Constraining CMIP6, CESM2 AND CESM3 sea ice simulations with ICESat-2

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Use new observations from ICESat-2 to constrain CMIP6



Model plausibility: obs uncertainty and internal variability

Plausible range:

$$P = +/-2\sqrt{(\sigma_{int}^2 + \sigma_{obs}^2)}$$

$$\phi = |\overline{mod} + \overline{obs}|/\sqrt{(\sigma_{int}^2 + \sigma_{obs}^2)}$$



Variable	Low/high unc
Sea ice area (million km ²)	0.5 / 1.0
Total freeboard (cm)	1.5 /3.0
Winter Arctic thickness (cm)	15/30

*Heuristic (very educated guesses!) from synthesized lit review.

Plausibility assessments (lots of them)



Plausibility assessments (lots of them)



Plausibility across metrics

- Models ranked by mean plausibility across all 15 metrics with CMIP6 mean listed at the top.
- More implausible SO results as expected but some quite plausible models!
- CESM2/CESM2-WACCM one of the better performing over both hemispheres.
 - Late summer low sea ice bias \bigcirc kinda evident in our metrics...

			Arctic Ocean					Southern Ocean									
	Area		Fr	eeboa	rd	Tł	nickne	SS		Area		Fre	eeboa	ard			
CMIP60.0	0 -0.3	0.5	0.1	-1.8	0.2	-0.2	-0.8	-0.1	-2.4	-3.2	-1.3	-3.0	-2.2	-4.3			
ACCESS-ESM1-50.8	3 -0.7	-0.3	-0.8	-2.5	-0.4	-1.0	-1.7	-0.8	-1.1	-1.7	-0.5	-0.4	0.5	0.6			
TaiESM1 – 0.6	0.0	0.4	2.2	0.5	2.1	1.1	1.2	1.2	-0.2	-1.5	-0.4	0.5	1.5	-3.1			c
CESM2-WACCM - 0.2	-1.3	0.5	-1.0	-2.7	-1.2	-0.9	-1.6	-0.8	-0.4	-1.6	-0.7	-0.7	0.0	-3.3			- 6
NorESM2-LM - 0.7	0.2	0.6	0.2	-0.1	0.0	0.6	1.3	0.6	-3.0	-4.6	-0.8	-3.0	-2.1	-0.9			
CESM2 - 0.2	-1.7	0.8	-1.0	-3.0	-1.0	-0.9	-1.7	-0.8	-0.8	-2.0	-0.9	-1.0	-0.2	-3.5			
UKESM1-0-LL - 0.6	0.7	0.5	2.6	0.1	2.8	2.2	1.1	2.2	-0.4	-1.8	0.3	0.2	1.4	-3.5			
MRI-ESM2-01.3	3 -2.1	-0.3	-1.5	-3.5	-1.5	-1.9	-2.5	-1.6	1.8	2.5	0.3	0.0	0.7	0.3			
CanESM5 – -1.3	1 -0.6	-0.8	-0.2	-0.9	-0.2	-0.6	0.2	-0.8	2.1	1.5	2.1	3.2	3.7	3.7		-	- 4
GFDL-CM4 - 1.5	1.3	1.6	0.2	-2.5	0.2	-0.7	-1.4	-0.6	-0.2	1.3	-1.8	-2.6	-1.9	-6.0			
CNRM-CM6-1 - 1.2	0.8	1.5	-0.3	-1.6	-0.2	-1.9	-2.6	-1.9	-1.0	0.2	-1.9	-2.8	-1.6	-5.8			
FIO-ESM-2-02.0	0 -3.7	-0.3	-1.6	-4.0	-1.4	-1.6	-2.7	-1.1	-0.4	-1.4	-0.5	0.1	1.0	-3.8			
CanESM5-10.8	3 -1.1	-0.1	-0.6	-1.8	-0.6	-1.1	-0.7	-1.2	2.1	1.2	2.4	3.3	3.7	5.2			
IPSL-CM6A-LR1.2	2 -2.6	0.6	-1.8	-3.9	-1.6	-1.6	-2.6	-1.1	0.7	1.8	-0.6	2.0	3.1	-0.9			
ladGEM3-GC31-LL1.2	2 -2.8	-0.2	-0.8	-4.2	-0.5	-0.9	-3.0	-0.5	-1.8	-3.4	-1.0	-1.7	-0.4	-4.6		-	- 2
ACCESS-CM2 - 0.8	-0.3	1.8	1.2	-1.6	1.1	1.0	-0.8	1.1	-2.5	-3.1	-1.9	-3.1	-2.1	-5.7			
GFDL-ESM4 – -0.3	3 -0.3	-0.6	-1.0	-3.4	-0.9	-1.4	-2.5	-1.2	-1.8	-1.4	-1.6	-3.9	-3.3	-5.6			
CNRM-CM6-1-HR - 0.8	0.4	0.9	-1.1	-2.2	-1.4	-2.1	-2.8	-2.1	-1.9	-1.3	-2.2	-4.2	-3.2	-6.4			
EC-Earth3-Veg – -0.1	L 0.2	-0.0	1.3	0.2	1.0	1.3	1.5	1.4	-4.5	-5.4	-2.1	-5.1	-4.4	-5.5			
MPI-ESM1-2-HR1	/ -2.0	-0.9	-0.4	-3.3	0.2	-0.8	-2.4	-0.6	-3.4	-2.8	-2.2	-4.1	-3.3	-6.4			
CNRM-ESM2-1 = 0.9	-0.0	1.6	-1.1	-2.6	-0.9	-2.2	-2.9	-2.2	-2.8	-2.5	-2.2	-4.2	-3.0	-6.2		-	- 0
FGOALS-f3-L - 0.7	-1./	2.3	-0.4	-3.0	-0.1	-0.4	-1.8	0.0	-3.9	-3.5	-2.3	-5.1	-4.0	-6.5			
NorESM2-MM - 2.2	2.9	1.2	3.3	1.8	3.0	3.4	3.2	3.3	-2.8	-3.6	-0.9	-2.1	-1.6	-0.9			
EC-Earth30.	L 0.4	-0.1	11.7	0.4	1.4	11./	1./	1.8	-4.6	-5.7	-2.2	-5.4	-4.7	-5.8			
MPI-ESM1-2-LR1	L -0.9	-1.0	0.3	-2.3	0.6	-0.1	-1.2	-0.2	-5.2	-6.5	-2.3	-5.8	-5.3	-5.9			
EC-Earth3-CC0.	-0.9	-0.3	-0.6	-1.4	-1.0	-0.6	-0.2	-0.6	-5.8	-7.8	-2.4	-6.4	-6.0	-6.1			2
KIUSI-ESM = 1.3	4.2	-0.7	3.3	1.6	3.8	2.8	2.9	2.5	-3.2	-4.6	-1.8	-4.0	-3.1	-5.0			2
	-3.1	4.9	-2.0	-5.2	-1.0	-1.8	-3.8	-1.4	-2.0	-2.5	-2.0	-4.2	-3.1	-0.6			
CAMS-CSMI-0 - 5.3	4.1	7.5	1.3	-1.7	1.7	0.4	-0.7	0.3	-3.9	-3.1	-2.5	-5.0	-4.6	-0.0			
	3 -4.8	-2.2	-4.5	-5.8	-4.3	-3.3	-4.4	-3.1	-1.8	-2.0	-1.9	-1./	-0.4	-0.3			
BCC-CSM2-MR = 3.1	1.3	4.5	-1.4	-3.9	-1.2	-1./	-2.7	-1.9	-4.3	-0.3	-2.2	-5.9	-5.7	-0.0			
	1 0 0	-0.0	-2.9	-5.5	-2.7	1 2.9	10	1.0	-4.0	-0.2	-2.4	-4.0	-3.5	-0.4			4
	+ 0.0	-2.9	5.4	1.1	5.0	1.2	1.0	1.0	-7.4	-11.5	2.4	-1.2	-7.5	-0.5			
	2 1 1	2.0	-5.4	1.0	-5.4	-4.2	1 0	2.6	77	-2.7	2.0	7.5	-0.7	6.6			
FC-Farth3-Vog-LR = 2.3	3 0	-2.0	5.6	1.0	5.0	2.5	1.9	2.0	-1.6	5 4	2.4	-7.5	-1.7	-0.0			
	2 1 6	-2.4	1.6	3.2	5.1	3.5	3.5	3.4	-4.0	-11.2	-2.2	-7.0	-4.5	-5.5			
CanESM5-CanOE = -1	3 -0.9	-0.8	4.0	5.2	5.1	5.4	5.0	J.2	1 9	13	1 9	7.0	7.0	0.4			
INM-CM5-00 (14	-0.5	(i .			-3.3	-4 4	-1.6					-	6
EGOALS-03 - 3 0	5 2	24	i						10	19	0.1						
INM-CM4-8 - 2 8	3.7	27							-5.0	-6.9	-2.2						
		1	· .	1	1	' i .	1	1	5.0	0.5	1	' I -	1	1			
AII	eb	lar	All	eb	lar	All	eb	lar	All	eb	lar	A	eb	lar			
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Plausibility Index

Had

Plausibility across metrics

Impacts of constraints on CMIP6 mean seasonal cycle and regional plausibility analysis described in our preprint :

Petty, A. A., C. Cardinale, M. Smith, <u>Constraining CMIP6 sea ice simulations with ICESat-2</u>, EGUsphere (preprint), 2025-766, doi: 10.5194/egusphere-2025-766, in review at Geoscientific Model Development (GMD).

Now working to add in more CESM models..!

Adding more CESM

- Access to CESM2-lessmelt and CESM3 development runs on Deracho (thanks Dave & Alice!).
- CESM2-lessmelt performs the best now, but it was calibrated to do so..! (Kay et al., 2022)
- The dev runs show a mixed response, we see some evidence of the positive bias in SO area but decent performance overall? Short time-period...

		Arctic Ocean						Southern Ocean									
Г	Area		Fr	eeboa	ard	t Th	nickne	SS		Area		Fre	eeboa	rd			
CESM2-lessmelt (7) - 0.	6 -0.3	0.4	-0.1	-2.0	-0.1	-0.2	-0.8	-0.2	0.1	-1.2	-0.1	0.4	1.1	-1.5			
ACCESS-ESM1-5 (40)0	9 -0.7	-0.4	1-0.8	-2.0	-0.4	1-1.0	-1./	-0.8	-1.1	-1./	-0.5	-0.4	0.5	0.6			
	0 0.0	0.4	12.2	0.5	2.1	1.2	1.5	1.2	-0.2	-1.5	-0.4	0.5	1.5	-3.2			6
CESM2-WACCM(3) = 0.	2 -1.5	0.5	-1.0	-2.7	-1.2	-0.9	-1.0	-0.8	-0.4	2.0	-0.7	-0.7	1.0	-3.4			0
NorESM2 M (6) - 0	8 03	0.8	0.9	-1./	0.1	0.7	13	1.0	3.01	2.2	-0.9	3.0	2.1	-0.6			
Multi-Model Mean - 0	1 0.5	0.1	0.2	-2.0	0.1	0.0	1.5	0.0	2.2	20	1 3	-3.0	1 0	-0.0			
CESM2(3) = 0	2 - 17	0.4	-1.0	-2.0	1.1.1	-1.0	-1.8	-0.2	-0.8	-2.9	-0.0	-1.0	-0.2	-4.5			
$UKESM1_0_U (5) = 0$	6 07	0.6	27	0.2	3.0	2.2	12	23	-0.0	-1.8	03	0.2	14	-3.6			
AWI-CM-1-1-MR (1) = -1	7 .24	-0.0	-12	-3.9	-0.4	-15	-2.0	-1.5	0.0	0.9	-13	-1 3	-0.8	-25			
MRL-ESM2-0 (5)1	3 -2 1	-0.3	-16	-3.5	-15	-2.0	-2.5	-17	1.8	2.5	03	0.0	0.7	0.4		-	- 4
CanESM5(25) = -1	1 -0.6	-0.8	-0.2	-1.0	-0.3	-0.6	0.2	-0.8	21	1.5	21	32	3.7	39			
HadGEM3-GC31-LL (2)0	8 -2 2	0.1	-0.6	-3.5	-0.4	-0.6	-24	-0.3	-17	-3.2	-0.9	-15	-0.1	-47			
CESM2-LE (50)0	5 -2.3	0.0	-1.6	-3.7	-1.5	-1.4	-2.5	-1.3	-0.9	-2.2	-0.9	-1.0	-0.3	-3.6			
GFDL-CM4 (1) - 1.	6 1.3	1.6	0.2	-2.5	0.3	-0.7	-1.5	-0.6	-0.2	1.3	-1.8	-2.6	-1.9	-6.2			
CNRM-CM6-1 (6) - 1.	2 0.8	1.5	-0.3	-1.6	-0.2	-1.9	-2.6	-1.9	-1.0	0.2	-1.9	-2.8	-1.6	-6.0			
FIO-ESM-2-0 (3)2	1 3.8	-0.3	-1.6	-4.1	-1.4	-1.7	-2.7	-1.1	-0.4	-1.4	-0.5	0.1	1.0	-3.9			2
IPSL-CM6A-LR (11)1	2 -2.6	0.6	-1.8	-4.0	-1.6	-1.7	-2.6	-1.1	0.7	1.8	-0.6	2.0	3.2	-0.9		_	2
CanESM5-1 (20)0	9 -1.1	-0.1	-0.7	-1.8	-0.6	-1.1	-0.7	-1.3	2.7	2.0	2.7	3.3	3.7	5.4			
GFDL-ESM4 (3)0	3 -0.3	-0.6	-1.0	-3.5	-0.9	-1.4	-2.5	-1.2	-1.8	-1.4	-1.7	-3.9	-3.3	-5.8			
ACCESS-CM2 (10) - 0.	6 -1.0	1.8	0.5	-2.5	0.5	0.4	-1.6	0.6	-2.8	-3.5	-2.0	-3.4	-2.4	-6.2			
ESM-dev121pond (1)1	.6 -4.2	-0.0	-1.7	-5.6	-1.1	-1.5	-4.2	-0.7	2.0	2.7	-0.6	0.7	1.5	-3.7			
CNRM-CM6-1-HR (1) - 0.	8 0.4	1.0	-1.2	-2.2	-1.4	-2.1	-2.8	-2.1	-1.9	-1.3	-2.2	-4.2	-3.2	-6.6			
EC-Earth3-Veg (6)0	.1 0.2	-0.0	1.3	0.2	1.1	1.3	1.5	1.4	-4.5	-5.5	-2.1	-5.1	-4.4	-5.6		-	0
MPI-ESM1-2-HR (2)1	.7 -2.0	-1.0	-0.4	-3.4	0.2	-0.8	-2.4	-0.6	-3.4	-2.8	-2.2	-4.1	-3.3	-6.6			
CNRM-ESM2-1 (6) - 0.	9 -0.0	1.6	-1.1	-2.6	-0.9	-2.3	-3.0	-2.2	-2.8	-2.5	-2.2	-4.3	-3.0	-6.4			
FGOALS-f3-L (1) - 0.	7 -1.7	2.4	-0.4	-3.1	-0.1	-0.4	-1.8	0.0	-4.0	-3.5	-2.3	-5.1	-4.0	-6.7			
NorESM2-MM (2) - 2.	3 2.9	1.3	3.4	1.8	3.0	3.5	3.3	3.3	-2.8	-3.6	-0.9	-2.7	-1.6	-0.9			
EC-Earth3 (26)0	.1 0.4	-0.1	1.7	0.4	1.5	1.7	1.7	1.8	-4.6	-5.7	-2.2	-5.4	-4.8	-5.9			
MPI-ESM1-2-LR (30)1	.2 -0.9	-1.1	0.3	-2.2	0.6	-0.2	-1.2	-0.2	-5.2	-6.3	-2.3	-5.8	-5.2	-6.1			-
EC-Earth3-CC (1)1	.1 -1.0	-1.0	-0.7	-1.4	-1.0	-0.6	-0.2	-0.6	-6.0	-8.0	-2.4	-6.4	-6.0	-6.3		-	-2
KIOST-ESM (1) - 1.	3 4.3	-0.7	3.4	1.6	3.9	2.9	3.0	2.6	-3.2	-4.6	-1.8	-4.0	-3.1	-5.1			
NESM3 (2) – 1.	7 -3.1	5.0	-2.1	-5.3	-1.6	-1.8	-3.9	-1.5	-2.0	-2.5	-2.0	-4.2	-3.1	-6.7			
CAMS-CSM1-0 (2) - 5.	5 4.1	7.7	1.3	-1.7	1.7	0.4	-0.7	0.3	-3.9	-3.1	-2.5	-5.6	-4.6	-6.8			
CMCC-ESM2 (1)4	.9 -4.8	-2.3	-4.6	-5.9	-4.4	-3.5	-4.5	-3.2	-1.8	-2.0	-1.9	-1.7	-0.4	-6.5			
BCC-CSM2-MR (1) - 3.	1 1.3	4.6	-1.5	-3.9	-1.2	-1.8	-2.1	-1.9	-4.3	-6.3	-2.2	-5.9	-5.7	-6.8			
MIROC6 (50)1	.5 0.0	-3.0	2.5	1.2	3.1	1.2	1.8	1.0	-7.4	-11.5	-2.4	-7.2	-7.3	-6.7		-	-4
CIESM (1) -	.9 -4.7	-0.8	-3.0	-5.6	-2.1	-2.9	-4.2	-2.1	-4.6	-6.2	-2.4	-4.6	-3.5	-6.6			1
CMCC-CM2-SR5(1) = -6	.1 -4.9	-3.4	-5.6	-5.9	-5.5	-4.3	-4.5	-4.2	-2.1	-2.1	-2.0	-2.2	-0.7	-6.6			
MIROC-ES2L (30)1	.9 -1.1	-2.0	2.1	1.0	3.5	2.3	2.0	2.1	-1.1	-11.9	-2.4	-7.6	-1.1	-6.7	_		
EC-Earth3-Veg-LR (3) - 2.	4 3.0	2.5	5.7	4.3	5.2	5.0	5.0	5.5	-4.0	-5.4	-2.2	-0.3	-4.5	-0.1			
MIROC-ES2H(3) = -0	.2 1.0	-2.2	4.8	3.2	5.2	3.5	3.9	3.3	-1.2	-11.2	-2.4	-/.1	-7.0	-0.0			
EC-Earth3-HR $(1) = -U$	3 -1.2	-0.1				0.3	-0.2	0.4	-0.2	-8.5	-2.4						
CarresMS-Carroe (3) = -1	0 1 4	0.9				1			1.9	1.5	1.9						-6
EGOALS a2(4) = -0	0 1.4	25									0.1						
INM-CM4-8 (1)	8 37	2.5				i			-5.0	-6.9	-2.2						
INIM-CM4-0 (1) - 2.	0 3.7	2.7	· · ·	1	1	· .	1	1	5.0	0.9	-2.2	1	1	1			
	d	a'	₹	d.	a	₹	d	ā	₹	d	a	₹	0	ja I			
7 +	S S	Σ	A	Se	Σ	A	Se	Σ	Ŧ	Se	Σ	Ŧ	Se	Σ			
12	프	득	-	M	M	Ē	M	M	S	H	H	S	H	H			
4	4	A	E	8	8	SI.	느	E	AIS	A	A	E	B	B			
v	SIJ	SIJ		Ē	Ē		S	S	01	SI	SI	F	E	H			

Plausibility Index

CESM2-CMIP6 vs CESM2-LE (time series)



ICESat-2 era shows an interesting positive bias in CESM2-CMIP6 (red)

Exploring impact of small ensemble size

Inspired by emails with Marika/Alice/Dave!

- Compare CESM2-LE (50+ members) and CESM2-CMIP6 (3 members)
 same forcing, but initialized a little differently...
- Use Bootstrapping applied to CESM2-LE (50 mems)
 - Randomly sample
 3-member means for
 CESM2-LE and
 compare with
 CESM2-CMIP6
 - Repeat for metrics & plausibility scores.



Exploring impact of small ensemble size

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- Compare CESM2-LE (50+ members) and CESM2-CMIP6 (3 members)
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 - Repeat for metrics & plausibility scores.



New work: Sea ice melt in CMIP6/CESM

Model		Pond scheme	Albedo scheme
ACCESS-CM2	CICE5.1.2	<i>Topographic (Flocco et al., 2012)</i>	Dual band (CCSM3)
CESM2-LE	CICE5.1.2	Level ice (Hunke et al., 2013)	delta-Eddington
HadGEM3-GC31	CICE5.1.2	<i>Topographic (Flocco et al., 2012)</i>	Dual band (CCSM3)
NorESM2-LM	CICE5.1.2	Level ice (Hunke et al., 2013)	delta-Eddington
NorESM2-MM	CICE5.1.2	Level ice (Hunke et al., 2013)	delta-Eddington
UKESM1-0-LL	CICE5.1.2	<i>Topographic (Flocco et al., 2012)</i>	Dual band (CCSM3)

5 CMIP6 models + CESM2-LE provide outputs of sea ice melt pond coverage (all CICE)

New work: Sea ice melt in CMIP6/CESM



5 CMIP6 models + CESM2-LE provide outputs of sea ice melt pond coverage (all CICE)

New work: Sea ice melt in CMIP6/CESM



CESM2-LE similar to multi-model mean but much higher than the obs (Sentinel-3 based MPD2).

Quick shout-outs..

- We have all-season/dual-hemisphere ICESat-2 freeboard down to 50% SIC but just winter (September to April) Arctic sea ice thickness estimates.
 - Trying to increase ICESat-2 coverage down to 0% SIC using fancy interpolation schemes (Gregory et al., 2024)
 - Also working on all-season thickness estimates from ICESat-2, showing good agreement with CryoSat-2/validation data.

Petty, A. A., A. Cabaj, J. Landy, <u>Initial assessment of all-season Arctic sea ice thickness from ICESat-2</u>, submitted to Journal of Glaciology (preprint hosted on EarthArXiv). Thickness data available on <u>Zenodo</u>.

• Working towards all-season ICESat-2 sea ice volume! Getting there...

Summary

- We have a sea ice plausibility framework in place to assess CMIP-like sea ice output with estimates of sea ice area, freeboard and thickness.
 - Can combine with existing longer-term analyses.
- Freeboard is proving to be a useful extra diagnostic
 - v. reliable and available across all months and hemispheres.
- Looking into ensemble size/internal variability concepts in preparation for CMIP7 analysis.
 - Impacts of extra years of IS-2 vs CS-2 data.
- Related projects on sea ice melt and improved all-season IS-2 data showing promise!

Extra



CESM2-CMIP6 vs CESM2-LE (Arctic, 2018-2024)



CESM2-CMIP6 vs CESM2-LE (Arctic, 2025-2030)

