months/yr. Such values are very close to the interannual variability in areas occupied by seasonnal sea-ice cover (cf. de Vernal et al., 2013b)."

- For other proxies:

> I understand the authors attributed values of 0.15 and 0.95 for min and max sea-ice concentration at sites where sea ice was interpreted to be perennial, but I miss the info on how those values were defined for other sea-ice categories (or what are the sea-ice states corresponding to the 3 other min-max SIC combinations: 0.3-0.95, 0.3-0.6 and0.1-0.3).

> The rationale for the attribution of min and max sea-ice cover durations is also not clear to me (in section 3.3 the authors mention they "define perennial sea ice to have at least 9 months of coverage", but I am confused because sites with min-max sea-ice concentrations of 0.15-0.95 have either min-max sea-ice cover durations of 9-12 mth/yr for IP25 or 3-11 mth/yr for faunas).

- Regarding the sites with PIP25-based interpretations, have the attributed min-max range of sea-ice concentration values been compared to some sea-ice concentration quantifications based on the calibrations recently proposed (Xiao et al., 2015, http://dx.doi.org/10.1016/j.gca.2015.01.029; Smik et al., 2016,

http://dx.doi.org/10.1016/j.orggeochem.2015.12.007) to see if both methods yield rather similar results?

We have updated Table 1 to respond to this point and considered it is not possible to give quantitative durations of sea ice cover for the Central Arctic cores. These are also the cores with the most uncertain chronology, and this information has also been added to the table, as well as a qualitative description of the sea ice state. The data-model comparison has been updated accordingly.

The new table 1 is as follows:

Latitude (◦N)	**Longitude** (◦E)	**Sea-ice** indicator	**Core name**	**Reference for original data**	**Core number on map**	**Chronological control** 1 = good; 2 = uncertain	**Qualitative sea ice state**	**# months during the year with sea ice cover > 50%** months		**Annual mean sea ice concentration** [0-1]	
								Min	Max	Min	Max
87,08	144,77	Ostracodes	Oden96/12-1pc	Cronin et al. (2010)	6	2	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
85,32	-14	IP25/PIP25	PS2200-5	Stein et al. (2017)	8	2	Perennial sea ice	?	?	?	?
85,32	-14	Ostracodes	PS2200-5	Cronin et al. (2010)	8	2	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
85,14	-171,43	IP25/PIP25	PS51/38-3	Stein et al. (2017)	5	2	Perennial sea ice	?	?	?	?
84,81	-74,26	Subpolar foraminifers	GreenICE (core 11)	Nørgaard-Pedersen et al. (2007)	7	2	Reduced sea ice cover, partly even seasonally ice-free	?	?	?	?
81,92	13,83	IP25/PIP25	PS92/039-2	Kremer et al. (2018b)	10	1	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
81,54	30,17	Dinocysts	PS2138-1	Matthiessen et al. (2001), Matthiessen and Knies (2001)	9	1	Seasonal sea-ice conditions, summer probably ice-free	0	5	0	0,3
81,54	30,59	IP25/PIP25	PS2138-1	Stein et al. (2017)	9	1	Seasonal sea-ice conditions, summer probably ice-free	?	?	0,1	0,3
81,19	140,04	IP25/PIP25	PS2757-8	Stein et al. (2017)	4	2	Perennial sea ice	?	?	?	?
79,59	-172,5	Subpolar foraminifers	HLY0503-8JPC	Adler et al. (2009)	3	2	Seasonal sea-ice conditions, summer probably ice-free	?	?	?	?
79,32	-178,07	Ostracodes	NP26-32	Cronin et al. (2010)	1	2	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
79,2	4,67	IP25/PIP25	PS93/006-1	Kremer et al. (2018a)	11	1	Seasonal sea-ice conditions, summer probably ice-free	?	?	0,3	0,6

78,98	-178,15	Ostracode faunas	NP26-5	Cronin et al. (2010)	2	2	Perennial sea ice (summer sea ice concentration >75%)	?	?	?	?
8,36	76,85	Dinocysts	M23455-3	Van Nieuwenhove et al. (2011)	12	1	Nearly ice free all year round	0	1	0	0,15
-12,43	70,01	Dinocysts	M23352	Van Nieuwenhove et al. (2013)	13	1	Nearly ice free all year round	0	1	0	0,15
-17,12	69,49	Dinocysts	PS1247	Van Nieuwenhowe (pers. com.); Zhuravleva et al. (2019) for the chronology	14	1	Nearly ice free all year round	0	4	0	0,3
5,92	67,77	Dinocysts	M23323	Van Niewenhove et al. (2011)	15	1	Nearly ice free all year round	0	1	0	0,15
2,91	67,09	Dinocysts	M23071	Van Niewenhove et al. (2008); Van Nieuwenhove and Bauch (2008)	16	1	Nearly ice free all year round	0	1	0	0,15
-22,07	60,58	Dinocysts	MD95-2014	Eynaud (1999)	17	1	Ice free all year round	0	0	0	0
-25,95	58,77	Dinocysts	MD95-2015	Eynaud et al. (2004)	18	1	Ice free all year round	0	0	0	0
-48,37	58,21	Dinocysts	HU90-013-13P	Hillaire-Marcel et al. (2001); de Vernal and Hillaire-Marcel (2008)	19	1	Nearly ice free all year round	0	1	0	0,15
-14,67	55,47	Dinocysts	MD95-2004	Van Nieuwenhove et al. (2011)	20	1	Ice free all year round	0	0	0	0
-45,26	53,33	Dinocysts	HU91-045-91	This manuscript	21	1	Ice free all year round	0	0	0	0
-33,53	53,06	Dinocysts	IODP1304	This manuscript; Hodell et al. (2009) for the chronology	22	1	Nearly ice free all year round	0	1	0	0,15
-45,63	50,17	Dinocysts	IODP1302/1303	This manuscript; Hillaire-Marcel et al. (2011) for the chronology	23	1	Nearly ice free all year round	0	1	0	0,15
-9,52	46,83	Dinocysts	MD03-2692	Penaud et al. (2009)	24	1	Ice free all year round	0	0	0	0
-10,17	37,80	Dinocysts	MD95-2042	Eynaud et al. (2000)	25	1	Ice free all year round	0	0	0	0

- Could it be specified in Table 1 whether it is IP25 and/or PIP25?

The reconstructions are based on both indicators, and this is now specified in Table 1.

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Minor comments:

- At my first reading (but not the following), it was not always clear whether it was referred to sea-ice cover duration, concentration or simply sea-ice cover. Maybe SIC, SICc and SICd abbreviations (or something similar) could be used to help with this?

The reviewer is right, this could be confusing. We use SIC for sea ice concentration as now specified at the end of section 2.2 and in table 1 in the revised manuscript. As explained in our response to reviewer 1, we have also better introduced the terms sea ice area (SIA) and sea ice extent (SIE), which are used in the literature on sea ice. We also define SICd50 as the duration, in months, computed from monthly data, of the period during which SIC > 0.50.

- L18: what is 21C?

21st century, we now spell it out.

- L69: "PI" abbreviation used as "pre-industrial" but defined as such only L133.

Abbreviations has been checked for consistency throughout the manuscript. Our apologies for these inconsistencies. This sentence now reads: "However, a quick assessment of the sea ice simulated in the reference state, i.e. the pre-industrial control experiment (referred to piControl in the CMIP6 terminology, and PI in this manuscript) was necessary."

- Table 1: maybe it would be clearer to specify "duration" in the "sea-ice cover" column (or cf. my first minor comment), as well as "per year" for the unit.

This is now corrected: we refer to "# months during the year with sea ice cover > 50%"

- L90: The error of prediction for sea-ice cover concentration is indicated, but not that for sea-ice duration.

This is now added, cf. our response to the first major point.

- Table 2: some info missing for CESM2 boundary conditions and LIG simulation length, LOVECLIM1.2 physical core components and LIG simulation length, and NESM3 boundary conditions and LIG simulation length.

The following information will be added:

- For CESM2:

    Aerosols: interactive dust

    Spinup (after PI ssinup): 325 years

    Simulation length: 700 years

- For LOVECLIM1.2: the atmosphere component is ECBilt, the ocean and sea ice component is CLIO, the land component is VECODE, the spin-up is 3000 yrs long and the production length is 1000 years.

- For NESM3: interactive vegetation ; the aerosols are prescribed to the pre-industrial values, the ice sheets are prescribed to modern values, the spin up is 500 years-long; the production run is 100 years-long.

- L134: GHG abbreviation not defined

The definition has been added. The sentence is now: "The prescribed LIG (*lig127k*) protocol differs from the CMIP6 Pre-industrial (PI) simulation protocol in astronomical parameters and the atmospheric greenhouse gases concentrations (GHG). "

- L156: should the reference to Figure 3 here be to Table 4 instead, as Figure 3 is referred to 4 lines after when talking about the "The detail of the geographical distribution of sea ice"?

We have included the reference to Table 4 at the end of this sentence (and removed it from the end of the following sentence to avoid repetition)

- L175-177: maybe it would be clearer to mention that the reduction is "between the PI and LIG" in the first sentence rather than/in addition to in the second sentence (as done in the conclusion).

This sentence has been rewritten as: "Thus, compared to the PI results, there is a reduction of 49% in the MMM minimum (summer) monthly SIA in the LIG results, but almost no change for the winter monthly MMM SIA."

- L178: 12 rather than 13 models?

The number of models will be updated (there will be one more model: CNRM-CM6-1).

- L178-181: maybe specify that the third model is NESM3 and refer to the section above regarding the reason why it does not realistically capture the PI Arctic?

Taking both SIA and SIE into account, this paragraph has been updated to:

There is a large amount of inter-model variability for the LIG SIA and SIE during the summer (Figure 4 and Table 4). Out of the sixteen models, one model, HadGEM3, shows a LIG Arctic Ocean free of sea ice in summer, i.e. with an SIE lower than 1 million km2. CESM2 and NESM3 show low SIA values (slightly above 2 mill. km2) in summer for the LIG simulation but their minimum SIE values are around 4 mill. km2. Both HadGEM3 and CESM2 realistically capture the PI Arctic sea ice seasonal cycle. On the other hand, NESM3 overestimates winter ice and the amplitude of the seasonal cycle in SIA and SIE, while simulating realistic PI values for both SIA and SIE (Cao et al., 2018). This seasonal cycle is amplified in the LIG simulation, with an increase in SIA and SIE in winter and a decrease in summer, following the insolation forcing. Hence, the difference in the response of these models to LIG forcing in terms of sea ice does not appear to only depend on differences in PI sea ice representation.

- L188-191 and Figures 6 and 7: "the reconstructed values, classified into 3 categories: perennial cover (9 to 12 months), seasonal cover (3 to 9 months), ice free state (0 to3 months)" –> how were the reconstructions based on the same proxy with e.g. (from Table 1) 3 to 12 months/year classified? Does "ambiguous interpretations" (here but I also mean in general in the MS) refer to those from the same core/area and based on different proxies (which is what I understand) or does it also refer to reconstructions from the same core and same proxy? If so, maybe it would be worth clearly mentioning it too, as it also plays a role in the difficulty to compare model and data (and highlight the proxy limitations from this other perspective) and in model-data discrepancies.

We agree with the reviewer that this was not clear. In the new version of the manuscript, this is described in more detail and Table 1 has been be updated accordingly.

- L191: the first “to” may be removed in “it is not possible to for any one model to match”

Ok, corrected.

- L192: maybe something like “comparison between the PI and LIG model *results*and PI and LIG sea ice *proxy* data” would be clearer

The sentence has been corrected as follows: “the comparison between the PI and LIG results and PI and LIG sea ice reconstructions as a function of the latitude of the LIG data sites is remarkably similar for each individual model (Figure 5)”

- L209-210: I understand that the authors do not want to solve this here, and I think it is not necessary as the focus of this paper is on the models. That said, given the proxy and model dataset presented here, and the authors being one of the world experts on these proxies, I have to admit that I was kind of expecting / hoping for this initially...:-)

=> our apologies for disappointing the reviewer… but we preferred to be honest here and point to remaining work which has to be done.

- L213: “we” instead of “to”

=> this is corrected.

- L224: SW abbreviation not defined

=> SW stand for short wave, indicated just before in the text.

- L276: no need to redefine LIG abbr.

=> ok, we have removed the abbreviation.

- L281: I would maybe rather say “These southern sea ice records are (or “correspond to” or equivalent) quantitative estimates based on dinoflagellate cysts (dinocysts)” to avoid confusion.

=> Fine, this has been changed.

- L288-289: there has been a shortcut, “periods” does not refer to anything here.

=> The sentence is now: “the comparison between the PI and LIG results and PI and LIG sea ice reconstructions as a function of the latitude of the LIG data sites is remarkably similar for each individual model (Figure 5)”.

- L299: 12 models + no need to redefine MMM abbr.

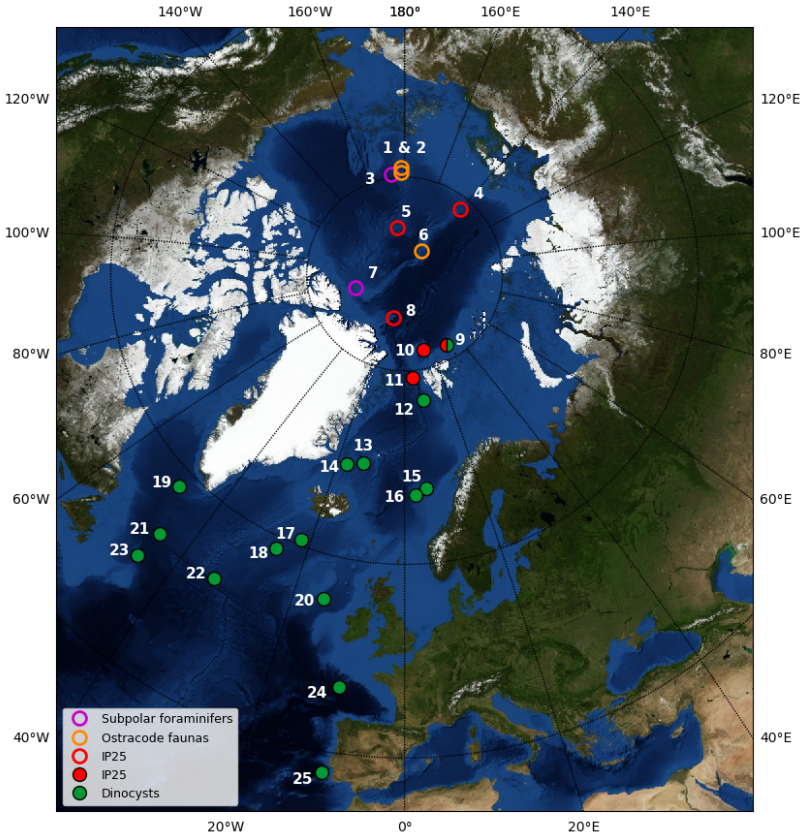
=> We redefine the abbreviations in the conclusion in case readers go to them directly. As stated above the number of models will be updated.

- L305-306: needs to be rephrased

The sentence has been rephrased to “In general, the models that fail to realistically represent the numbers of months per year of sea ice cover in the PI also provide unlikely LIG results.”

- Figure 1: the colour code for the cores is missing + why are there only some cores labelled? If this is a matter of space, numbers could be used in Table 1 and Figure 1.

=>The figures has been completed. The colour code corresponds to the sea ice proxies as used in other figures throughout the manuscript. Numbers have been added for the sites which were not labelled. The new map is as follows.



Core name	Map number
Oden96/12-1pc	6
PS2200-5 - Stein et al. (2017)	8
PS2200-5 - Cronin et al. (2010)	8
PS51/38-3	5
GreenICE	7
PS92/039-2	10
PS2138-1	9
PS2138-1	9
PS2757-8	4
HLY0503-8JPC	3
NP26-32	1
PS93/006-1	11
NP26-5	2
M23455-3	12
M23352	13
PS1247	14
M23323	15
M23071	16
MD95-2014	17
MD95-2015	18
HU90-013-13P	19
MD95-2004	20
HU91-045-91	21
IODP1304	22
IODP1302/1303	23
MD03-2692	24
MD95-2042	25