Supplementary Material

Citations	Date range	Timing	Threshold	Consecutive Days
Break-up				
Bliss et al. (2019); Steele et al. (2019)	1 March to SIC minimum date	last day	below 15%	–
Serreze et al. (2016)	*X*	first day	below 30%	–
Stammerjohn et al. (2008, 2012)	mid-September to mid-September	last day	below 15%	–
Stroeve et al. (2016)	1 March to SIC minimum date	last day	below 15, 30, 50%	–
Wang et al. (2018)	1 March and 30 September	first day	below 15%	2
Freeze-up				
Bliss et al. (2019); Steele et al. (2019)	SIC minimum date to 28 February	first day	above 15%	–
Serreze et al. (2016)	SIC minimum date to *X*	first day	above 30%	–
Stammerjohn et al. (2008, 2012)	mid-September to mid-September	first day	above 15%	5
Stroeve et al. (2016)	SIC minimum date to 28/29 February	first day	above 15, 30, 50%	–
Wang et al. (2018)	1 September to 31 March	first day	above 15%	2
Open water period				
Barnhart et al. (2016)	11 March to 11 March	number of days	below 15%	–

Table S1. Definitions for break-up (retreat), freeze-up (advance) and the open water period. All studies in the table except Barnhart et al. (2016) calculate the open water period as the number of days between break-up and freeze-up. Information designated with *X* is not provided in the cited manuscripts.

Model	Ocean model	Sea ice model	Ice-ocean Resolution (latitude x longitude)	Citations
ACCESS-CM2	MOM5	CICE5	primarily 1°x 1°	Dix et al. (2019)
BCC-CSM2-MR	MOM4	SIS2	0.3-1°x 1°	Wu et al. (2018, 2019)
BCC-ESM1	MOM4	SIS2	0.3-1°x 1°	Zhang et al. (2018); Wu et al. (2019)
CanESM5	NEMO3.4.1 ORCA1	LIM2	0.3-1°x 1°	Swart et al. (2019a, b)
CESM2	POP2	CICE5	0.9°x 1.25°	Danabasoglu (2019a); DeRepentigny et al. (submitted 2020)
CESM2-FV2	POP2	CICE5	0.9°x 1.25°	Danabasoglu (2019b)
CESM2-WACCM	POP2	CICE5	0.9°x 1.25°	Danabasoglu (2019c); DeRepentigny et al. (submitted 2020)
CESM2-WACCM-FV2	POP2	CICE5	0.9°x 1.25°	Danabasoglu (2019d)
CNRM-ESM2-1	NEMO3.6 eORCA1	GELATO6	primarily 1°x 1°	Seferian (2018); Voldoire et al. (2019)
CNRM-CM6-1	NEMO3.6 eORCA1	GELATO6	primarily 1°x 1°	Voldoire (2018); Voldoire et al. (2019)
EC-Earth3	NEMO3.6 eORCA1	LIM3	0.3-1°x 1°	Döscher et al. (in preparation); EC-Earth-Consortium (2019)
IPSL-CM6A-LR	NEMO-OPA eORCA1.3	LIM3	~1°x ~1°	Boucher et al. (2018, submitted 2019)
MRI-ESM2-0	MRI.COM4.4	MRI.COM4.4	0.3-0.5°x 1°	Yukimoto et al. (2019a, b)
NorESM2-LM	MICOM	CICE5	primarily 1°x 1°	NCC (2018a); Seland et al. (submitted 2020)
NorESM2-MM	MICOM	CICE5	primarily 1°x 1°	NCC (2018b); Seland et al. (submitted 2020)
CESM LE	POP2	CICE4	0.3-1°x 1°	Hurrell et al. (2013); Kay et al. (2015)

Table S2. Ocean and sea ice models used by the coupled models, as well as their primary ice-ocean resolutions and associated citations.

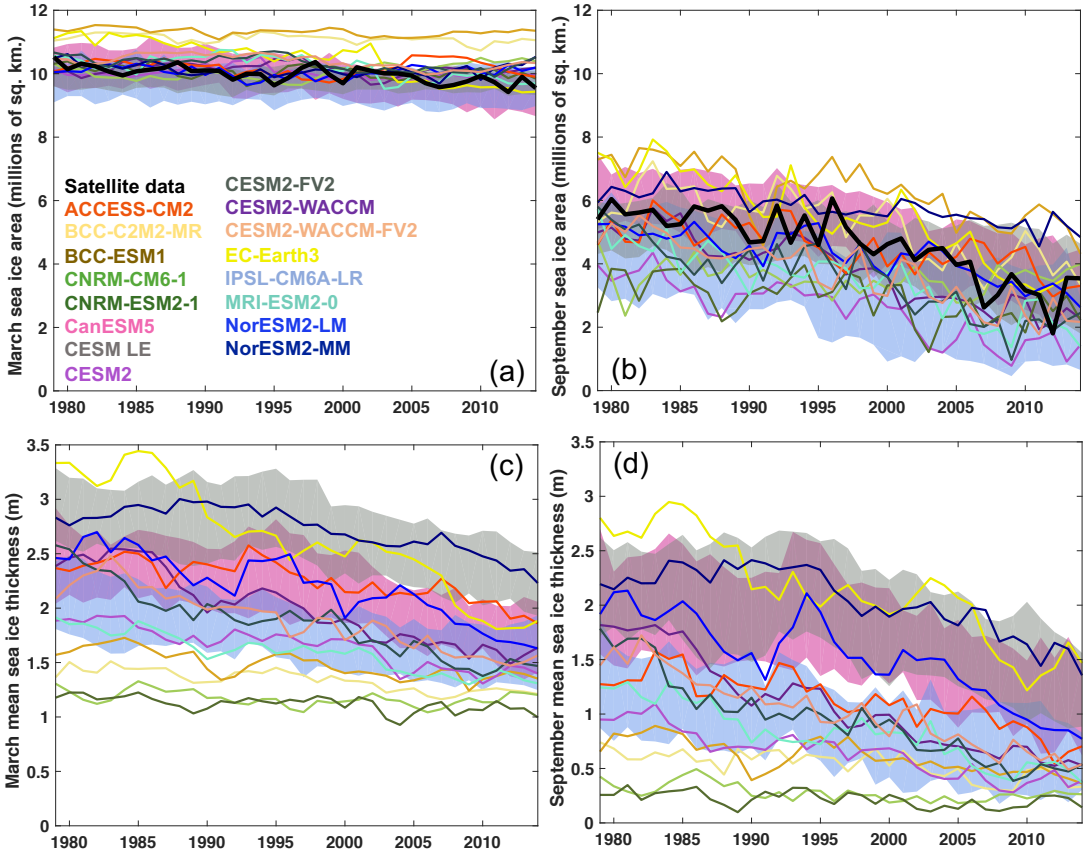

Figure S1. From 1979–2014, (a) March sea ice area (b) September sea ice area (c) March mean ice thickness and (d) September mean ice thickness in CMIP6 models (various colors), CESM LE (gray) and satellite observations (black) in the Arctic. All ensemble members are shown for CESM (40 members), CanESM5 (35 members) and IPSL (30 members). Observations of sea ice thickness are not shown.

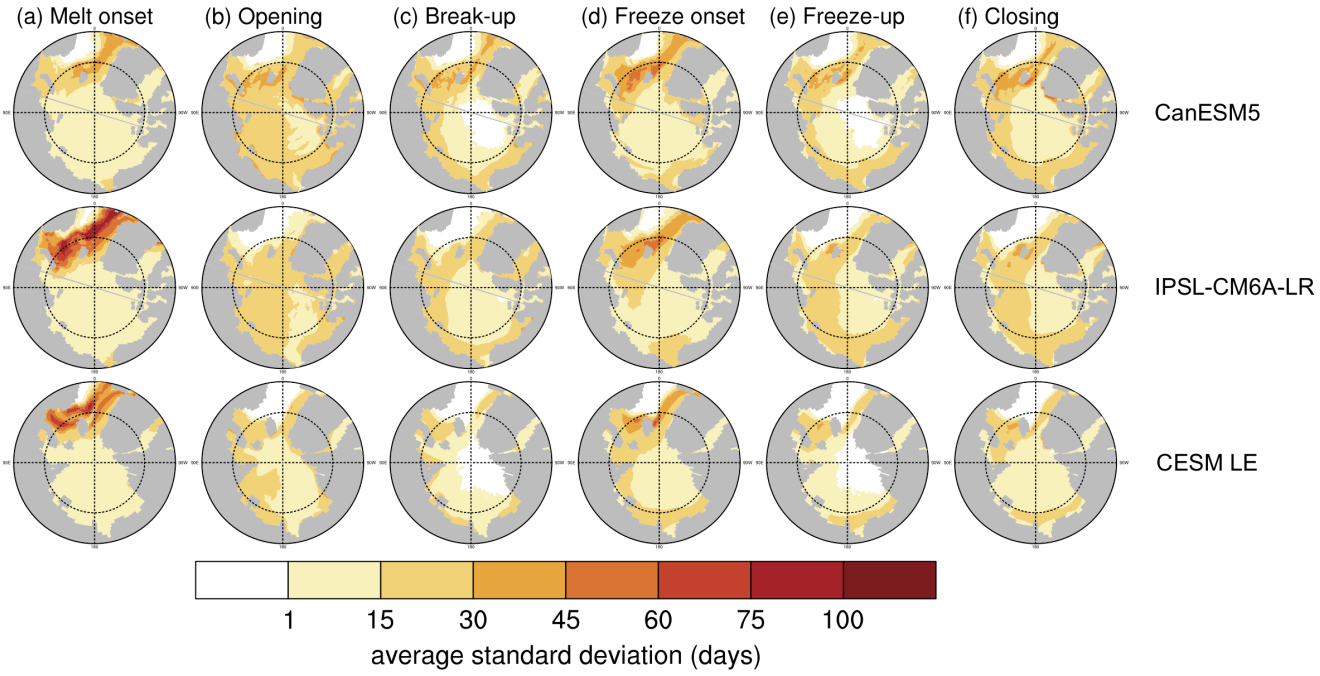

Figure S2. The average standard deviation between all available ensemble members over 1979–2014 for (a) melt onset (b) opening (c) break-up (d) freeze onset (e) freeze-up (f) closing. CanESM5 is displayed in the first row (35 members), IPSL is displayed in the second row (30 members) and CESM LE is displayed in the third row (40 members). The standard deviation is calculated at each grid cell for each year, and then the average of all years is plotted for each grid cell. The same figure using the first 30 ensemble members of each model is displayed in Fig. 9.

	Melt onset	Opening (80%)	Break-up (15%)	Freeze onset	Freeze-up (15%)	Closing (80%)
ACCESS-CM2	0.52[a]	0.74[a]	0.24	-0.76[a]	-0.74[a]	-0.67[a]
BCC-CSM2-MR	0.33	0.46[a]	0.16	-0.70[a]	-0.47[a]	-0.66[a]
BCC-ESM1	0.55[a]	-0.16	0.05	-0.69[a]	-0.58[a]	-0.47[a]
CESM2	0.38[a]	0.76[a]	0.30	-0.82[a]	-0.75[a]	-0.86[a]
CESM2-FV2	0.66[a]	0.73[a]	0.09	-0.85[a]	-0.69[a]	-0.74[a]
CESM2-WACCM	0.53[a]	0.65[a]	-0.07	-0.73[a]	-0.48[a]	-0.67[a]
CESM2-WACCM-FV2	0.49[a]	0.67[a]	0.36[a]	-0.79[a]	-0.67[a]	-0.73[a]
CNRM-ESM2-1	0.46[a]	-0.15	-0.11	-0.19	-0.13	-0.17
CNRM-CM6-1	0.19	-0.18	-0.11	-0.07	-0.04	-0.08
EC-Earth3	0.75[a]	0.53[a]	0.48[a]	-0.91[a]	-0.82[a]	-0.79[a]
MRI-ESM2-0	0.37[a]	0.46[a]	-0.18	-0.83[a]	-0.76[a]	-0.79[a]
NorESM2-LM	0.47[a]	0.63[a]	0.03	-0.68[a]	-0.46[a]	-0.61[a]
NorESM2-MM	0.44[a]	0.08	-0.47[a]	-0.53[a]	-0.4[a]	-0.38[a]
CanESM5	0.67[a]	0.49[a]	-0.12[a]	-0.6[a]	-0.53[a]	-0.57[a]
IPSL-CM6A-LR	0.41[a]	0.49[a]	-0.08[a]	-0.78[a]	-0.66[a]	-0.71[a]
CESM LE	0.35[a]	0.19[a]	-0.11[a]	-0.76[a]	-0.34[a]	-0.43[a]

Table S3. Correlation coefficients (R-values) between seasonal sea ice transition dates and summer (June–September) mean sea ice thickness of the same year from 1979–2014. Values with [a] are statistically significant at the 95% confidence level. Correlation coefficients and p-values for models in the first thirteen rows are determined using one ensemble member, for CanESM5 using all 35 ensemble members, for IPSL using all 30 ensemble members and CESM LE using all 40 ensemble members. All values are calculated between 66-84.5°N.

	Melt onset	Opening (80%)	Break-up (15%)	Freeze onset	Freeze-up (15%)	Closing (80%)
ACCESS-CM2	-0.16	0.06	-0.15	-0.13	-0.06	-0.03
BCC-CSM2-MR	0.49[a]	0.25	0.29	-0.34[a]	-0.21	-0.26
BCC-ESM1	0.29	-0.17	-0.19	-0.45[a]	-0.27	-0.21
CESM2	0.06	0.38[a]	0.15	-0.43[a]	-0.32	-0.39[a]
CESM2-FV2	0.44[a]	0.51[a]	0.14	-0.79[a]	-0.61[a]	-0.61[a]
CESM2-WACCM	0.21	0.42[a]	0.41[a]	-0.25	-0.20	-0.22
CESM2-WACCM-FV2	0.49[a]	0.44[a]	0.22	-0.68[a]	-0.44[a]	-0.48[a]
CNRM-ESM2-1	-0.51[a]	-0.49[a]	-0.46[a]	0.70[a]	0.58[a]	0.62[a]
CNRM-CM6-1	-0.09	-0.09	-0.28	-0.26	0.14	-0.13
EC-Earth3	0.79[a]	0.56[a]	0.44[a]	-0.85[a]	-0.72[a]	-0.73[a]
MRI-ESM2-0	0.29	0.43[a]	0.08	-0.66[a]	-0.54[a]	-0.52[a]
NorESM2-LM	-0.02	-0.07	0.18	-0.06	0.19	0.13
NorESM2-MM	0.32	-0.2	-0.05	-0.27	-0.14	0.00
CanESM5	0.49[a]	0.39[a]	0.04	-0.66[a]	-0.42[a]	-0.43[a]
IPSL-CM6A-LR	0.39[a]	0.36[a]	0.18[a]	-0.48[a]	-0.40[a]	-0.38[a]
CESM LE	0.12[a]	-0.02	-0.03	-0.11[a]	0.07[a]	0.06[a]
Satellite data	0.56[a]	0.42[a]	0.39[a]	-0.58[a]	-0.27	-0.44[a]

Table S4. Correlation coefficients (R-values) between seasonal sea ice transition dates and March sea ice area from 1979–2014. Spring transition dates (melt onset, opening and break-up) are correlated with March mean ice area from the same year, while fall transition dates (freeze onset, freeze-up and closing) are correlated with March mean ice area from the following year. Values with [a] are statistically significant at the 95% confidence level. Correlation coefficients and p-values for models in the first thirteen rows are determined using one ensemble member, for CanESM5 using all 35 ensemble members, for IPSL using all 30 ensemble members and CESM LE using all 40 ensemble members. All values are calculated between 66-84.5°N.

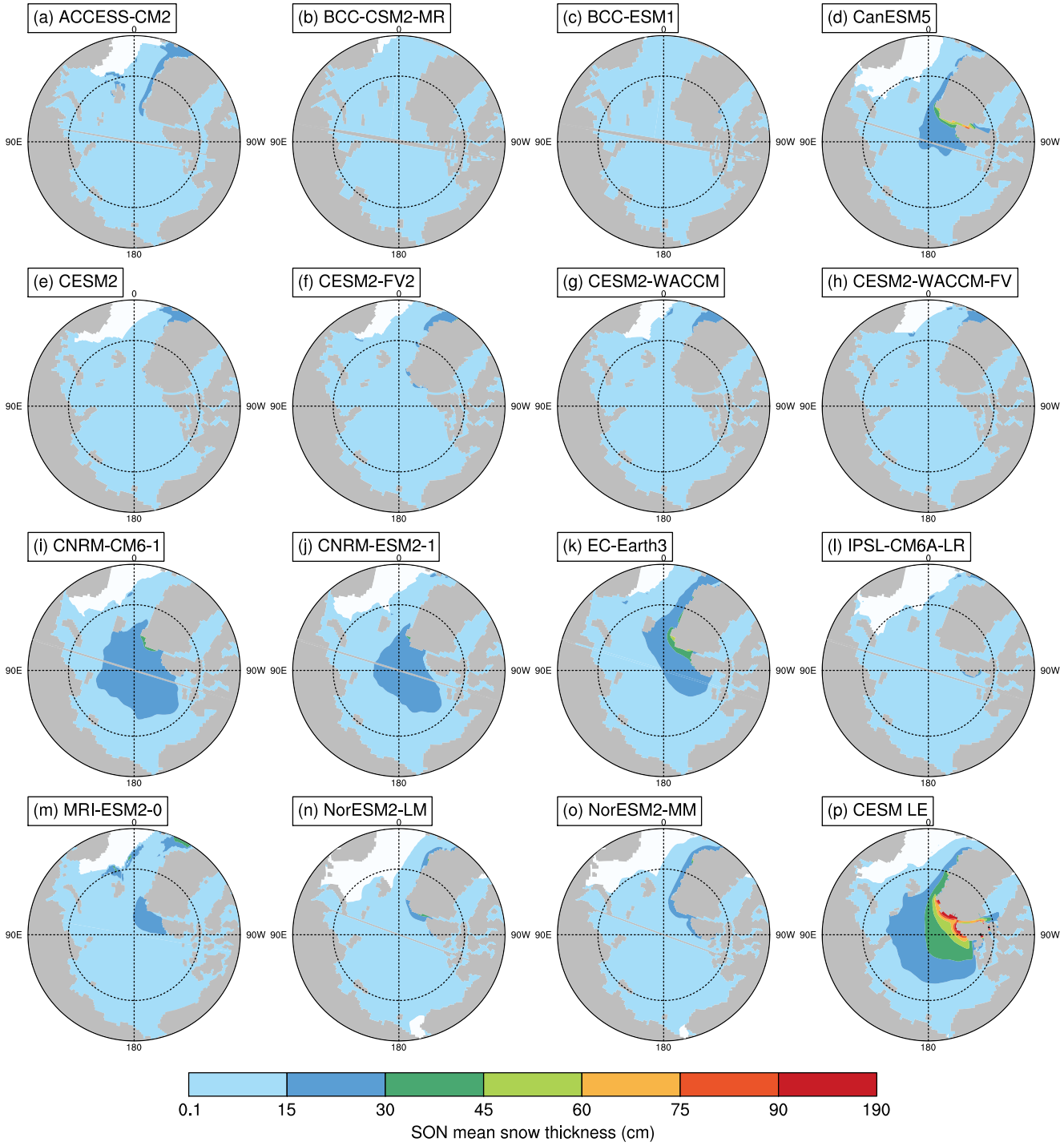

Figure S3. September–November mean snow thickness using the first ensemble member of each CMIP6 model (a-o) and the CESM LE (p) from 1979–2014. Note that the largest contour interval is 100 cm to account for high snow depths in the CESM LE.

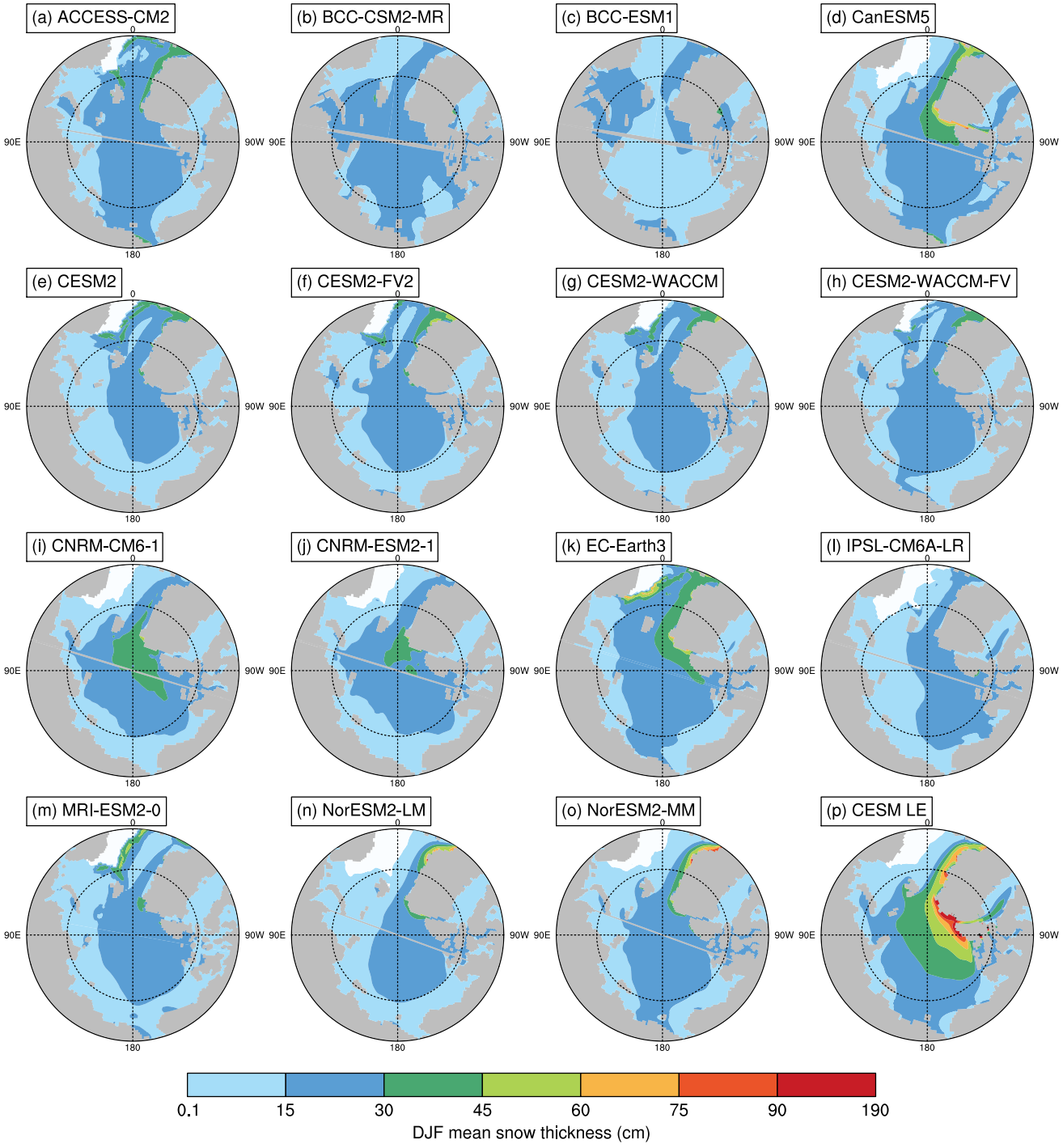

Figure S4. December–February mean snow thickness using the first ensemble member of each CMIP6 model (a-o) and the CESM LE (p) from 1979-2014. Note that the largest contour interval is 100 cm to account for high snow depths in the CESM LE.