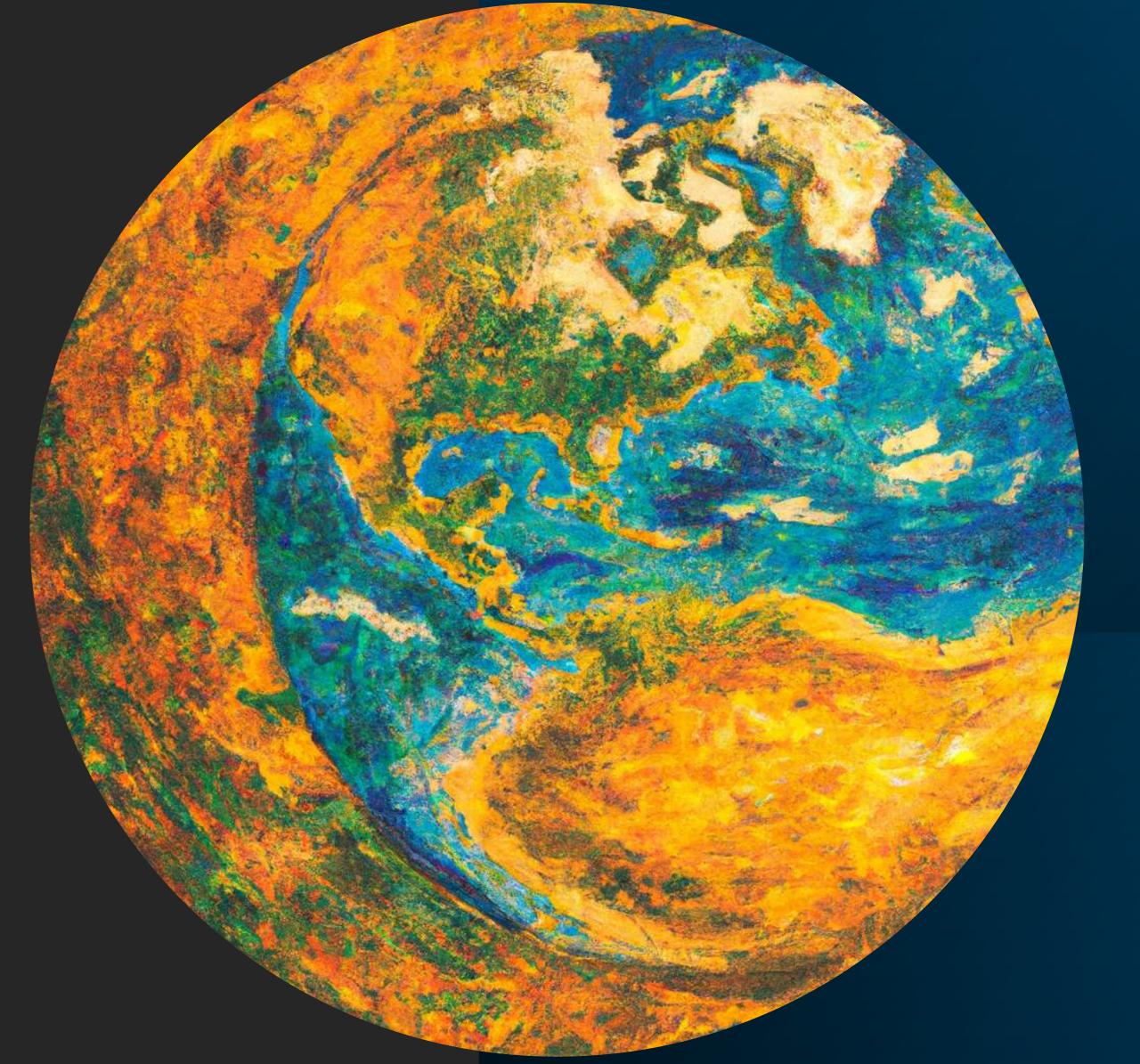
Assessing the Performance of CTSM in Simulating **Arctic Permafrost Regions** and its Sensitivity to **Atmospheric Forcings and Soil Properties**

Adrien Damseaux Heidrun Matthes





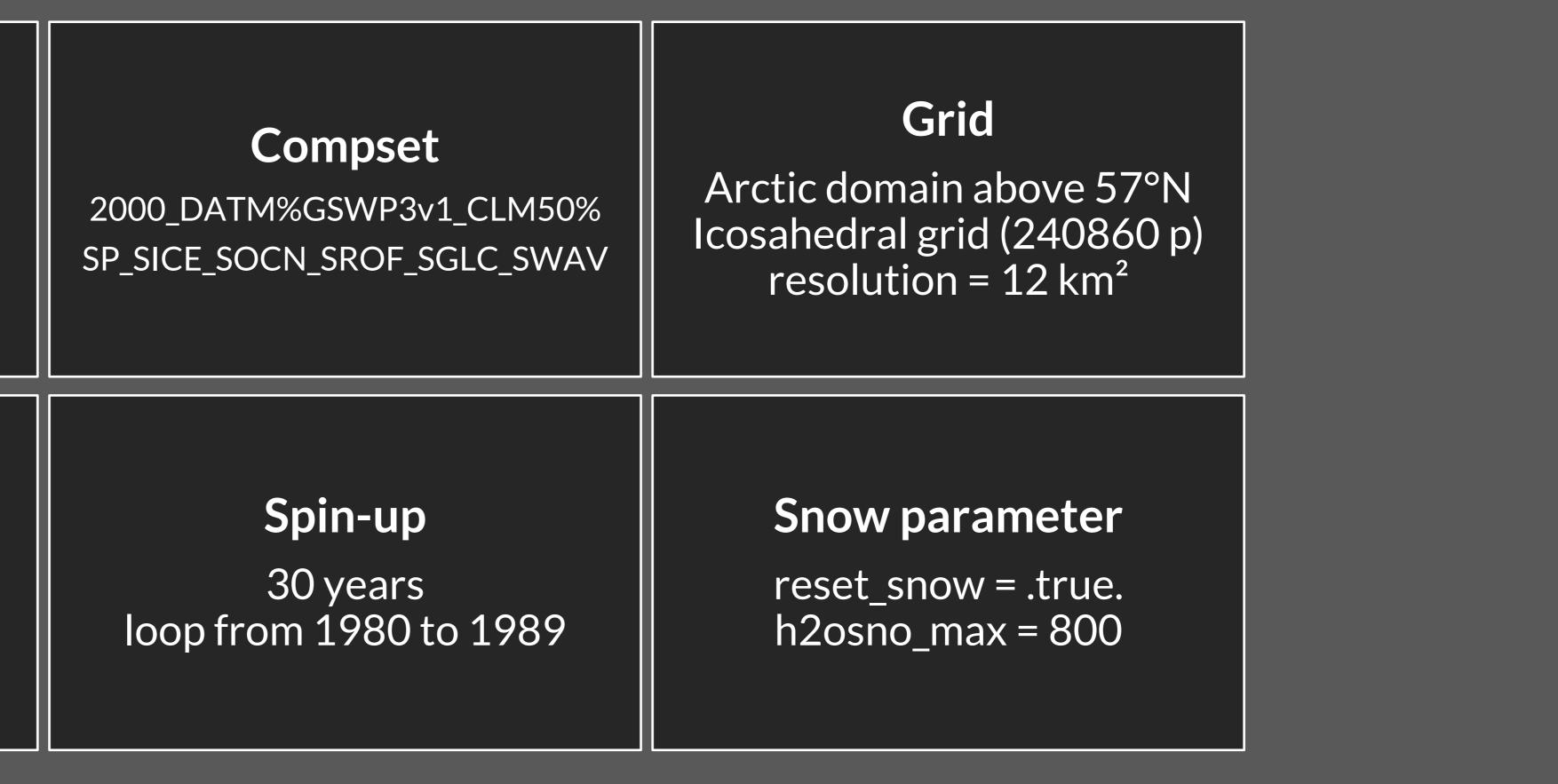
a Van Gogh painting of a globe over the Arctic by Dall-E

CTSM version 5.1.dev086

Atmospheric forcings

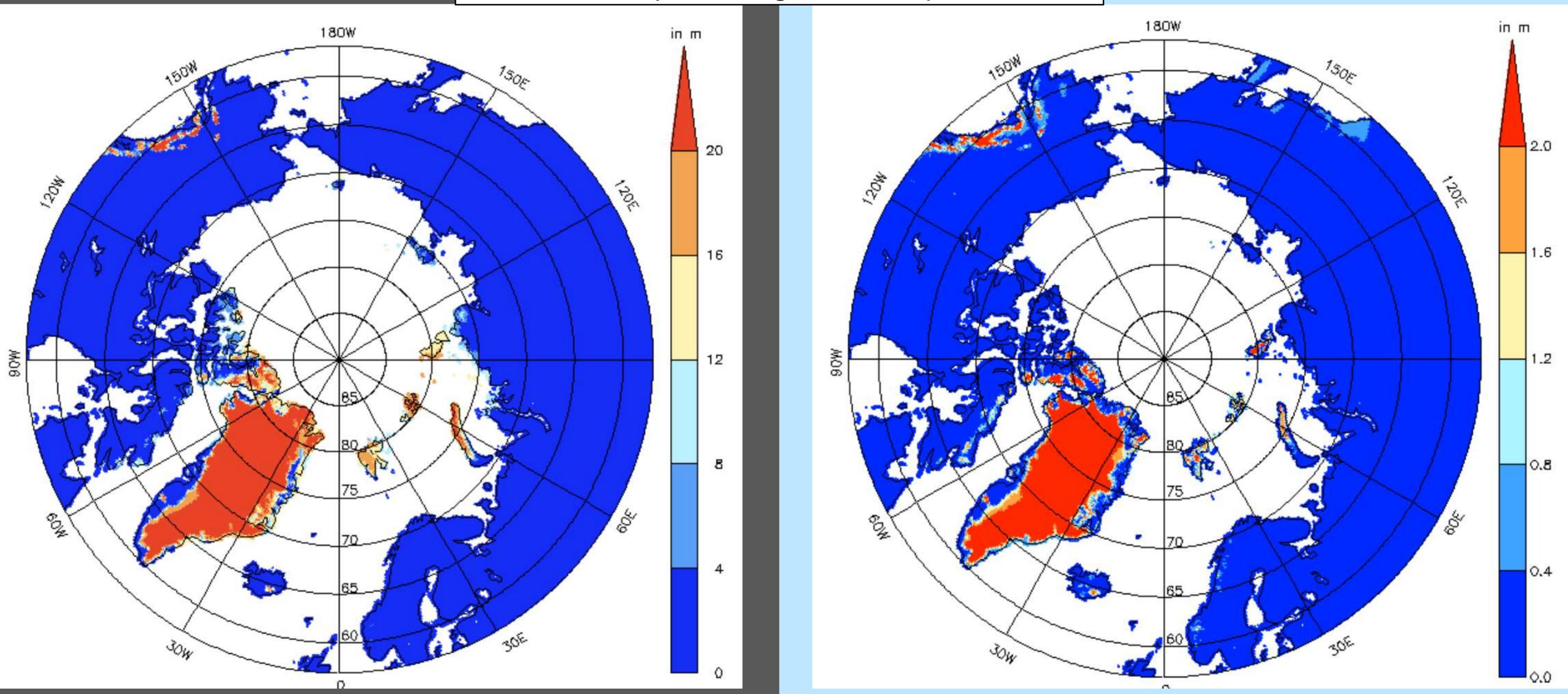
ERA5 from 1980-2021

Model setup





Default snow parameters Reset_snow = false h2osno_max = 10 m



Adjusted snow parameters Reset_snow = true h2osno_max = 0.8 m

Snow depth average in January 1980

ESACCI products

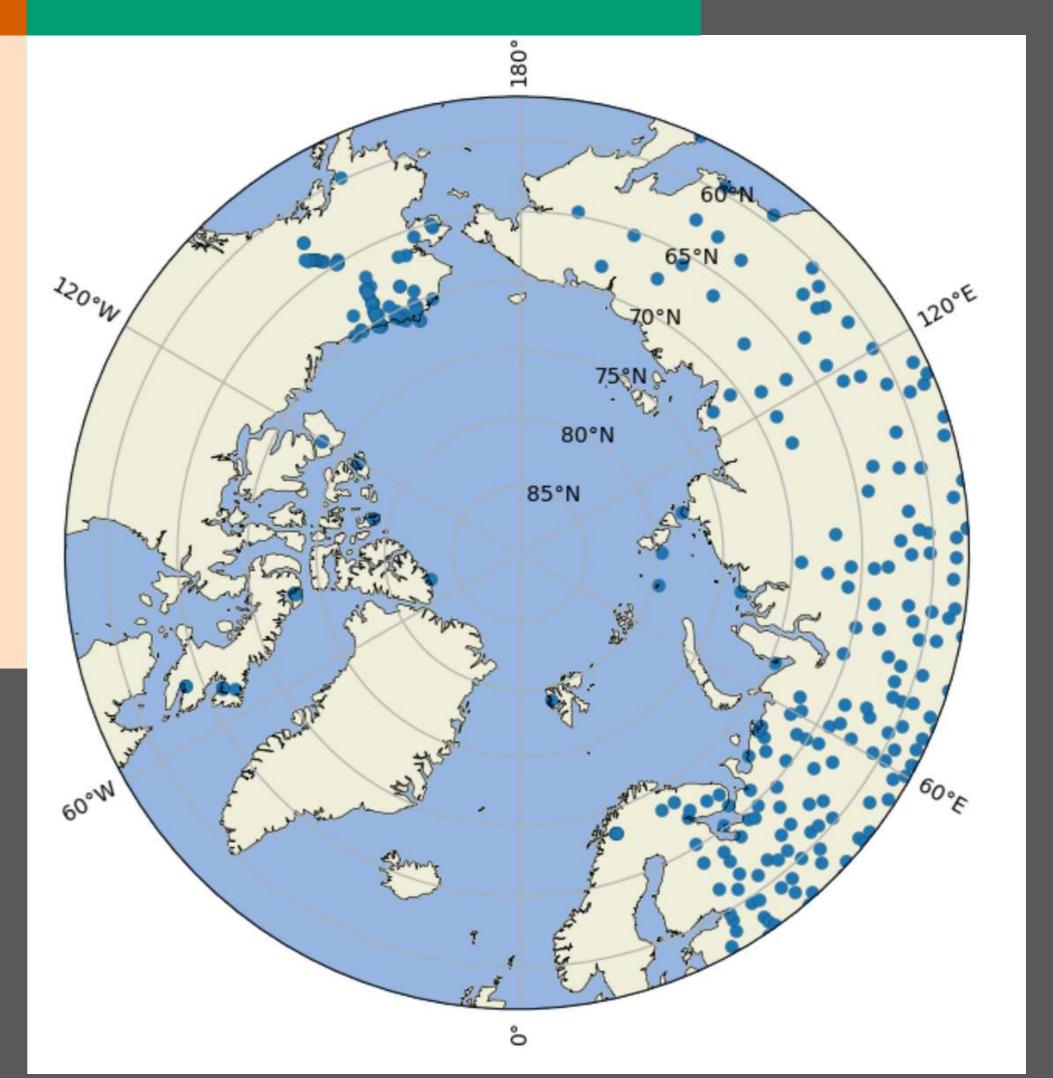
- From the ESA Climate Change • Initiative
- Remote sensing products
- Soil temperature (at 1, 5 and 10m), ALT and PFR extent
- Year averages (1997-2019)
- Period averaged
- Domain resolution 1 km²

Observation products

CALM network

In-situ observations

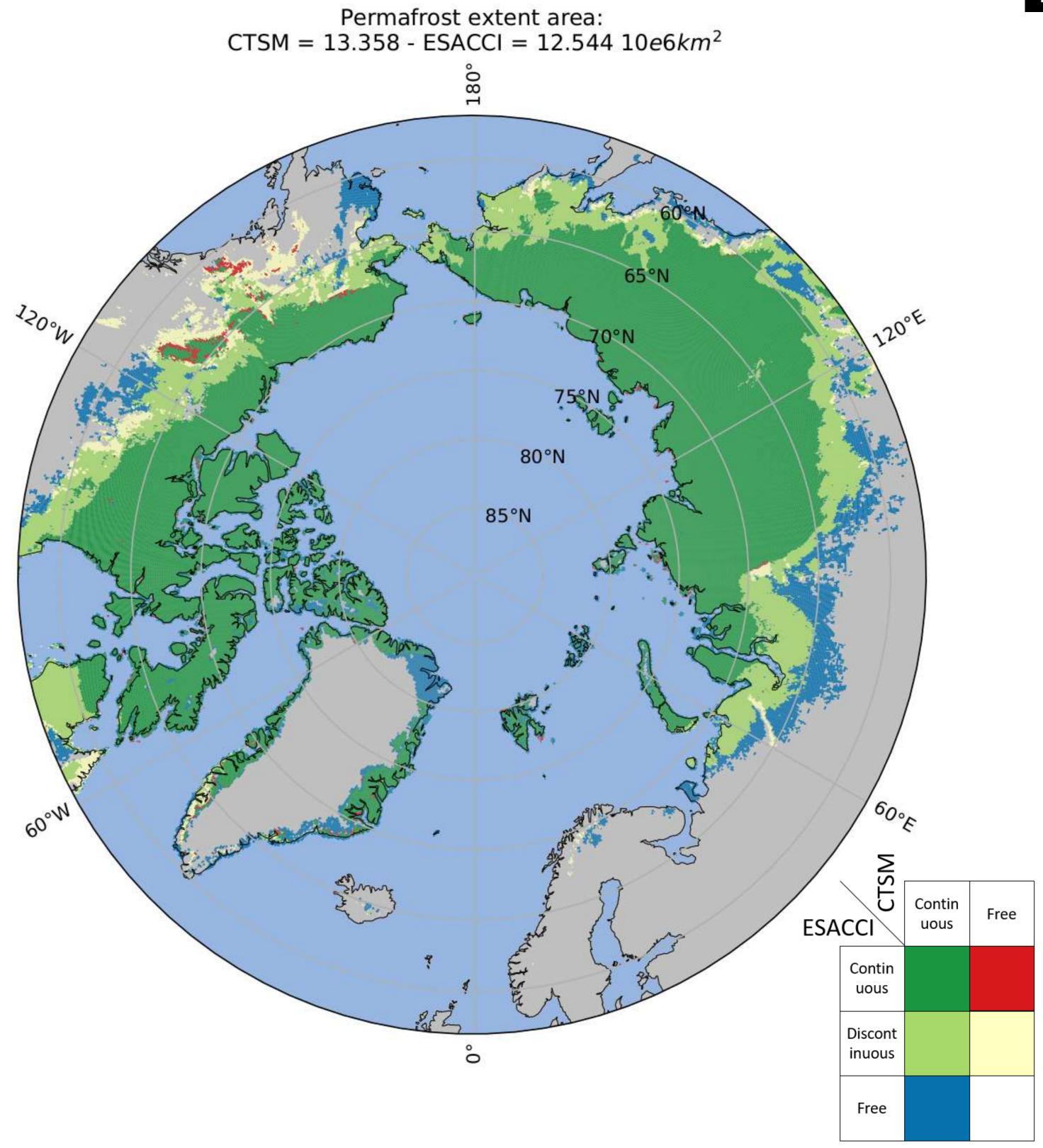
- **Circumpolar Active Layer** Monitoring (CALM) network
- 98 stations
- Active Layer Thickness (ALT) column
- Year averages (1991-2021)
- Period averaged





Permafrost extent mask difference CTSM – ESACCI

- Strong agreement with ESACCI (93%)
- Slight overestimation of the permafrost extent, mostly in Siberia

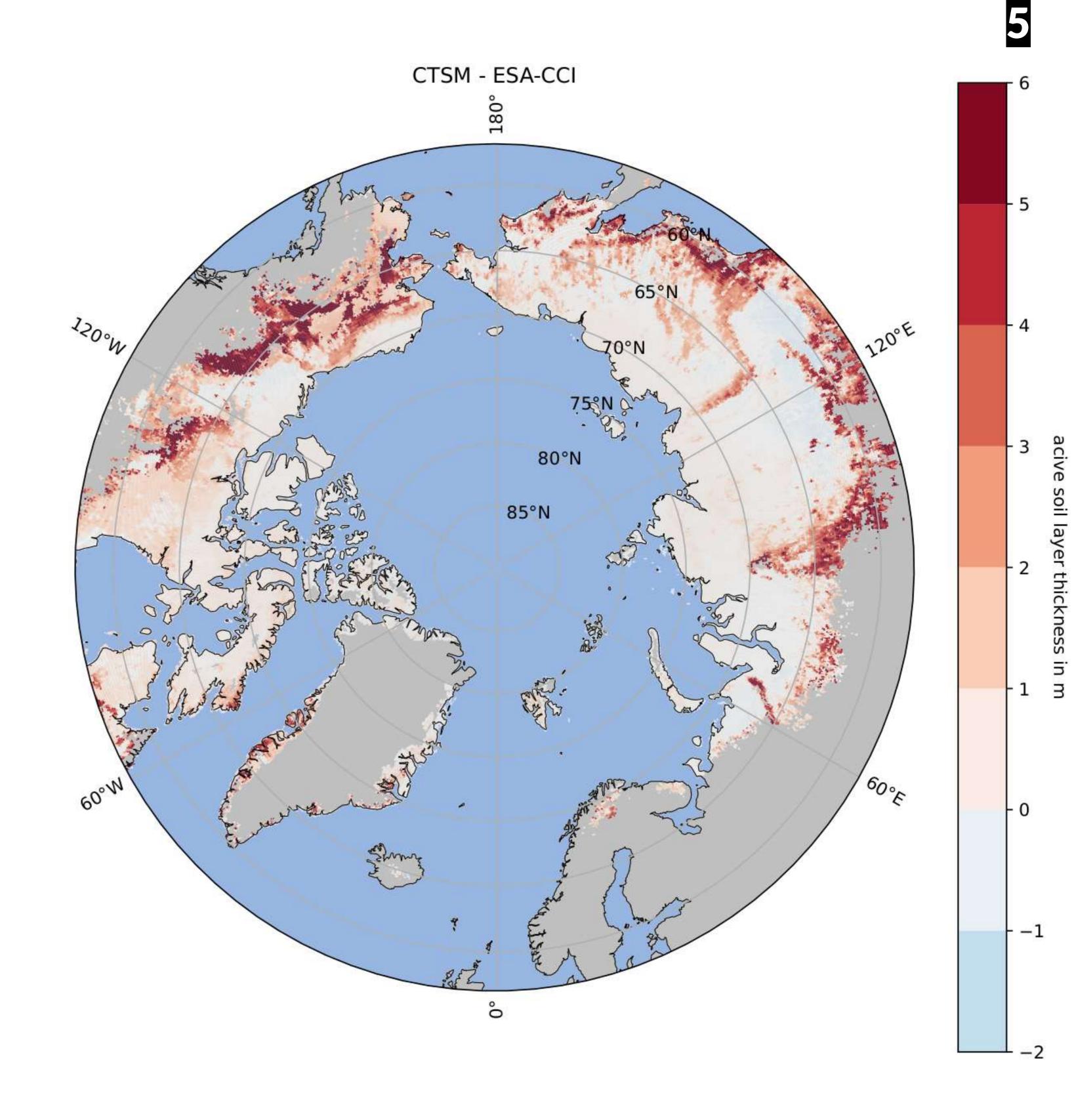






Active Layer Thickness difference CTSM - ESACCI

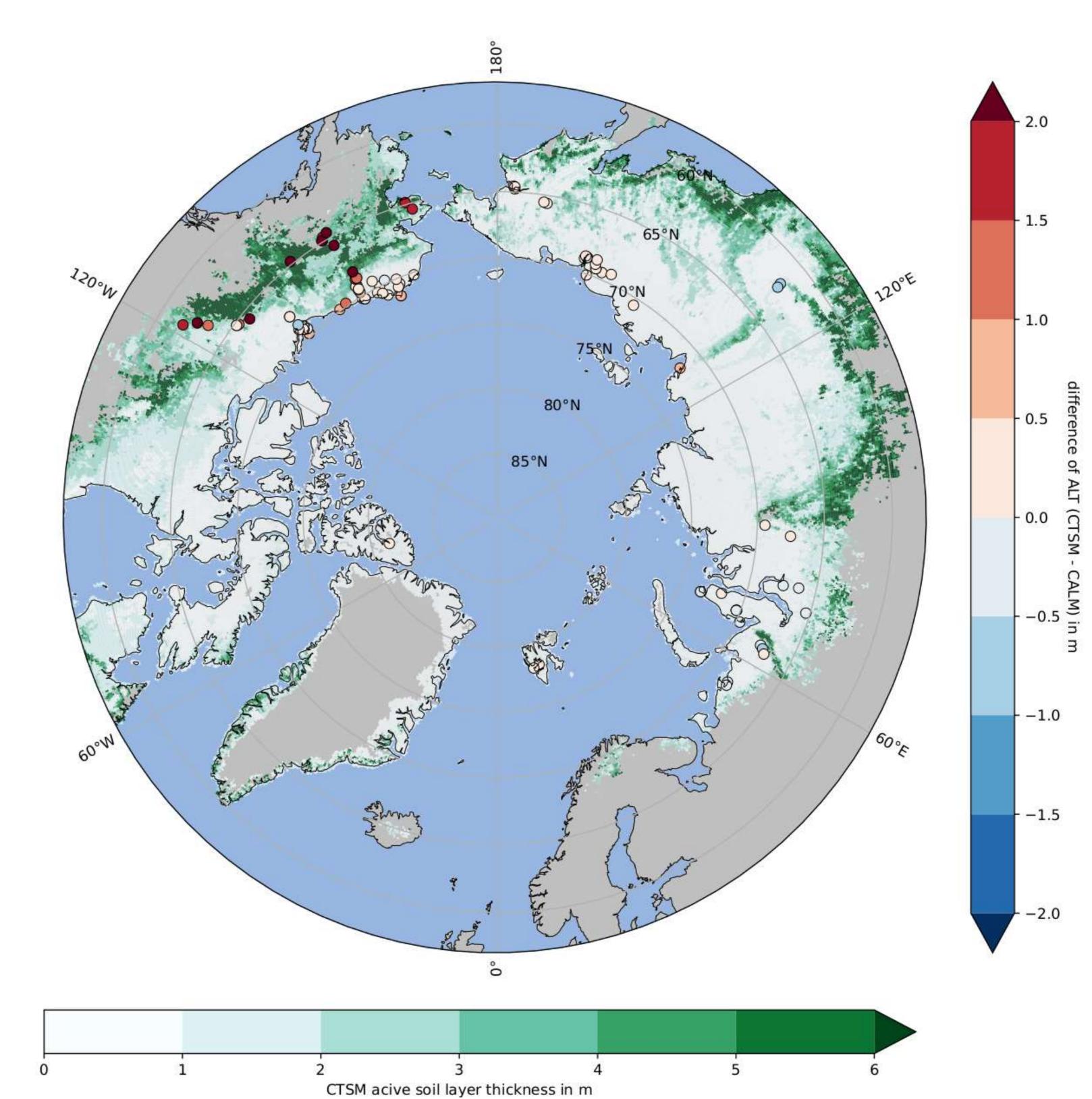
- Above 65°N, CTSM is within 1 m of ESACCI
- CTSM overestimates ALT in warm permafrost regions (borders)





Active Layer Thickness difference CTSM - CALM

- Same conclusion as ESACCI comparison
- Unfortunately, no station in warm
 permafrost over Siberia

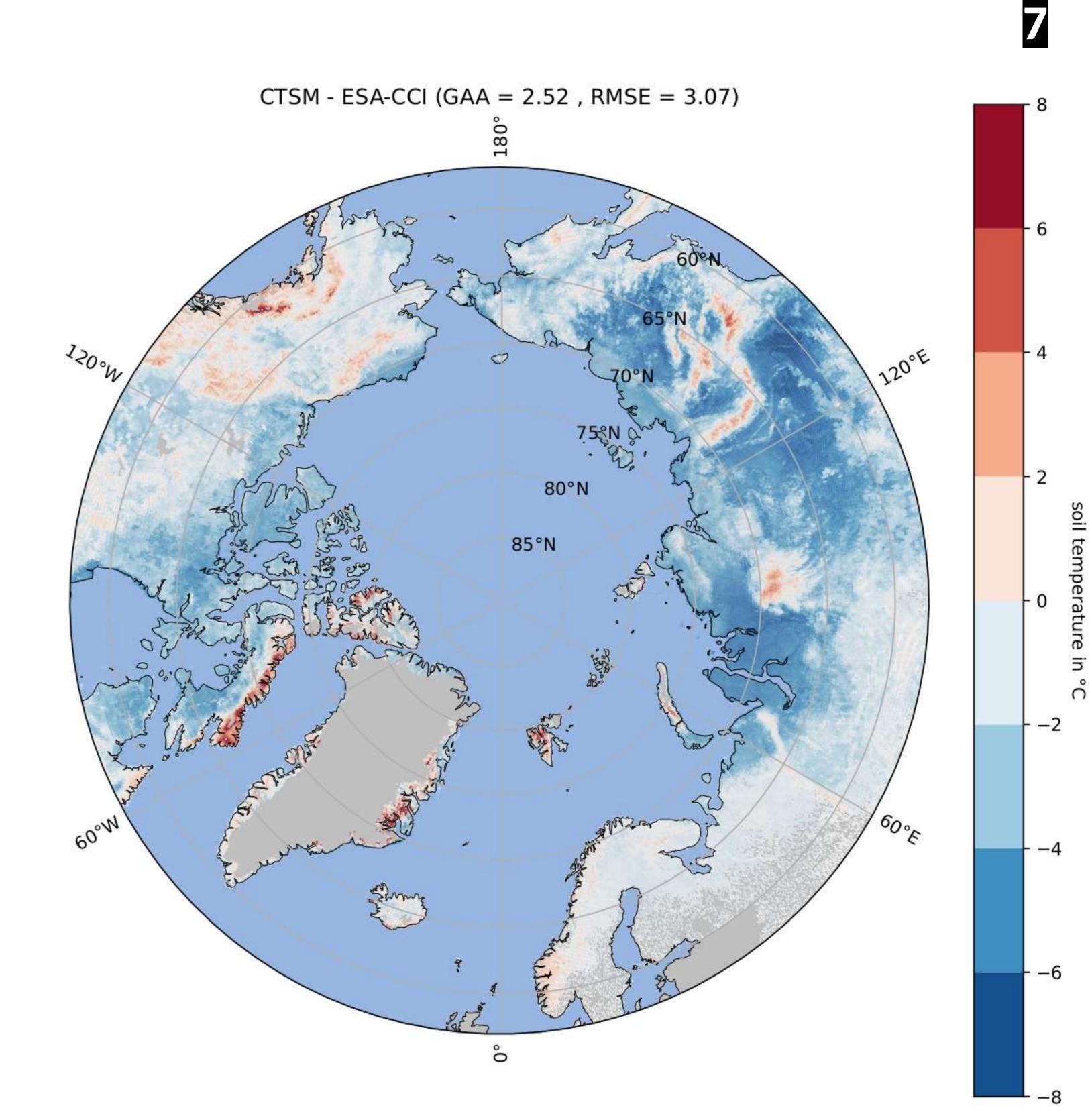


6



Soil temperature difference at -1 m CTSM – ESACCI

- Strong cold difference, up to -8°C in Siberia
- More significant over Siberia, less over Canada
- Same in -5 and -10 m (additional slides)

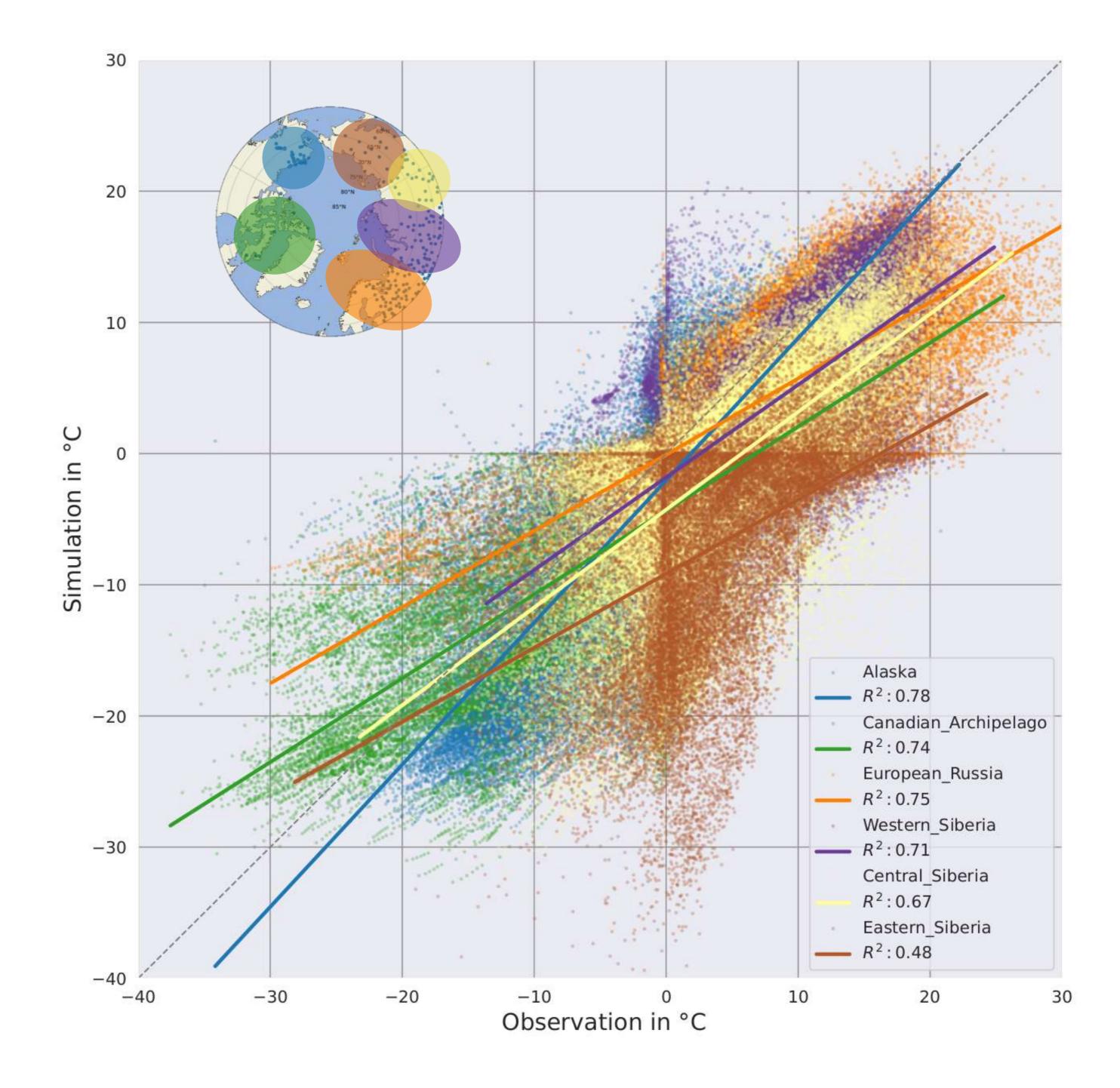




a cube consists of 1 million smaller cubes containing observations data by Dall-E

Soil temperature difference CTSM – In-situ Region clustering

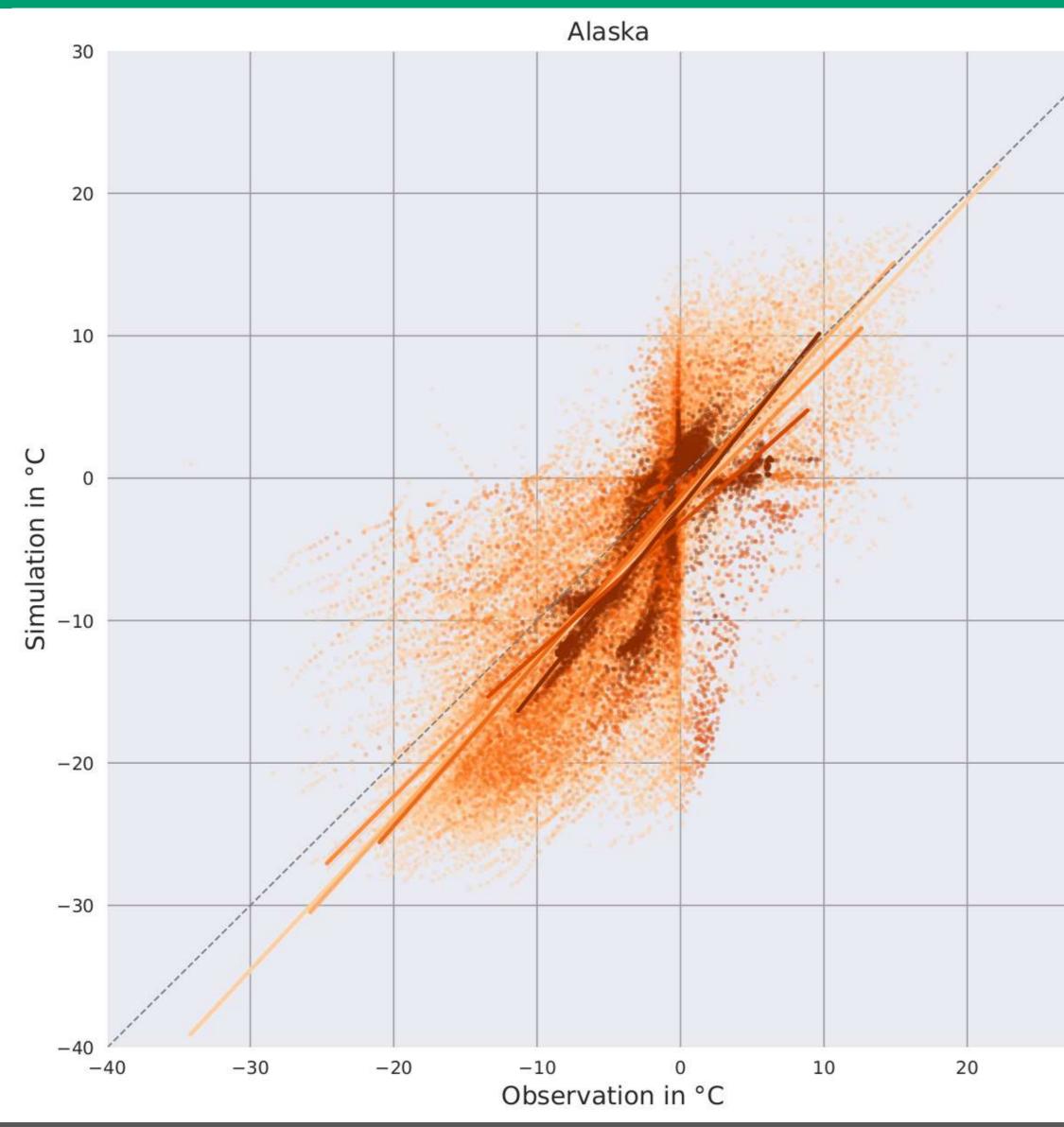
- R² highly dependent on regions
- Linear gradient from west with high coefficient to east with low coefficient

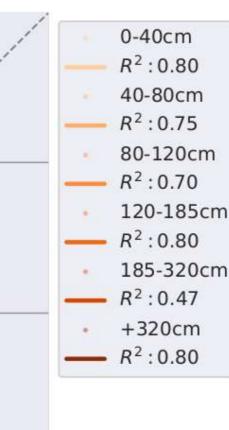


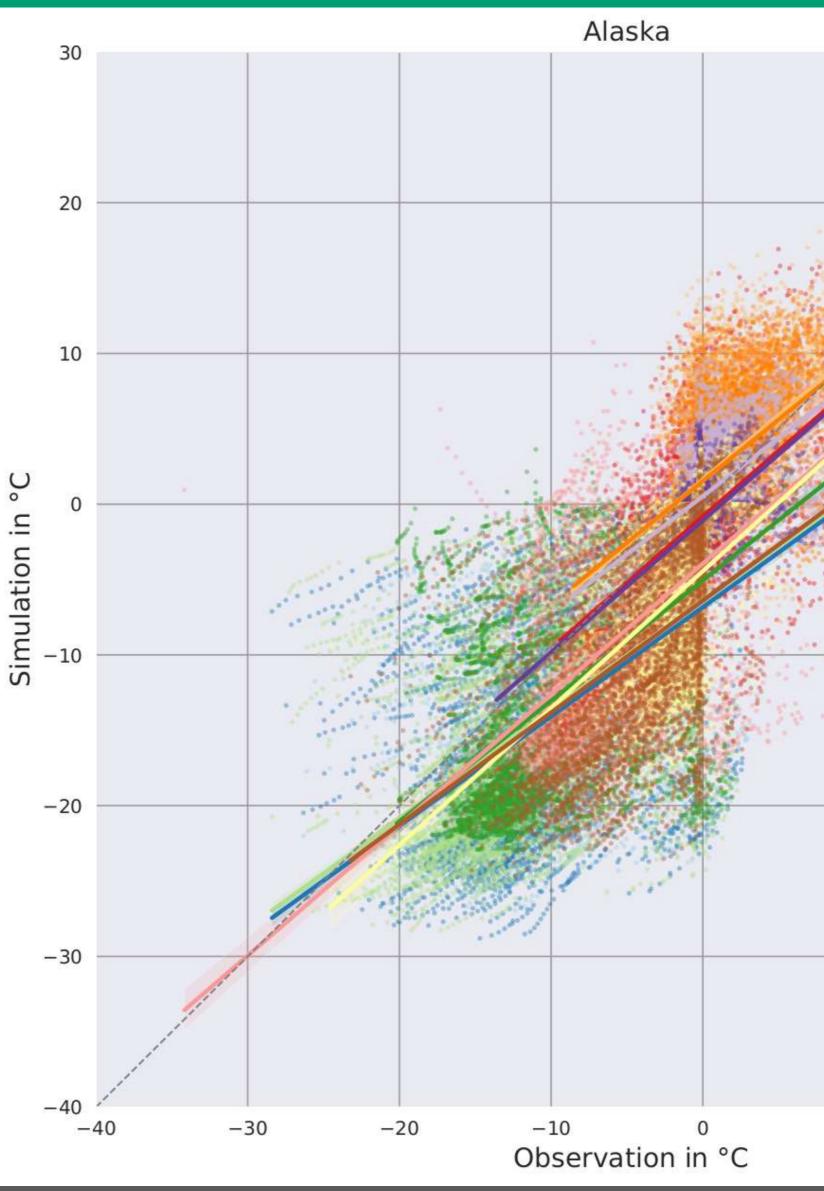
In-situ

Soil temperature difference only for Alaska

Depth clustering







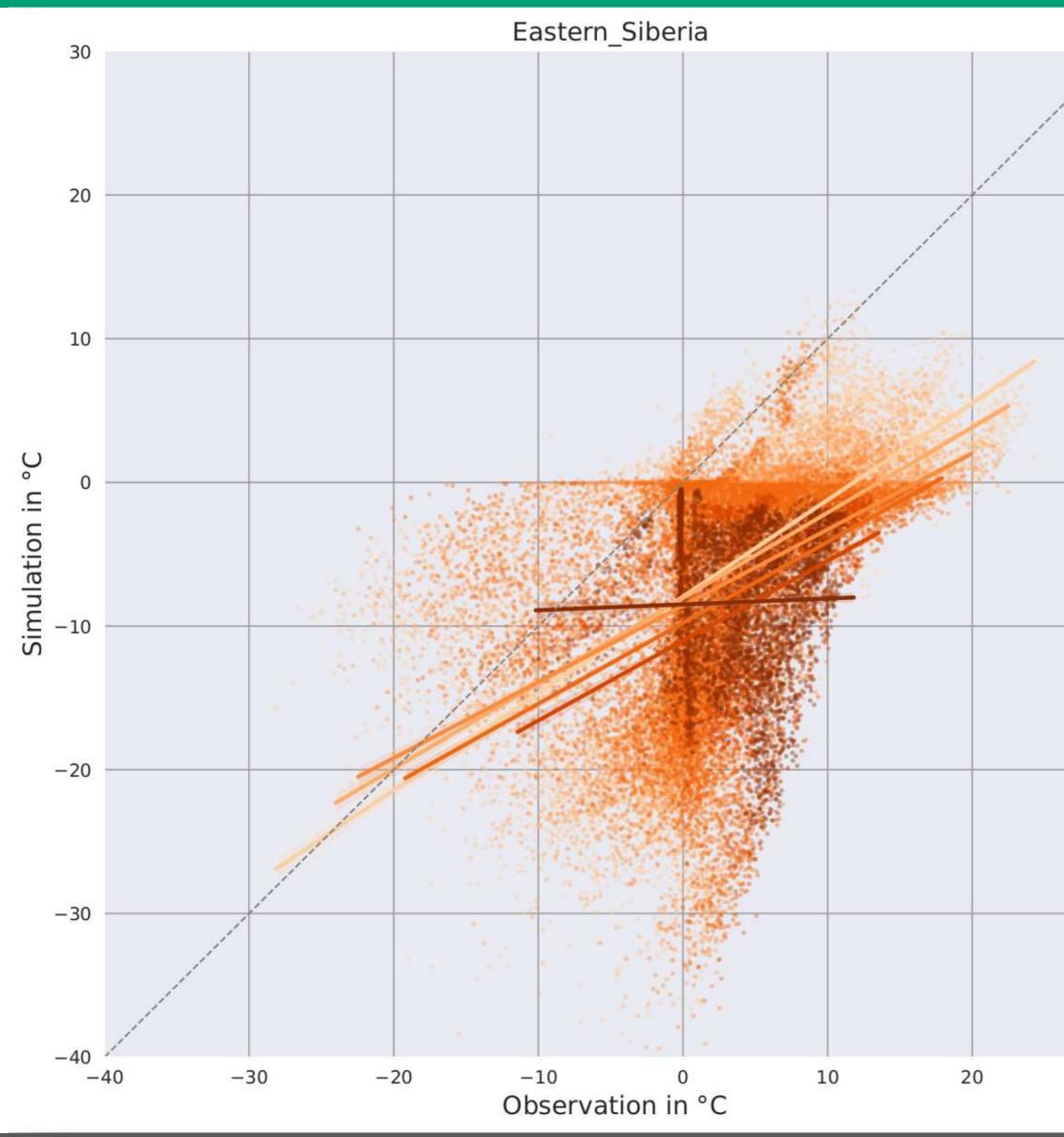


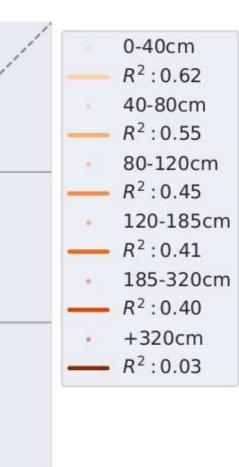
			January $R^2: 0.57$ February $R^2: 0.58$ March $R^2: 0.59$ April $R^2: 0.59$ May $R^2: 0.56$ June $R^2: 0.59$ July $R^2: 0.67$ August $R^2: 0.65$ September $R^2: 0.58$ October $R^2: 0.58$ October $R^2: 0.59$ November $R^2: 0.48$ December $R^2: 0.51$
10	20		
10	20	30	

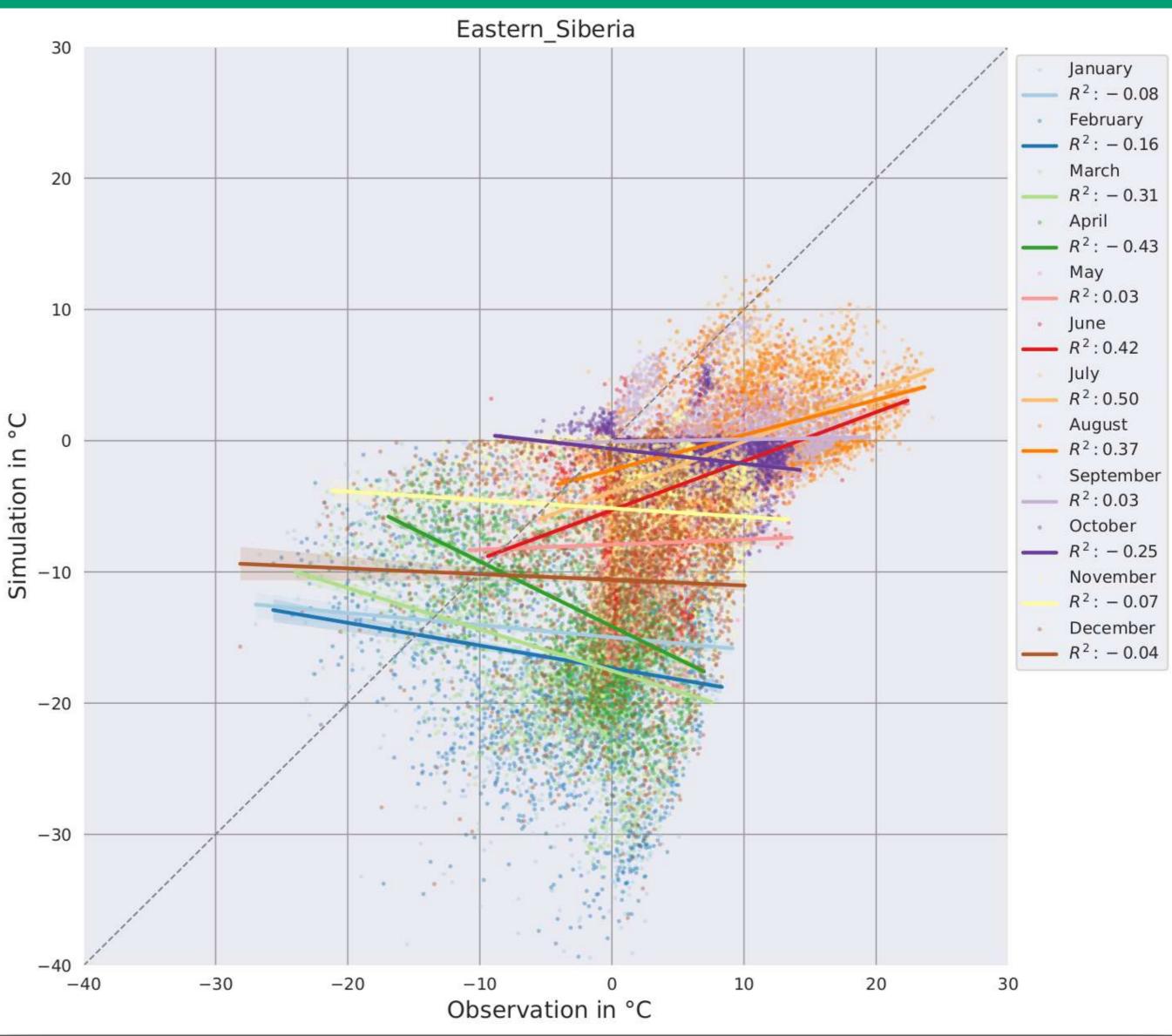
In-situ

Soil temperature difference only for Eastern Siberia

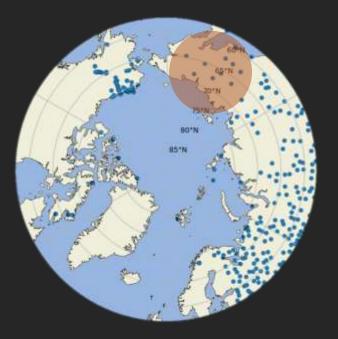
Depth clustering







10

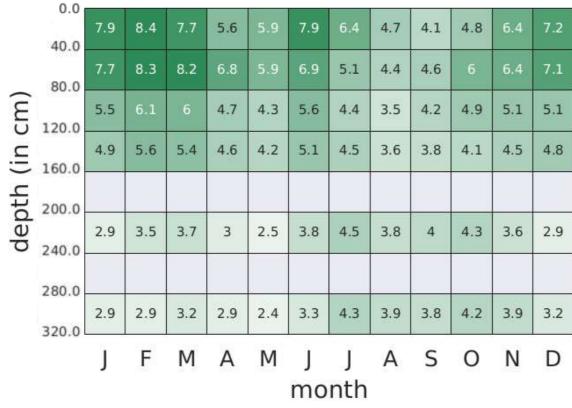


Heatmap of soil temperature difference CTSM – In-situ

Canada

	0.0	cts	m-s	stat	ior	IS S	oil	ten	npe	r
	0.0 40.0	4.3	5	4.4	1.5	-3.4	-6.4	-4.7	-2.9	
	80.0	2.3	3	2.8	0.9	-2.6	-5	-3.6	-2.7	The second of
Cm)	(10) (10) (10) (10) (10) (10) (10) (10)	1.6	2.3	2.3	0.8	-2	-4.1	-2.8	-1.9	
	120.0 160.0	-0.1	0.7	1.1	0.2	-1.8	-3.7	-2.7	-1.6	
deb	200.0 240.0	0.1	1.1	1.7	1.1	-0.5	-2.6	-2.5	-1.6	
	280.0									
	320.0	-0.6	0.5	1.2	0.9	-0.1	-2	-2.7	-2.1	
	520.0								_	

RMSE ctsm-stations



Alaska

2

1

0

 $^{-1}$

-2

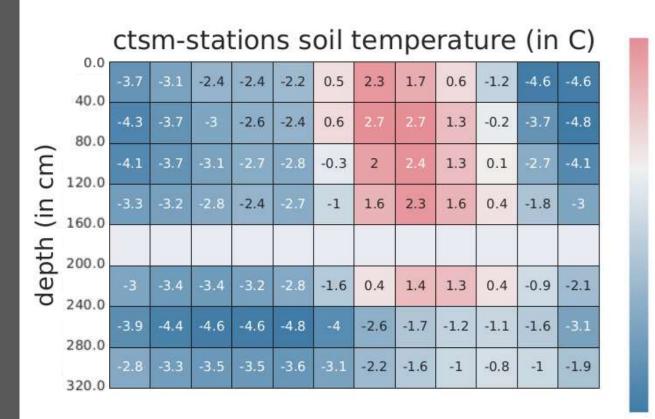
-3

-4

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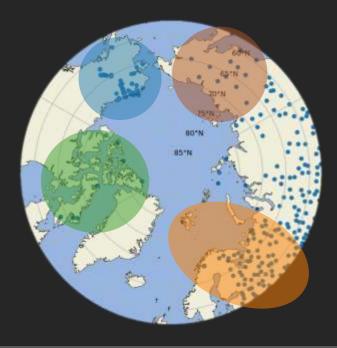
In-situ

RMSE ctsm-stations 4.3 5 4.6 2.9 1.3 4.7 E 120. <u>L</u> 160.0 6.7 6.9 6.8 6.6 4.9 3.3 3.7 3.9 2.9 1.7 3.1 depth 200.0 540.0 5.5 6.1 6.3 6.1 5.6 4.1 3.9 4.1 3.7 2.7 2.7 4.3 5.7 6.4 6.7 6.6 6.7 5.6 3.9 3 2.6 2.3 2.7 4.5 280.0 5 5.7 6 6.1 6.3 5.3 4.1 3.2 2.7 2.4 2.5 3.8 320.0 J F M A M J J A S O N D month

Eastern Siberia **European Russia** ctsm-stations soil temperature (in C) -1erature (in C) -2.1 -0.7 40.0 -5.6 -5.2 -4.8 -4.5 2.5 -2 -0.5 0.9 -2 80.0 E 120.0 -1.1 -2.7 2.3 -2.4 -1.5 U 1.9 -2.4 -2.2 -1.4 -3 pth depth 200.0 240.0 0 240.0 -1.7 -2.2 -1.8 -2 -4 -2.6 -2.4 -2.3 280.0 -2 -2.4 -2.2 -1.6 -5 -4320.0 **RMSE** ctsm-stations DMCE stem stations 0.0 40.0 5.3 7.9 7.8 7.3 6.9 6.1 5.1 3.9 2.6 cm) 4.1 6.9 7.4 7.1 6.8 6 2.8 2.4 2.5 3.9 6.4 7 6.8 6.6 6.2 5 5 4.8 3.6 <u>ц</u> 160.0 5 depth 240.0 3.4 2.9 2.8 3.6 5.6 6.5 6.6 6.4 6.1 5. depth 240.0 5 5.2 4.2 4 4 3.9 3.5 3.2 3.3 4.3 5.1 5.3 5.3 5.3 5.2 4.9 4.5 280.0 280.0 3 3 320.0 320.0 J F M A M J J A S O N D

month





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12	-12	-12	-8.6	-6.6	-7.6	-8	-8	-6.7	-5.2	-7.4	-9.5		
12	-12	-12	-9.2	-6.6	-7.7	-9.1	-8.8	-7.3	-5.1	-6.8	-9.2		-8
12	-13	-13	-11	-7.6	-6.9	-8.9	-9.5	-8.3	-6.1	-7.2	-10		
15	-16	-16	-14	-9.9	-7.9	-9.2	-11	-10	-8.3	-9.1	-13		-10
13	-14	-14	-13	-9.3	-6.6	-6.9	-8.1	-7.9	-7.3	-7.7	-11		10
													-12
15	-16	-17	-16	-14	-12	-10	-10	-10	-9.9	-9.9	-12		-14
			ç										-16

			RMS	SE (ctsr	n-s	tati	ons	5				18
٢7	17	16	12	8.6	9.1	9.8	9.8	8.7	7.5	11	14		
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16	17	17	14	9.4	8.3	10	11	10	7.8	9.9	14		14
17	18	18	15	11	8.9	10	12	11	9.4	11	14		14
16	18	18	16	12	8.3	8.5	9.6	9.7	9	9.9	14		12
16	18	18	17	14	12	11	11	11	11	11	14		10
J	F	Μ	A	Μ	J	J		S	0	Ν	D		8
					mo	nth							

Main observations Whv?

ESACCI

- Permafrost extent in strong agreement with ESACCI (slight overestimation) -> model too cold over Siberia
- Active Layer Thickness exaggerated over warm permafrost -> why?
- Strong cold temperature difference globally, especially over Siberia

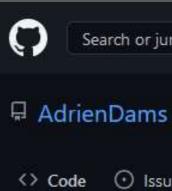
CALM

Same conclusions as ESACCI

In-situ stations

- 0.80-0.40 R² depending on regions
- Colder in Europe, worst in the east -> water content, snow representation, parametrization in Siberia is not adapted?
- Winter warmer in Canada -> observed very high snow depth values -> thermal insulation
- Higher coefficient in top soil layers in east side -> more dependent on atmospheric forcings?
- CTSM lacks proper representation of seasonality, leading to a spurious high yearly correlation as months are offsetting each others

12



Github project:

https://github.com/ AdrienDams/cegio

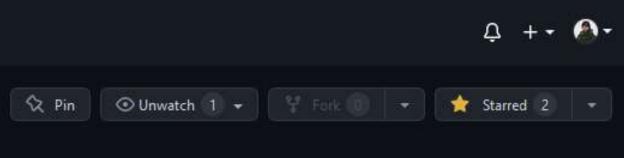
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Requirements

- Daily files from CTSM (minimum 3 years period)
- ESACCI and in-situ observation files (available by request at adamseau@awi.de)
- python3 (numpy, pandas, scipy, matplotlib, seaborn, netCDF4, similaritymeasures, cartopy libraries)
- cdo (minimum 2.0.3)
- nco (minimum 5.0.6)
- bash shell
- sbatch

Install

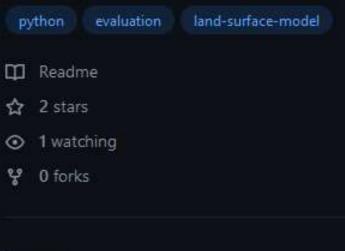




About

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CTSM Evaluation with Grid based and Insitu based Observations and reanalysis products on an arctic domain



Languages

Python 76.0% O Shell 24.0%



Additional slides

1

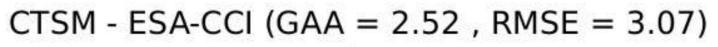
Default snow parameters Reset_snow = false $h2osno_max = 10 m$

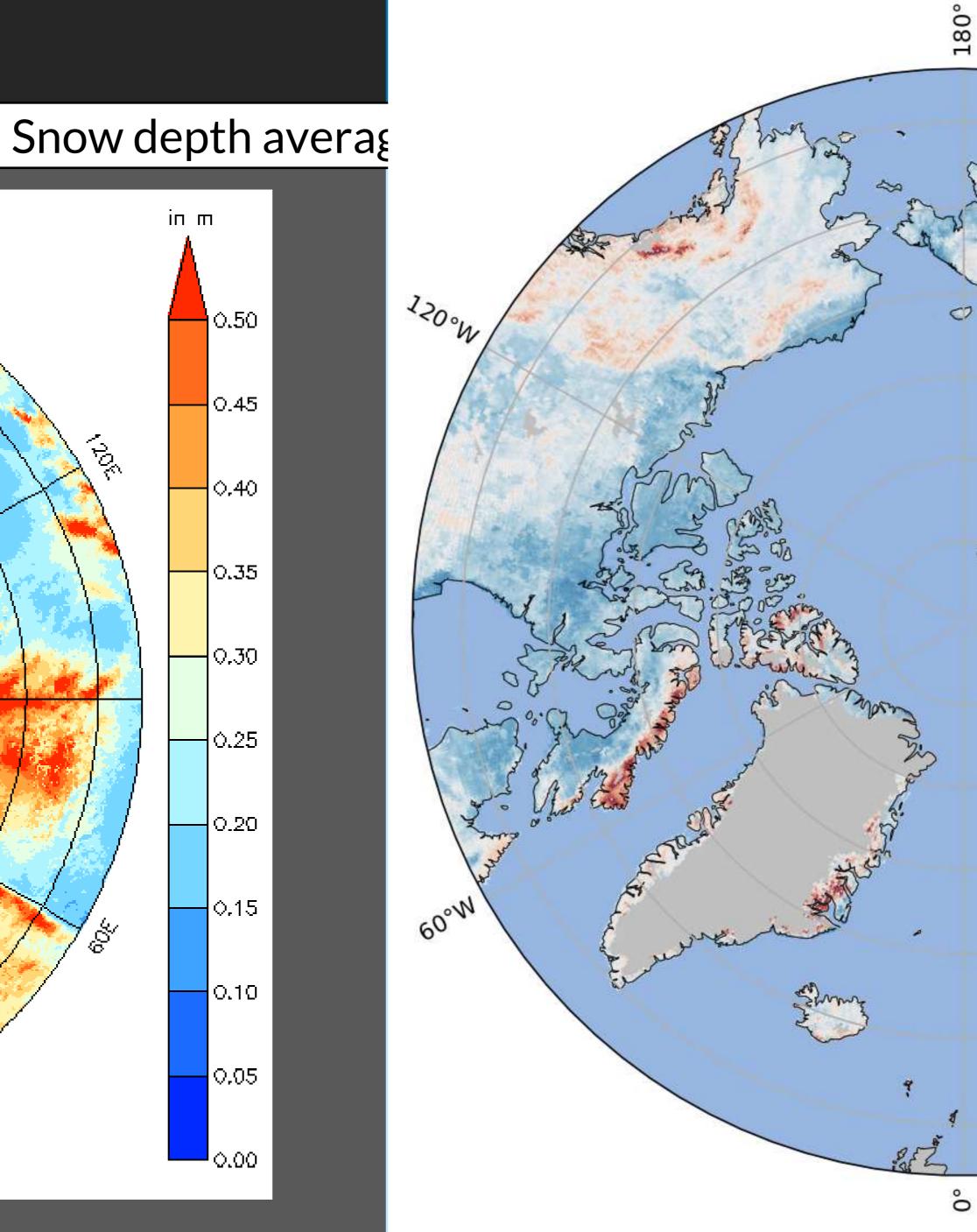
180W So<u>v</u> ಕ್ಷ 90% 84 ğ 30W

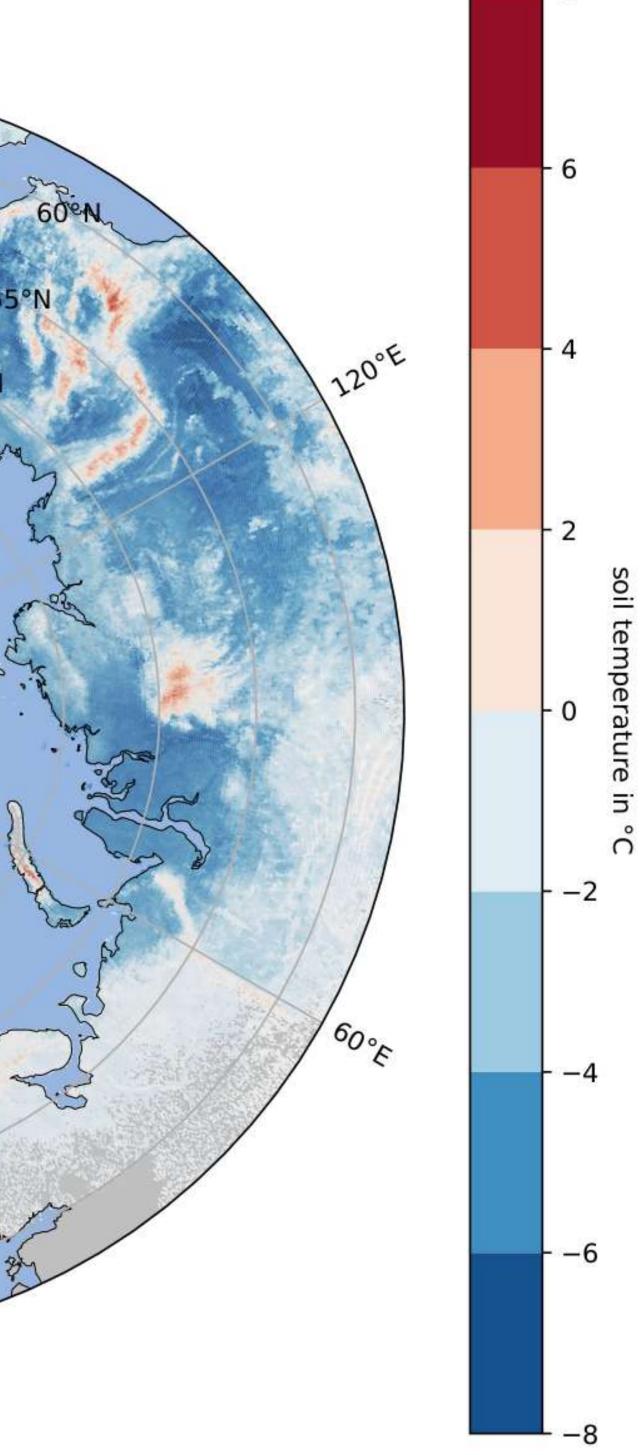
Adjusted snow parameters

80°N

85°N



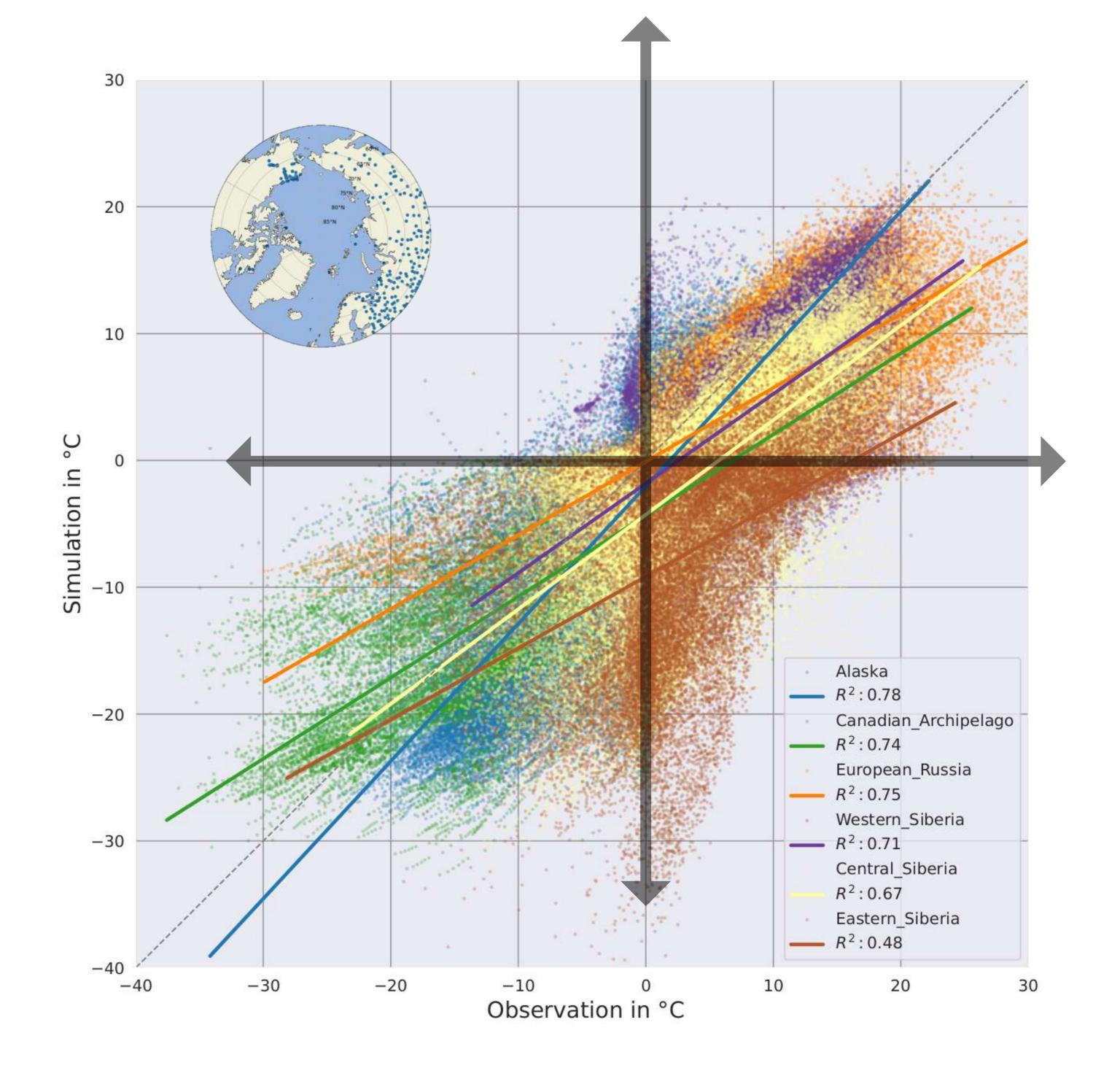




In-situ

Cross anomaly?

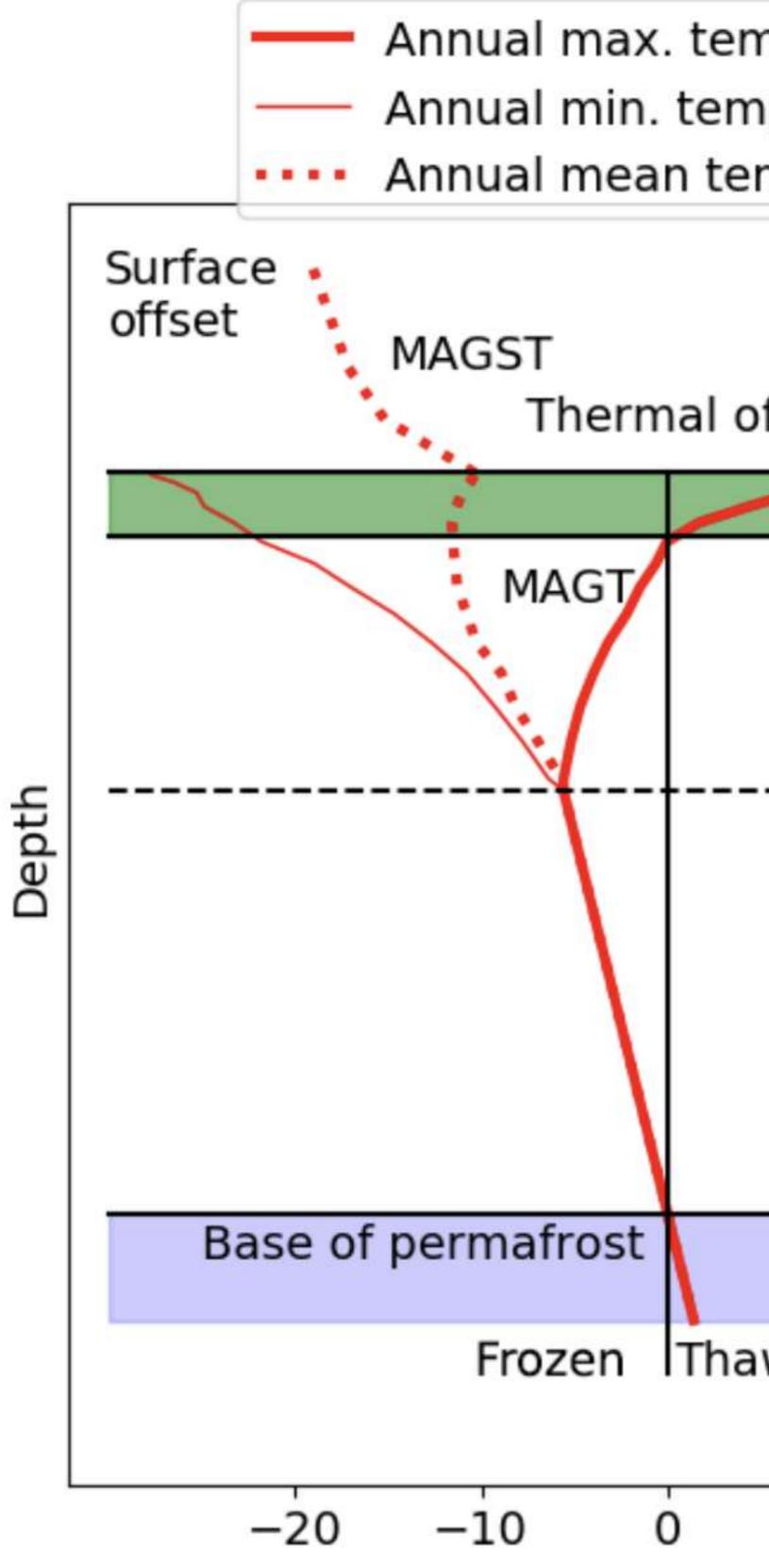
 Explained by the thawing and freezing timing mismatch during phase transition





What's the Active Layer?

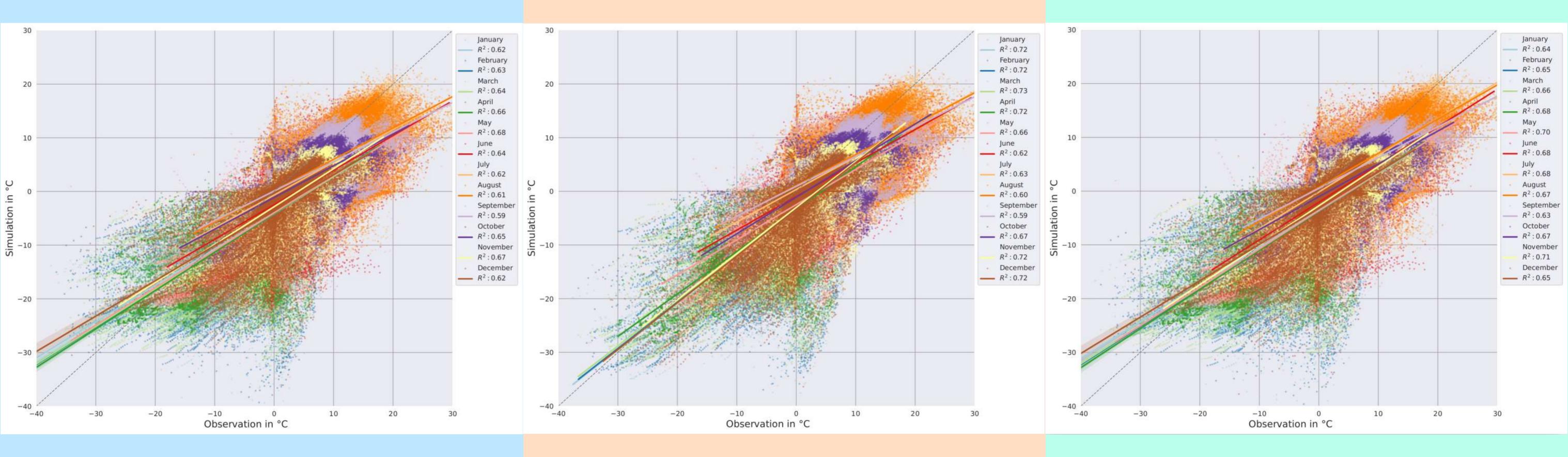
- The soil layer which thaws during the summer
- High decomposition of organic carbon
- Release of methane and other GHGs



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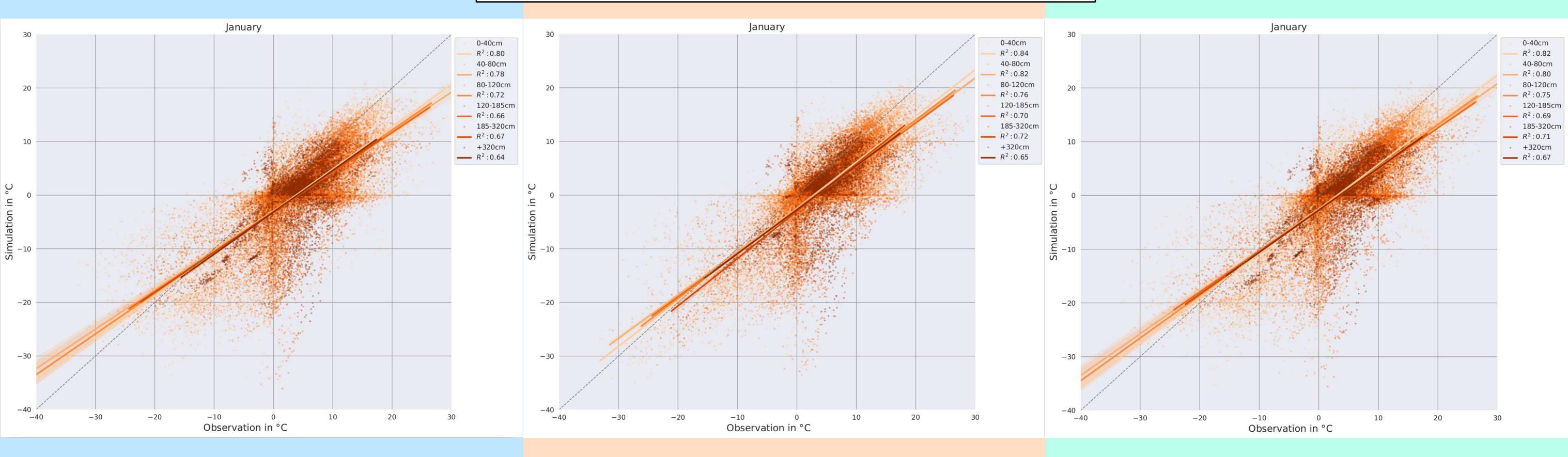
5

Soil temperature bias CTSM vs 274 stations

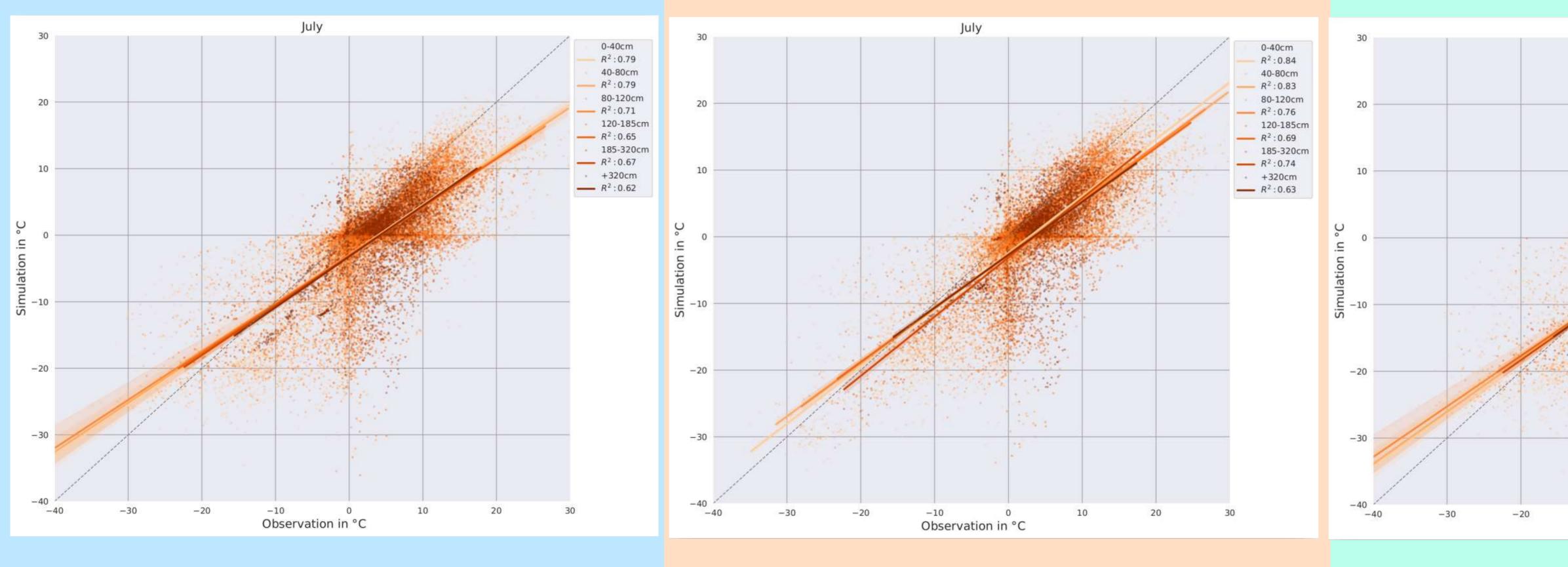


Run 002 GSWP3 Default soil 1980-2014

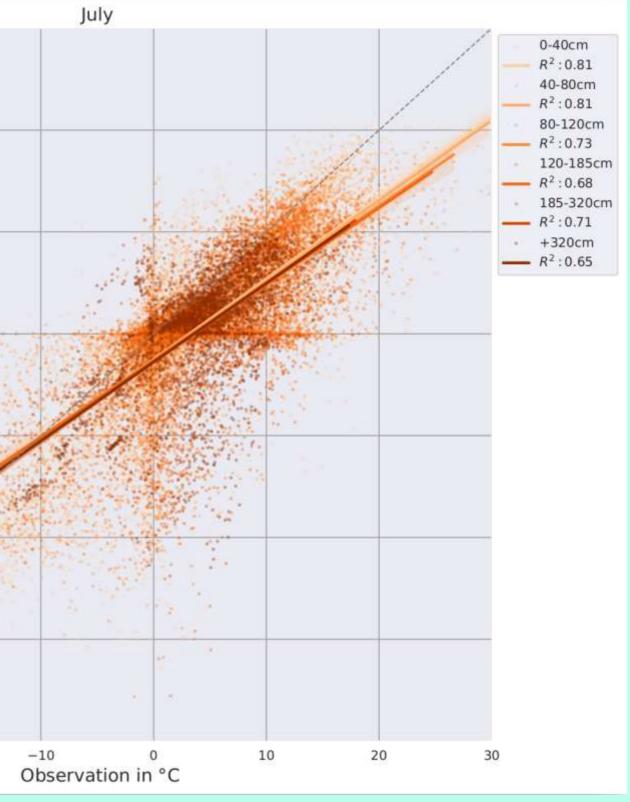
Soil temperature bias CTSM vs 274 stations in January - Depths clustering



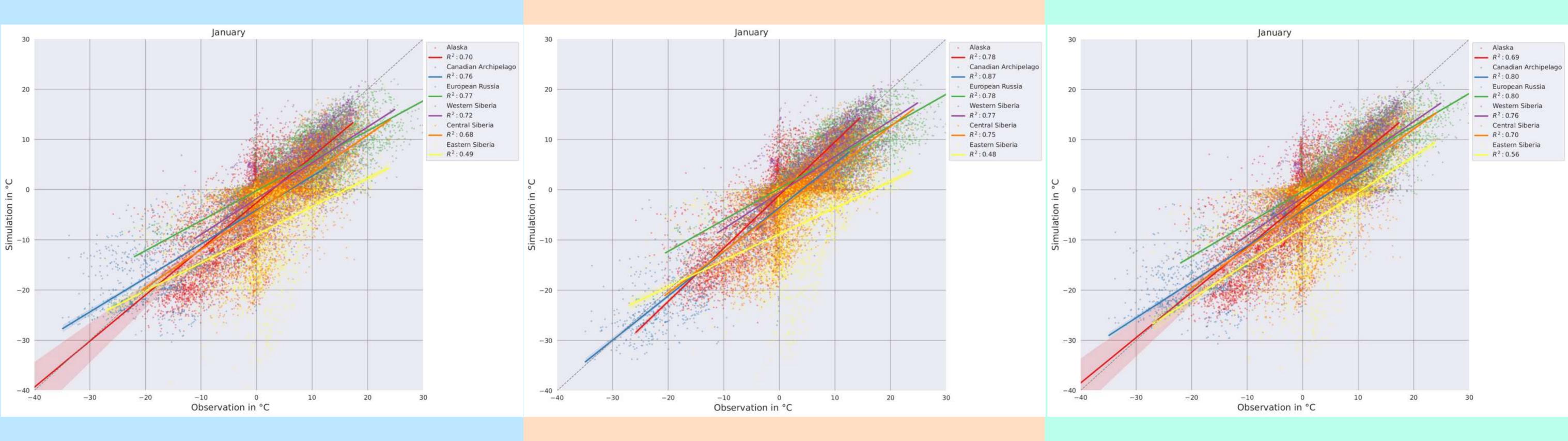
Run 002 GSWP3 Default soil 1980-2014



Run 002 GSWP3 Default soil 1980-2014



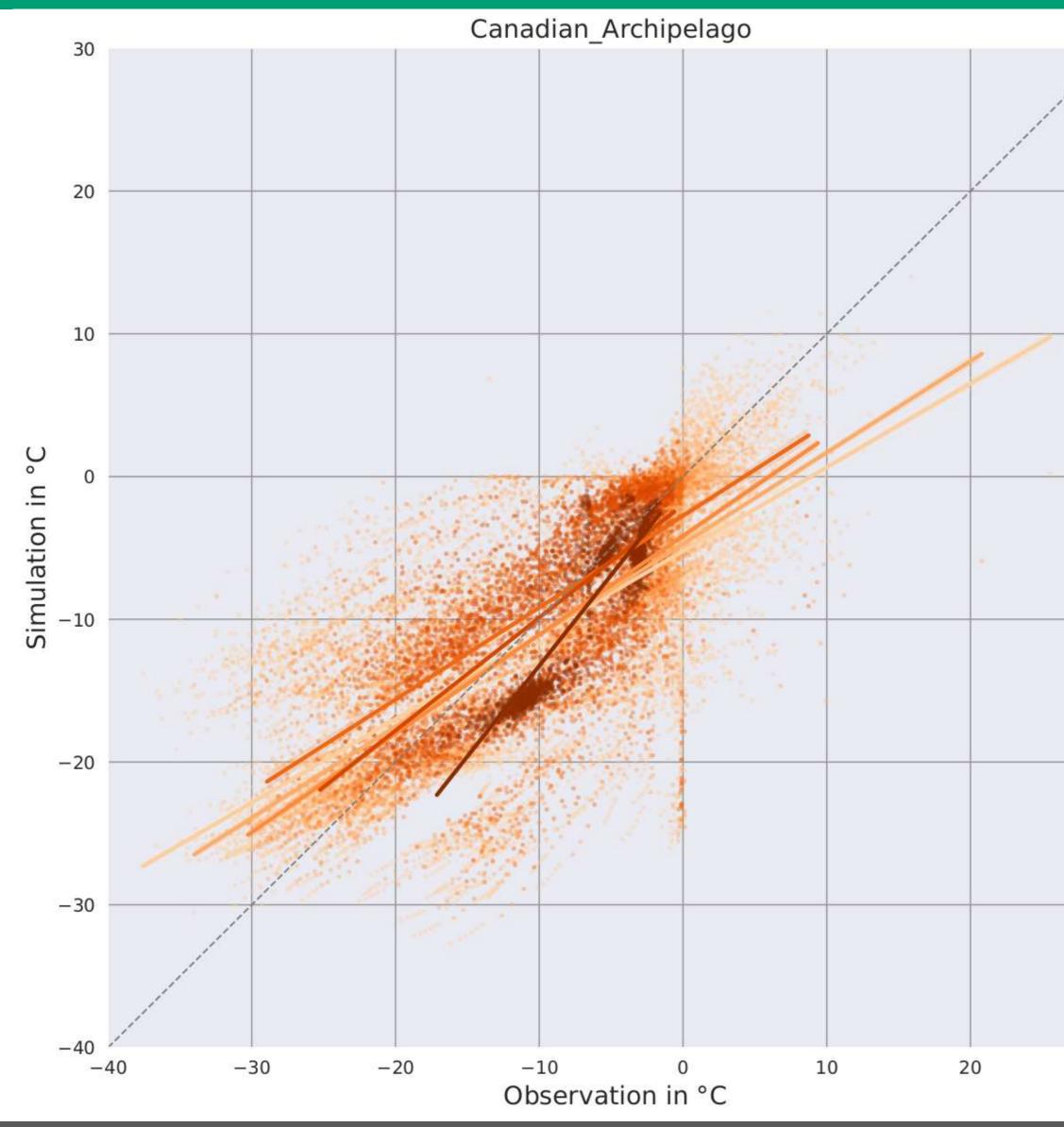
Soil temperature bias CTSM vs 274 stations in January - Regions clustering



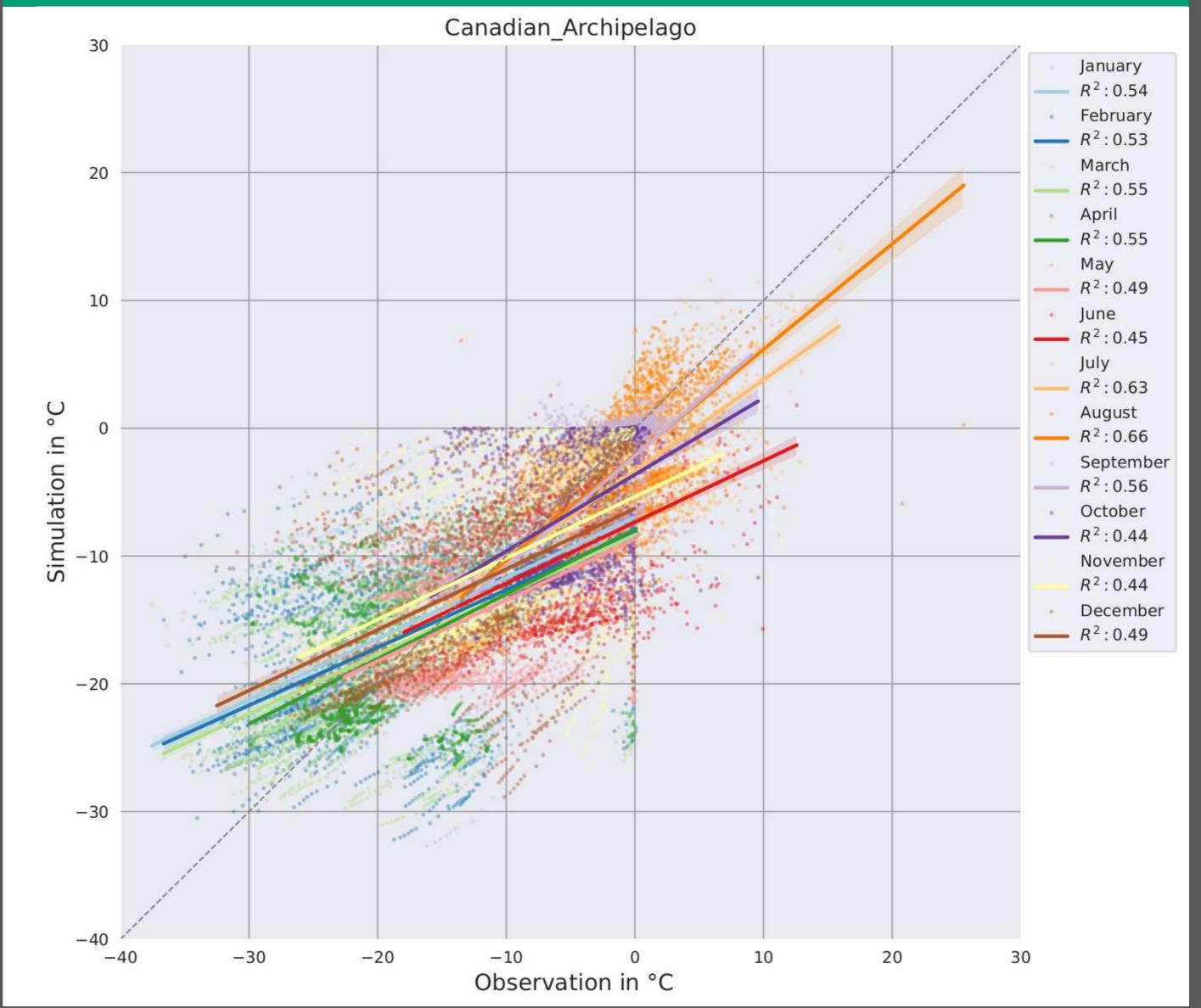
Run 002 GSWP3 Default soil 1980-2014

Soil temperature bias - only for Canada

Depth clustering



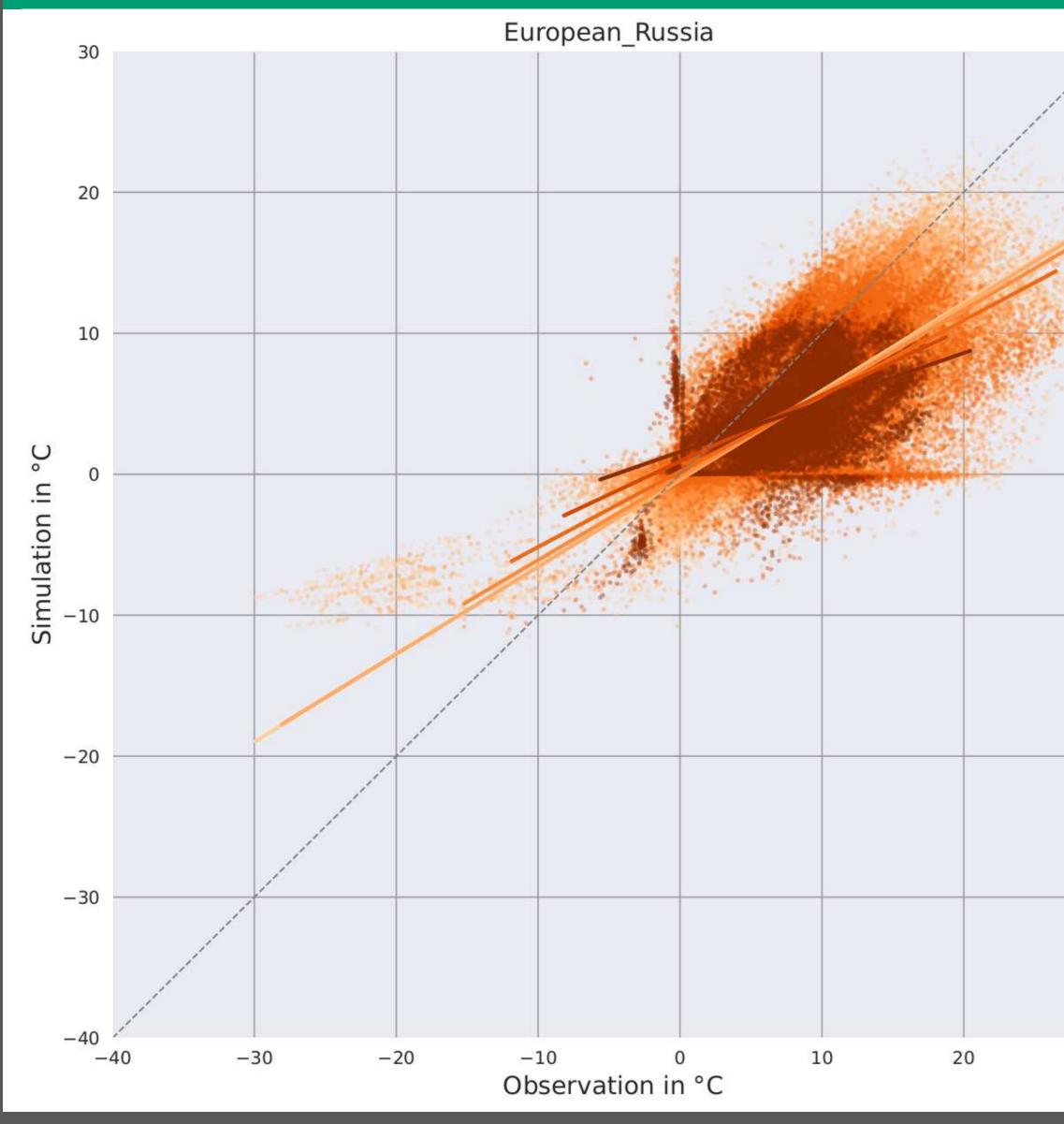


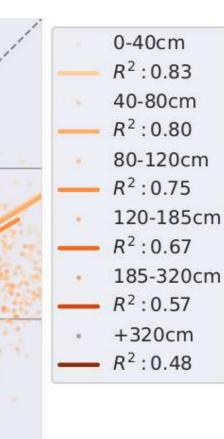


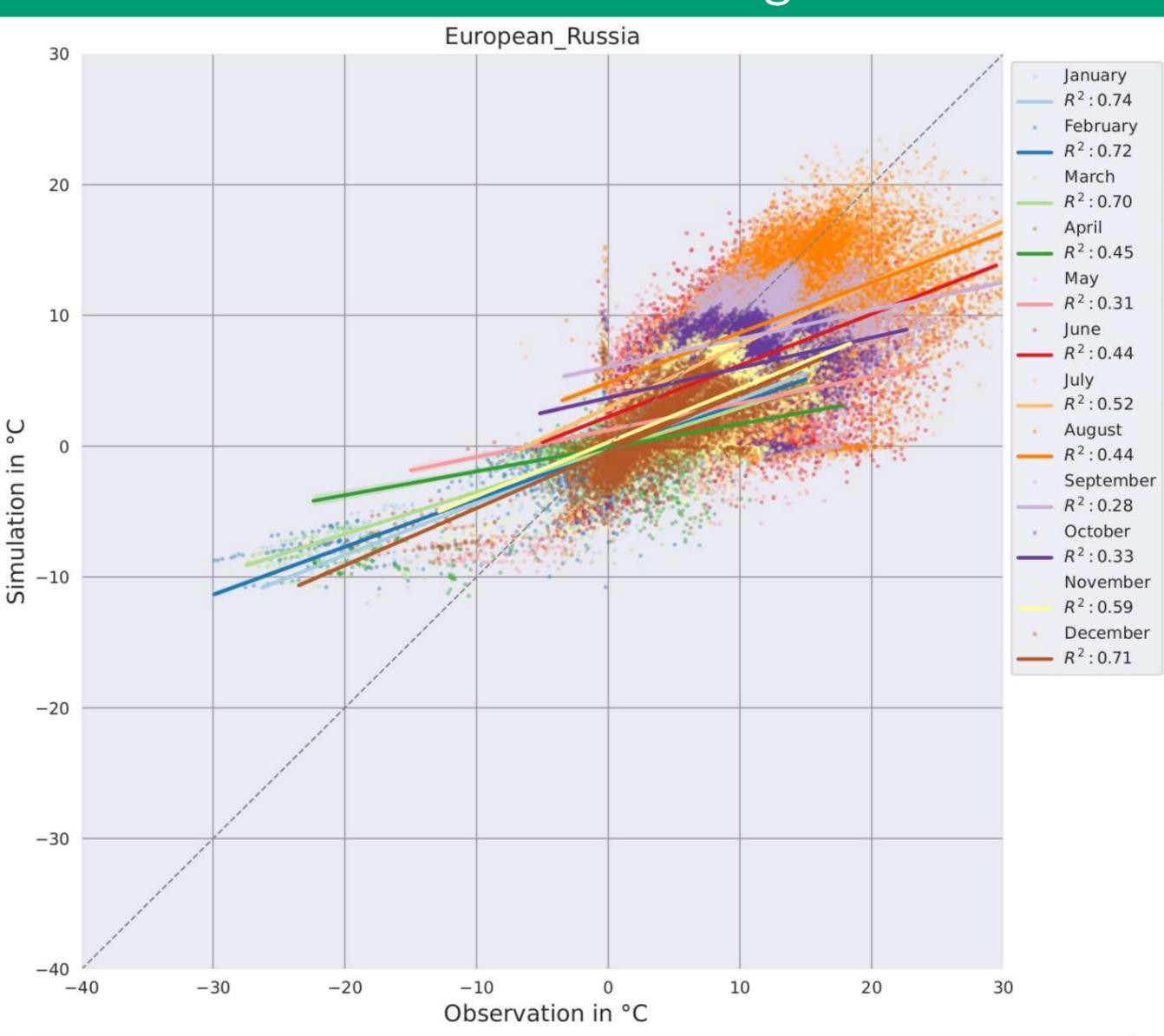
0-40cm R²:0.72 40-80cm R²:0.75 80-120cm R²:0.78 120-185cm R²:0.68 185-320cm $- R^2:0.78$ • +320cm $-- R^2:0.92$

Soil temperature bias - only for European Russia

Depth clustering

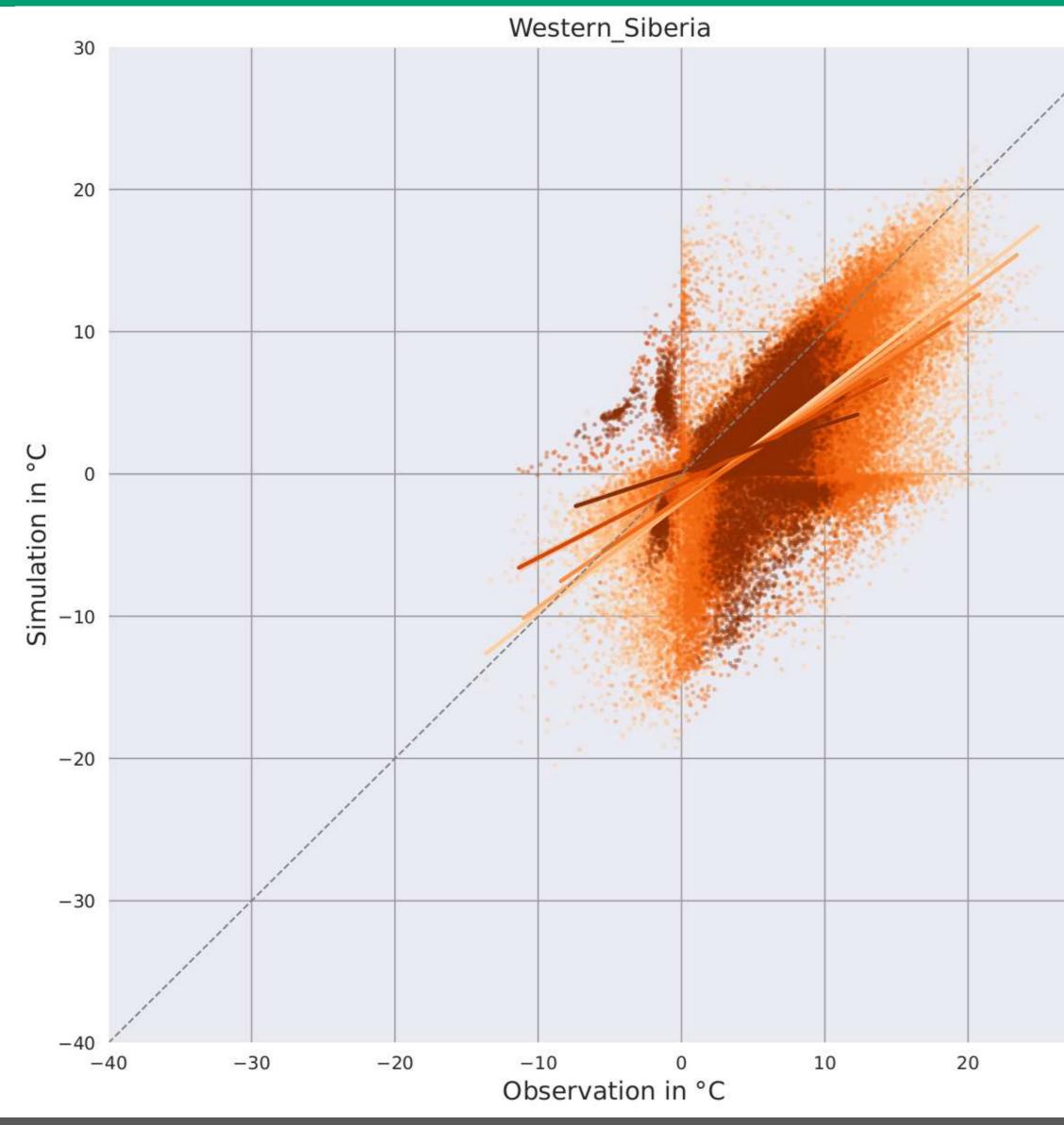


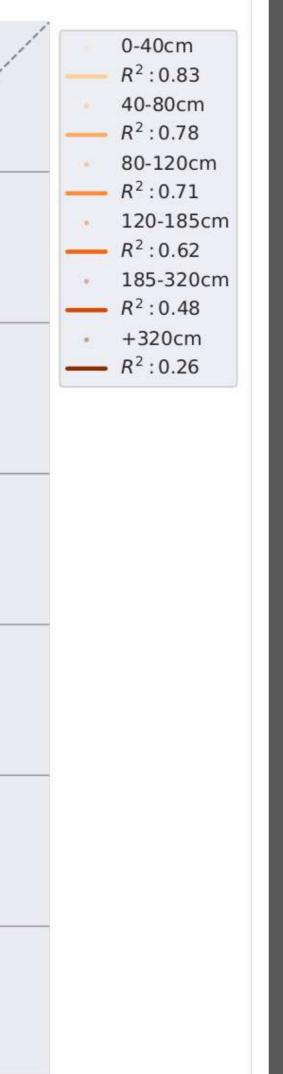


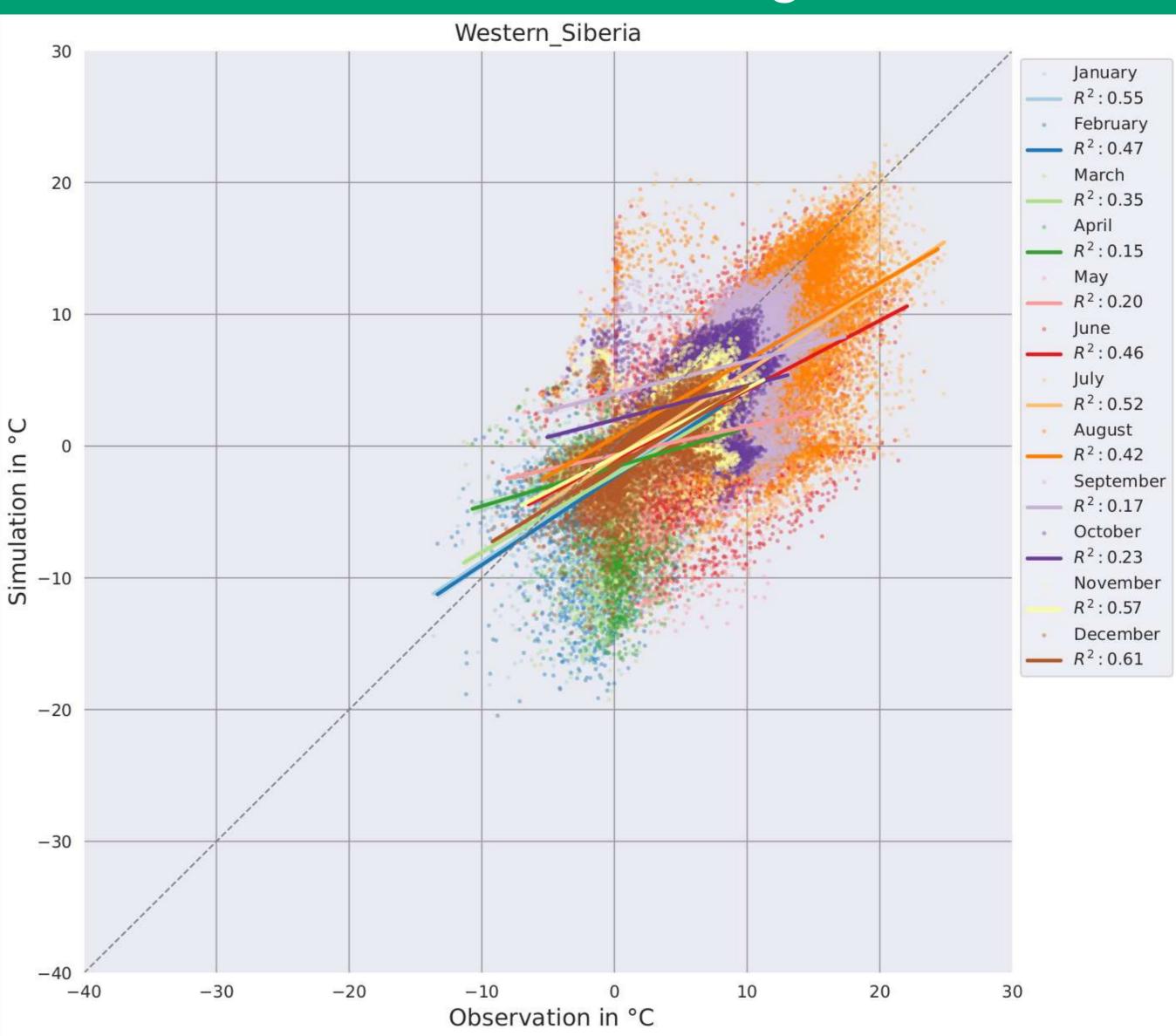


Soil temperature bias - only for Western Siberia

Depth clustering



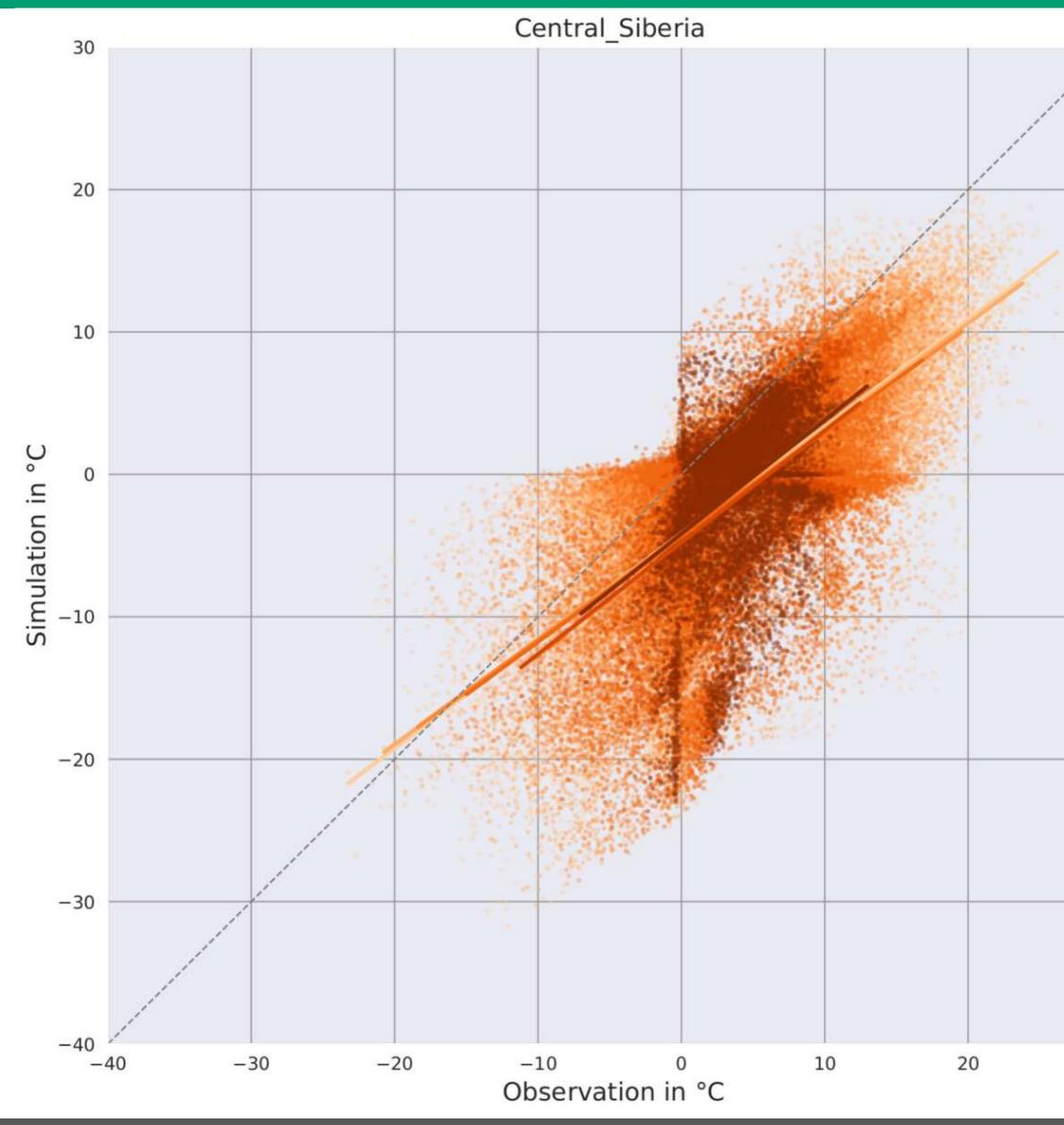


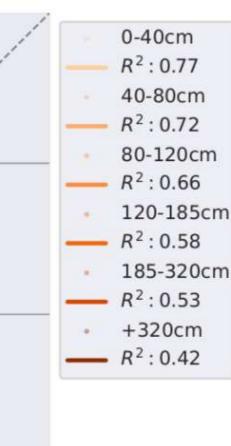


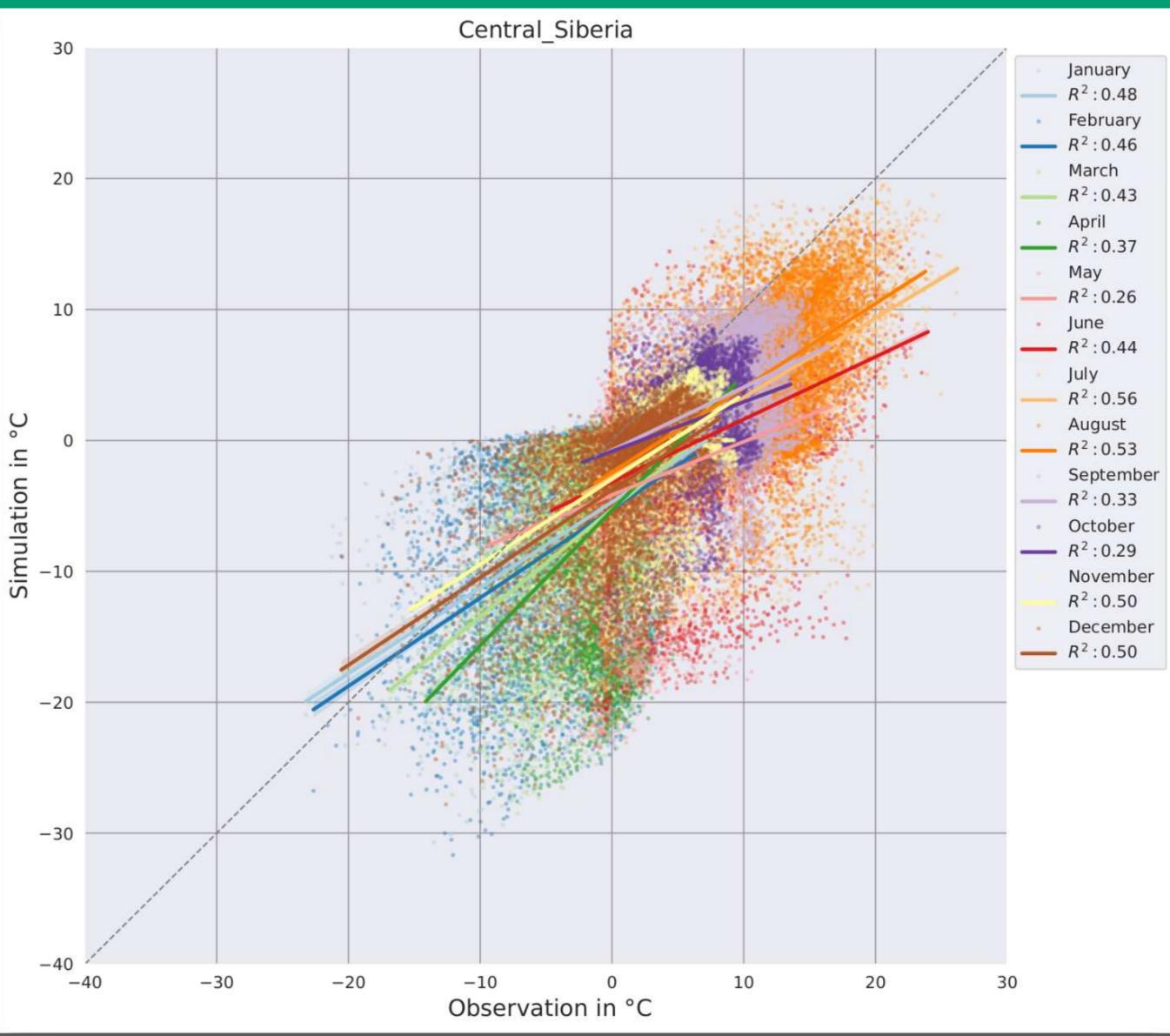
11

Soil temperature bias - only for Central Siberia

Depth clustering

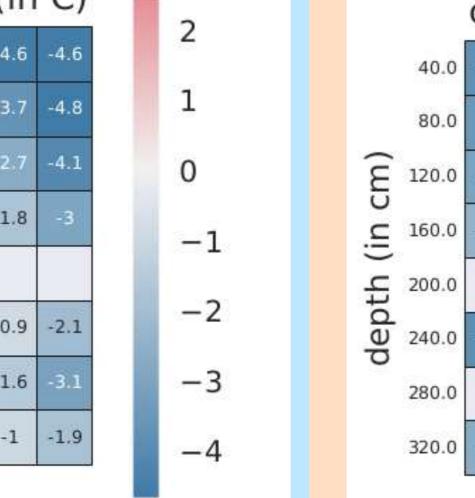






11

		cts	m-s	stat	ion	IS S	oil	ten	npe	rat	ure	(in	C)
	40.0	-3.7	-3.1	-2.4	-2.4	-2.2	0.5	2.3	1.7	0.6	-1.2	-4.6	-4.6
	80.0	-4.3	-3.7	-8	-2.6	-2.4	0.6	2.7	2.7	1.3	-0.2	-3.7	-4.8
cm)	120.0	-4.1	-3.7	-3.1	-2.7	-2.8	-0.3	2	2.4	1.3	0.1	-2.7	-4.1
(in o	160.0	-3.3	-3.2	-2.8	-2.4	-2.7	-1	1.6	2.3	1.6	0.4	-1.8	-3
	200.0												
depth	240.0	-3	-3.4	-3.4	-3.2	-2.8	-1.6	0.4	1.4	1.3	0.4	-0.9	-2.1
	280.0	-3.9	-4.4	-4.6	-4.6	-4.8	-4	-2.6	-1.7	-1.2	-1.1	-1.6	-3.1
	320.0	-2.8	-3.3	-3.5	-3.5	-3.6	-3.1	-2.2	-1.6	-1	-0.8	-1	-1.9



7

6

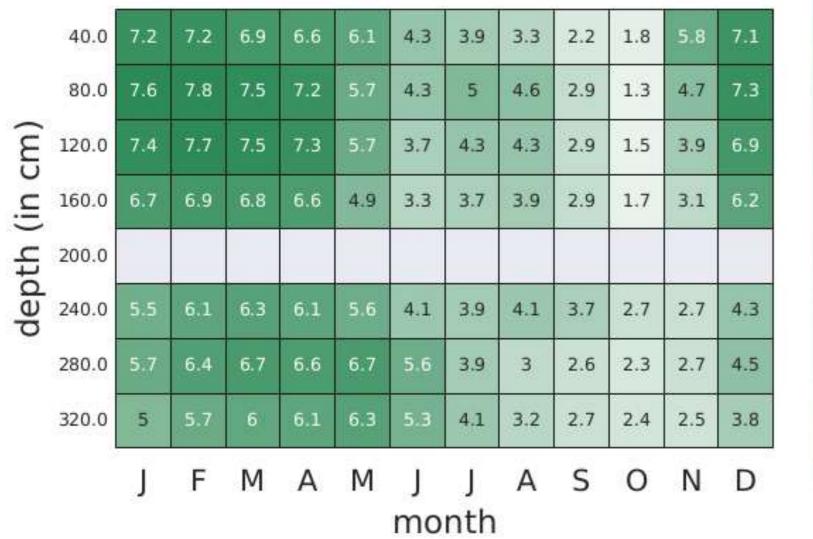
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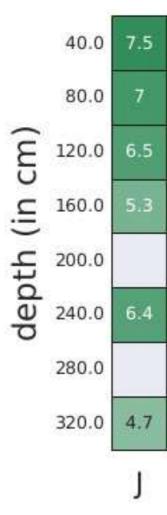
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40.0

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Run 002 GSWP3 Default soil 1980-2014

ctsm-stations soil temperature (in C)

i.4	-4.1	-2.7	-1	1.8	3.7	4.1	3.1	1.5	-2.1	-6.4	-6
5	-4.1	-3	-1.6	0.5	2.1	3.4	3.3	1.9	-0.5	-4.2	-5.3
1.4	-4	-3.1	-2.1	-0.4	1	2.1	2.4	1.5	-0.2	-2.7	-4.3
1.5	-3.3	-2.7	-2	-0.8	0.3	1.3	1.6	1.4	0.3	-1.4	-3.2
5.5	-6.6	-7	-6.7	-5.6	-3.6	-2.6	-1.8	-0.6	-0.9	-1.4	-3.1
.9	-5	-5.5	-5.5	-5.2	-4.2	-3.2	-2	-1.5	-1.3	-1.3	-2.3

RMSE ctsm-stations 40.0 7.5 7.1 6.4 4.1 2.4 2.9 5 7.2 5 6.5 5.6 4.2 3.6 4.8 1.6 3 5.1 4.3 2.7 4 4.2 2.8 1.5 3.9 5.7 6.5 6.7 5.3 4.6 3.9 2.6 2.9 3.1 2.4 1.3 2.7 4.6 7.6 8.2 7.8 6.7 4.5 3.4 3.2 3.1 2.5 2.4 4.1 5 3.9 3.1 2.6 2.3 2.3 3.4 6.1 6.1 59 FMAMJJASOND month

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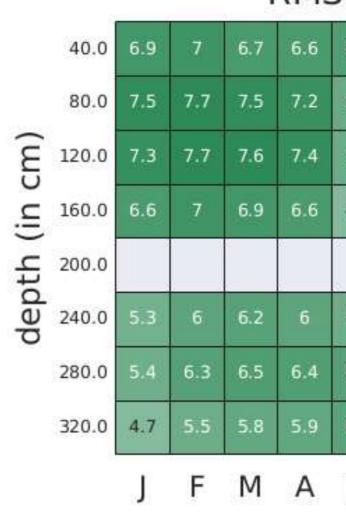
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2

		cts	m-s	stat	tion	IS S	oil	ten	npe	rat	ure	(in	C)
	40.0	-3.5	-3	-2.3	-2.2	-2.1	0.8	2.9	2.1	0.7	-1.2	-4.3	-4.4
	80.0	-4	-3.5	-2.8	-2.4	-2.5	0	2.3	2.7	1.4	0	-3.1	-4.4
	120.0	-3.7	-3.4	-2.9	-2.5	-2.8	-0.9	1.2	1.7	1.1	0.2	-2.1	-3.6
	160.0	-2.9	-2.8	-2.4	-2.1	-2.4	-1.2	0.8	1.6	1.3	0.5	-1.3	-2.5
	200.0												
1	240.0	-2.8	-3.1	-3	-2.8	-2.5	-1.7	-0.7	0.2	0.4	-0	-0.9	-2
	280.0	-3.5	-4	-4	-3.9	-4	-3.2	-1.6	-0.8	-0.5	-0.5	-0.9	-2.5
	320.0	-2.6	-3.1	-3.2	-3.2	-3.3	-2.8	-1.8	-1.1	-0.6	-0.4	-0.7	-1.6



Run 005 ERA5 New soil 1980-2021

2

1

0

 $^{-1}$

-2

-3

-4

7

6

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4

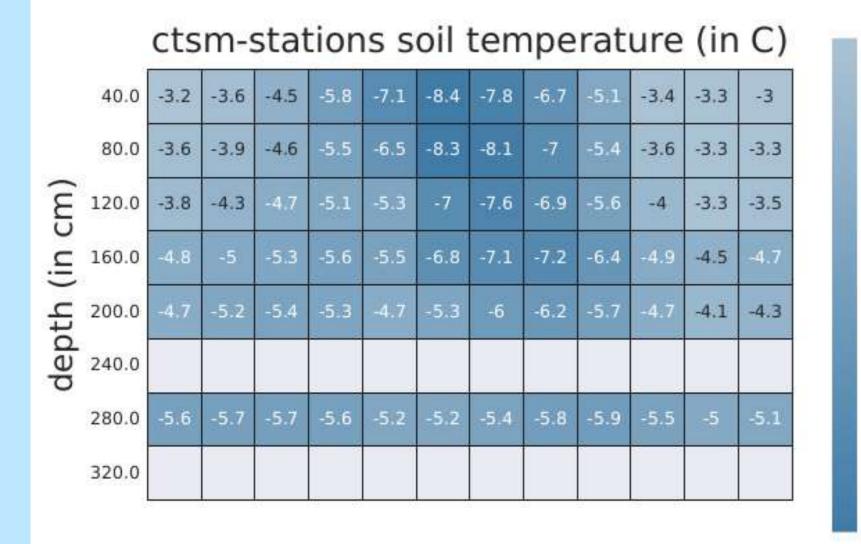
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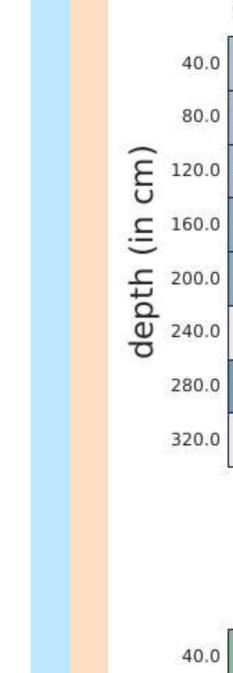
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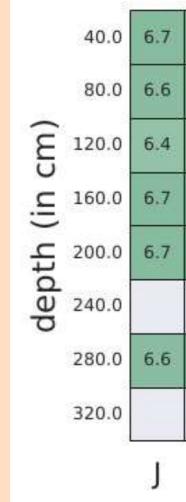
RMSE ctsm-stations

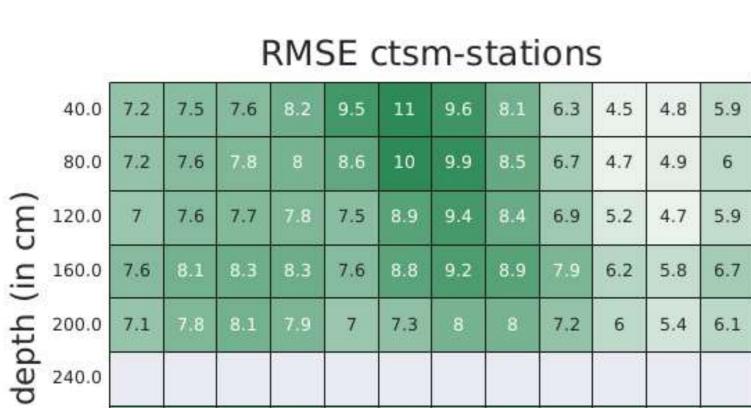
.9	7	6.7	6.6	6.4	4.7	4.6	3.7	2.4	1.9	5.3	6.6
.5	7.7	7.5	7.2	5.7	4	4.6	4.5	3.1	1.3	4.1	7
.3	7.7	7.6	7.4	5.6	3.4	3.5	3.8	2.9	1.5	3.4	6.6
.6	7	6.9	6.6	4.8	2.7	2.4	2.9	2.5	1.6	2.5	5.9
.3	6	6.2	6	5.5	3.9	3	3.3	3.1	2.5	2.5	4.1
.4	6.3	6.5	6.4	6.3	4.8	2.8	1.9	1.4	1.3	1.8	3.9
.7	5.5	5.8	5.9	6.1	5	3.5	2.4	1.9	1.7	1.8	3.2
J	F	М	А	М	J	J	А	S	0	Ν	D

month









280.0 7.2 7.6 7.8 7.7 7.1 6.9 7.2 7.6 7.4 6.7 6.1 6.4

J F M A M J J A S O N D

month

(in

320.0



5

-4

-5

-6

-7

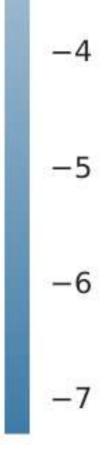
-8

Run 002 GSWP3 Default soil 1980-2014

ctsm-stations soil temperature (in C)

			11				1000			1999 C	
-3	-3.2	-3.8	-4.9	-5.8	-7.2	-7.4	-6.3	-4.3	-3	-3.4	-3.1
3.3	-3.4	-3.9	-4.7	-5.4	-7	-7.4	-6.5	-4.7	-3.1	-3.3	-3.3
3.5	-3.7	-3.9	-4.3	-4.5	-5.7	-6.5	-6.2	-4.8	-3.5	-3.3	-3.6
4.3	-4.2	-4.3	-4.7	-4.6	-5.7	-6	-6.2	-5.5	-4.2	-4.2	-4.7
4.4	-4.7	-4.7	-4.6	-4.1	-4.4	-4.9	-5.3	-4.9	-4.1	-3.8	-4.2
5.2	-5.2	-5	-4.9	-4.5	-4.5	-4.7	-5.2	-5.2	-4.9	-4.6	-4.9
1	с. — З	Š	8	0 ⁷	8 9	v 2	(<u>-</u>	S	8	70°	3 3

RMSE ctsm-stations 9 8.8 7.5 5.4 3.9 4.8 5.9 40.0 6.7 6.5 6.4 6.9 8.1 6.6 6.6 6.7 5.8 4.1 7.3 8.8 8.9 7.9 4.6 B 120.0 6.4 6.6 6.6 6.6 6.2 7.5 8.1 6 4.5 4.5 5.7 6.7 5.2 5.1 6.3 6.8 6.7 6.8 6.1 7.7 7.2 7.1 6.8 5.9 6.1 6.7 6.2 5.1 4.9 5.9 6.8 6.7 6.6 5.9 5.7 6.2 6.5 6.4 5.8 5.3 5.9 FMAMJJASOND month



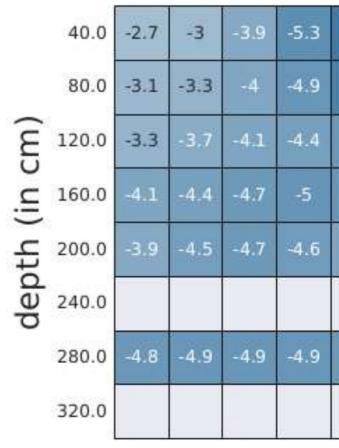
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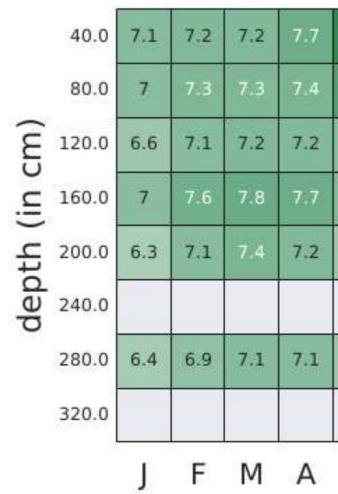
7

6

5

ctsm-stations soil temperature (in C)





Run 005 ERA5 New soil 1980-2021

-6.4	-6.4	-5.3	-4.8	-4.4	-3.7	-3.5	-2.7
-6	-6.7	-5.8	-5.1	-4.6	-3.7	-3.5	-3
-4.8	-6.1	-6	-5.3	-4.7	-3.9	-3.2	-3.1
-4.9	-6.1	-5.9	-5.7	-5.3	-4.5	-4.1	-4.1
-4.2	-4.8	-5.2	-5.2	-4.9	-4.3	-3.6	-3.6
						2 0	
-4.7	-4.7	-4.6	-4.8	-5.1	-4.9	-4.5	-4.4

-3.0	
-3.5	
-4.0	
-4.5	
-5.0	
-5.5	
-6.0	

RMSE ctsm-stations

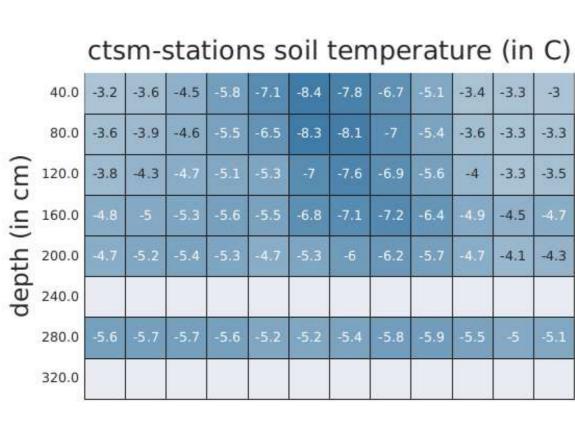
month

9.1	9.4	7.8	6.6	5.8	4.7	5.1	5.9
8.3	9.3	8.2	7	6.1	4.8	5.1	6
7.1	8.4	8.3	7.2	6.2	5.1	5.1 4.7	
7.2	8.4	8.6	8.2	7.3	6	5.4	6.1
6.6	6.9	7.5	7.2	6.6	5.8	5.1	5.5
6.6	6.5	6.8	7.1	6.9	6.3	5.7	5.8
					<i>n</i> -		
М	J	J	А	S	0	Ν	D

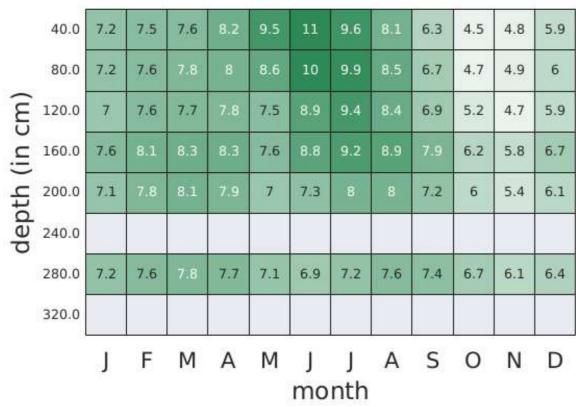
In-situ

Heatmap of soil temperature bias

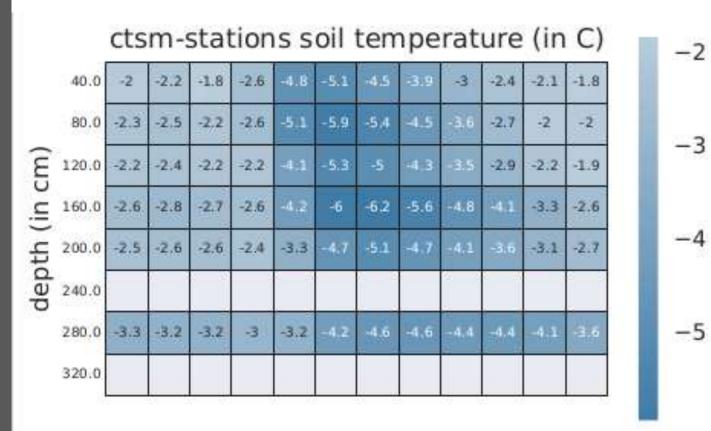
Central Siberia

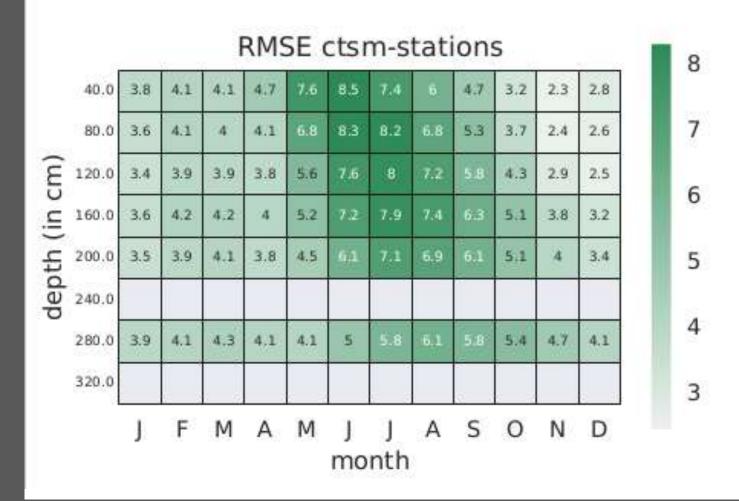


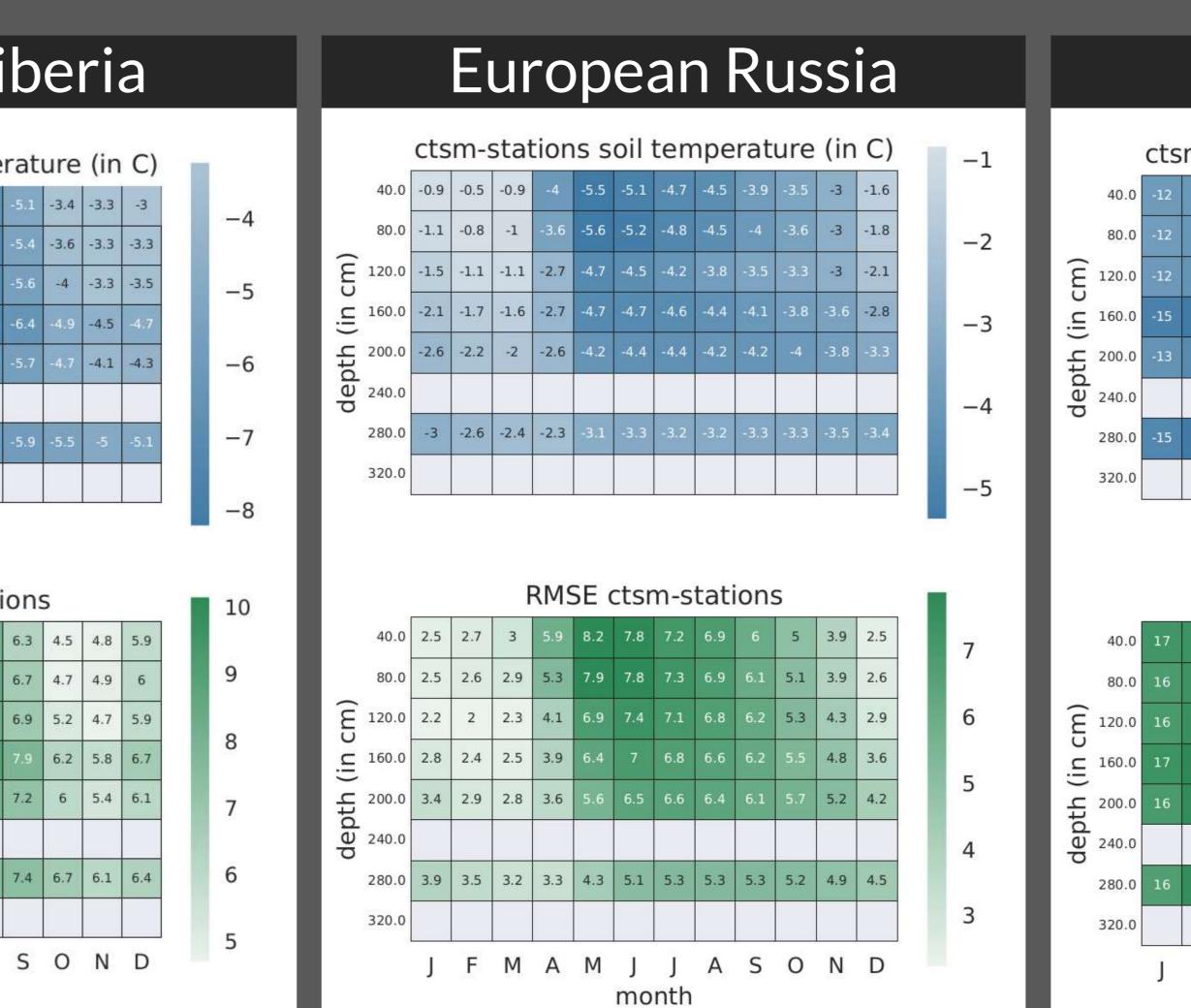
RMSE ctsm-stations

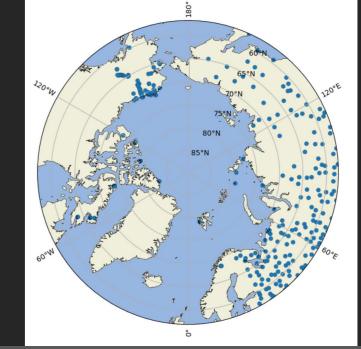


Western Siberia







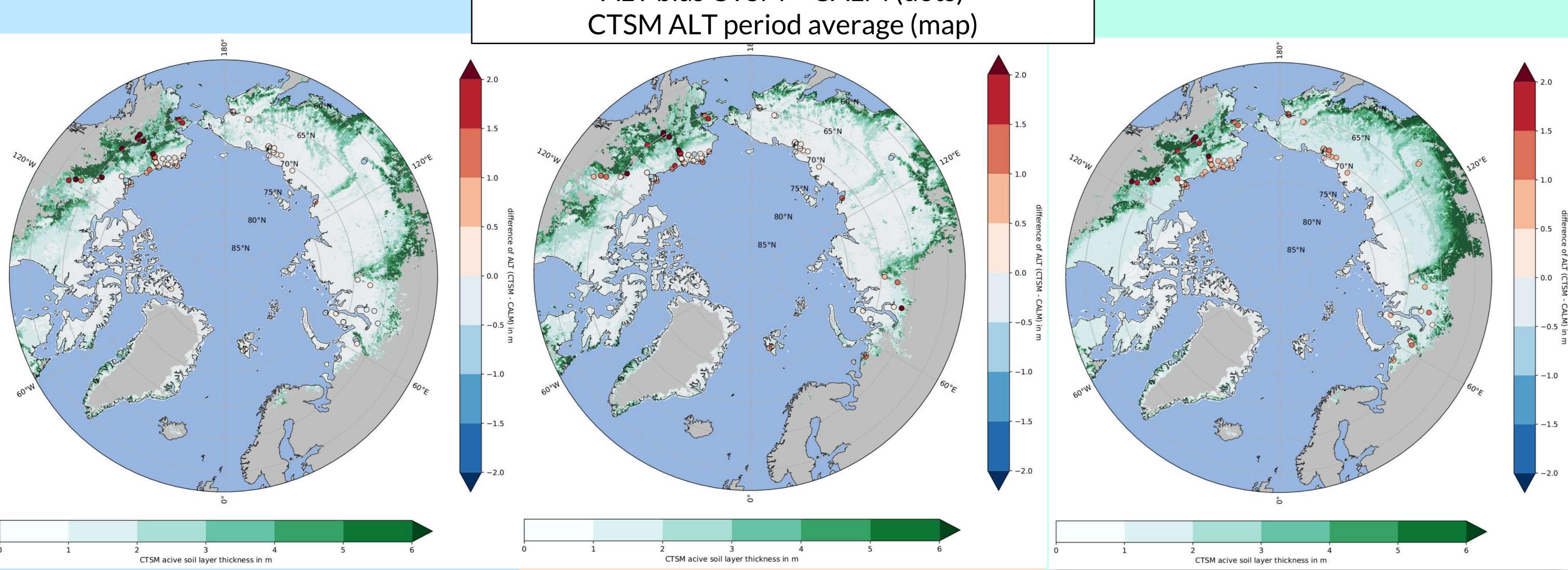


8

Eastern Siberia

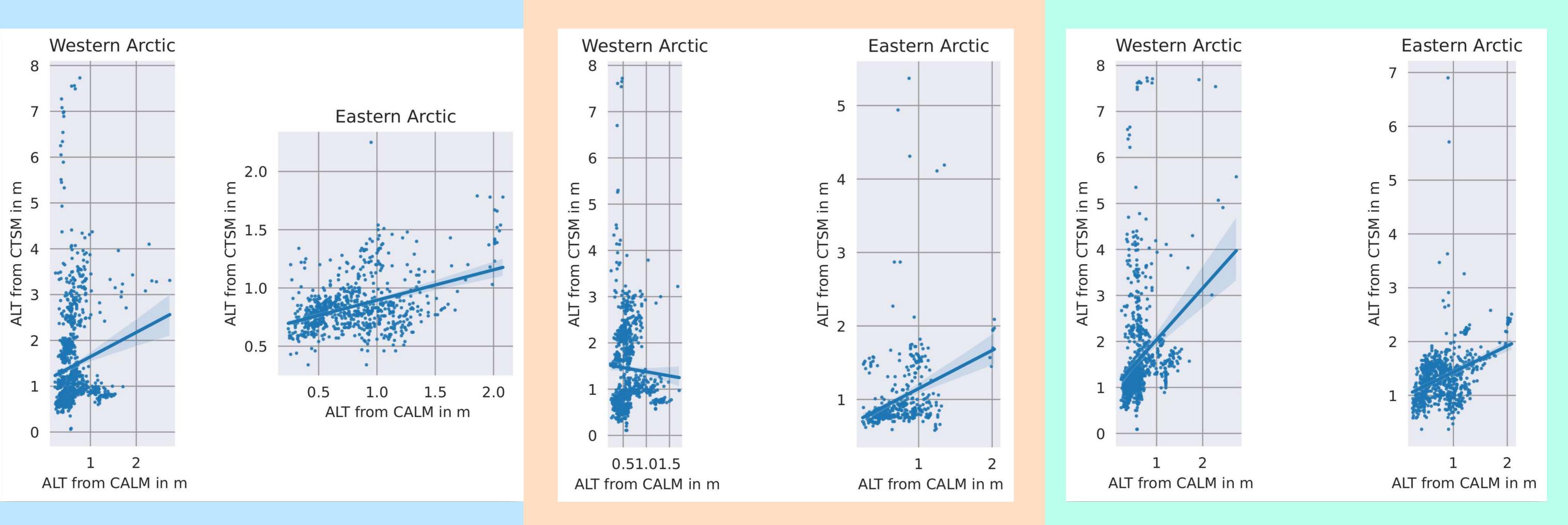
tsm-stations soil temperature (in C)											-6		
12	-12	-12	-8.6	-6.6	-7.6	-8	-8	-6.7	-5.2	-7.4	-9.5		
12	-12	-12	-9.2	-6.6	-7.7	-9.1	-8.8	-7.3	-5.1	-6.8	-9.2		-8
12	-13	-13	-11	-7.6	-6.9	-8.9	-9.5	-8.3	-6.1	-7.2	-10		
15	-16	-16	-14	-9.9	-7.9	-9.2	-11	-10	-8.3	-9.1	-13		-10
13	-14	-14	-13	-9.3	-6.6	-6.9	-8.1	-7.9	-7.3	-7.7	-11		10
													-12
15	-16	-17	-16	-14	-12	-10	-10	-10	-9.9	-9.9	-12		-14
													-2007 84
											-16		
	RMSE ctsm-stations												18

.7	17	16	12	8.6	9.1	9.8	9.8	8.7	7.5	11	14		
.6	17	16	12	8.6	9.1	11	11	9.2	7	9.7	13		16
.6	17	17	14	9.4	8.3	10	11	10	7.8	9.9	14		14
.7	18	18	15	11	8.9	10	12	11	9.4	11	14		14
.6	18	18	16	12	8.3	8.5	9.6	9.7	9	9.9	14		12
.6	18	18	17	14	12	11	11	11	11	11	14		10
J	F	М	А	Μ	J	J	А	S	0	Ν	D	,	8
					mo	nth							



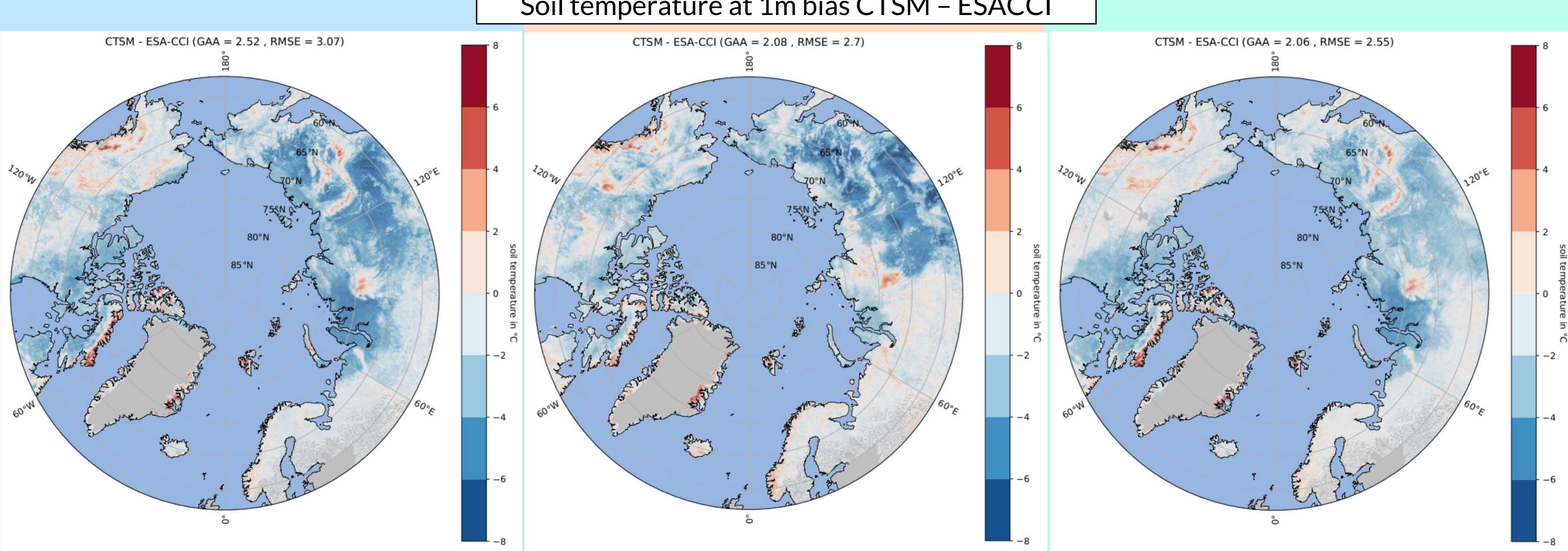
Run 002 GSWP3 Default soil 1991-2014

ALT bias CTSM – CALM (dots)



Run 002 GSWP3 Default soil 1980-2014

ALT bias CTSM – CALM

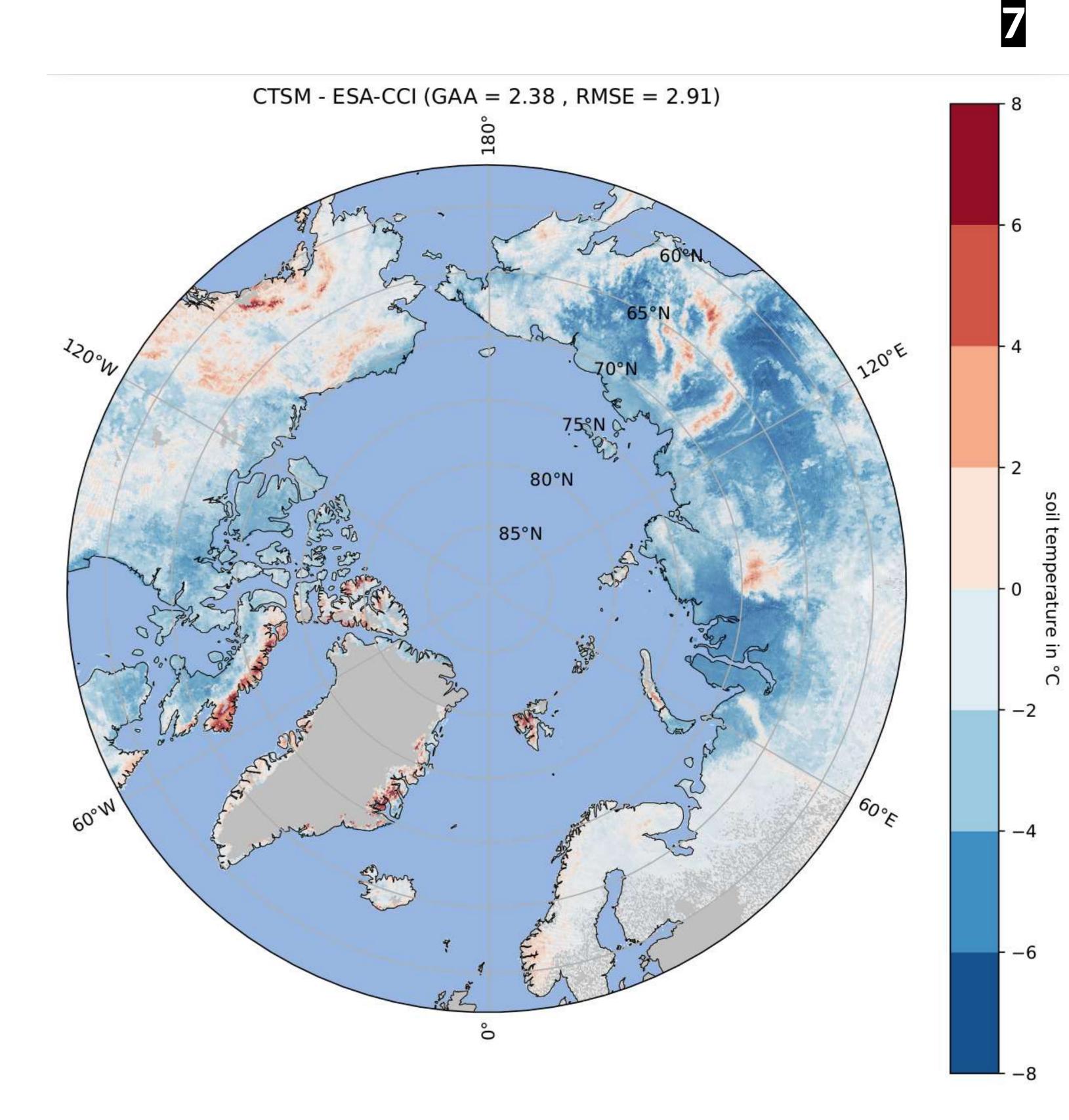


Run 002 GSWP3 Default soil 1980-2014

Soil temperature at 1m bias CTSM – ESACCI

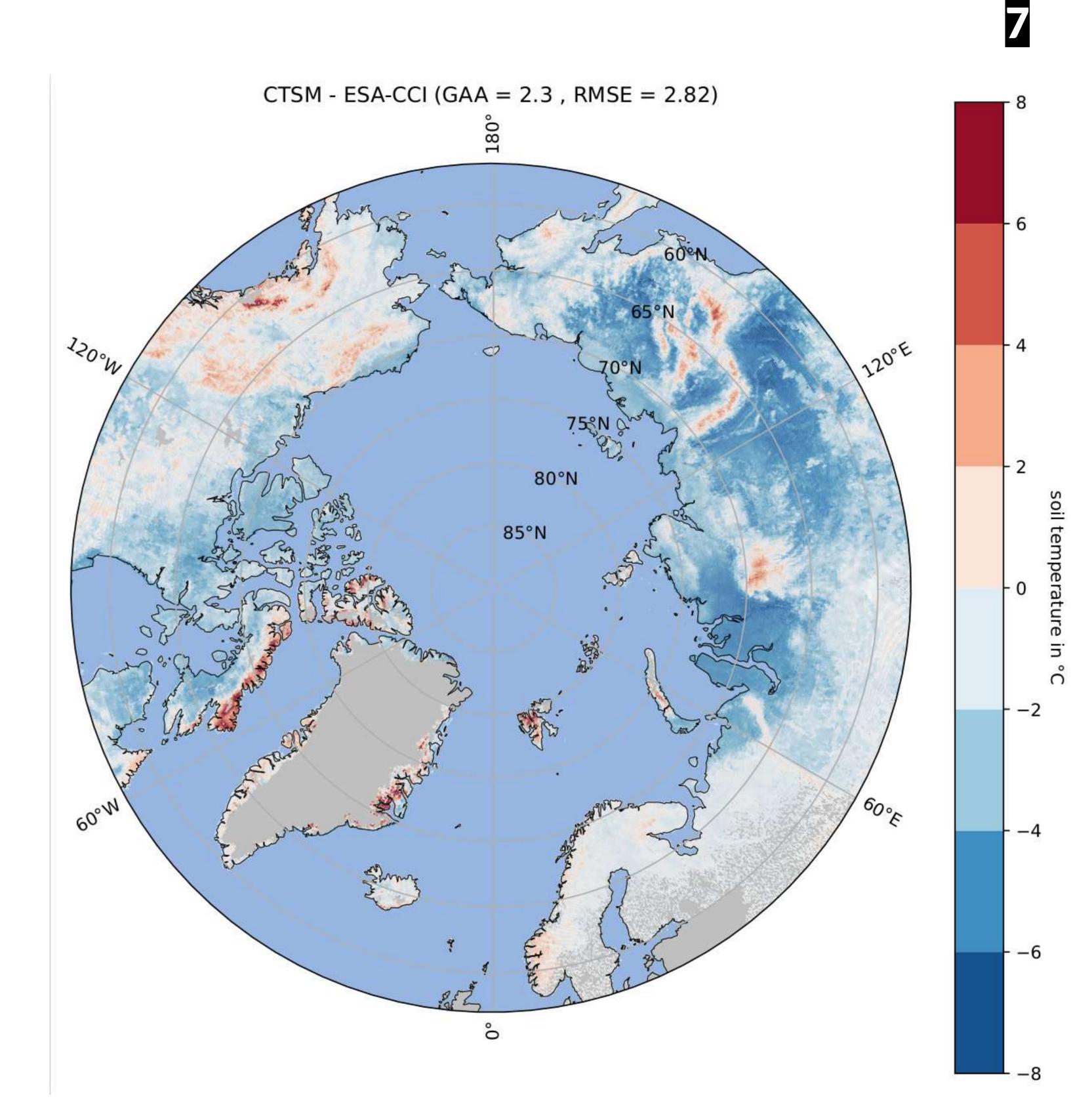


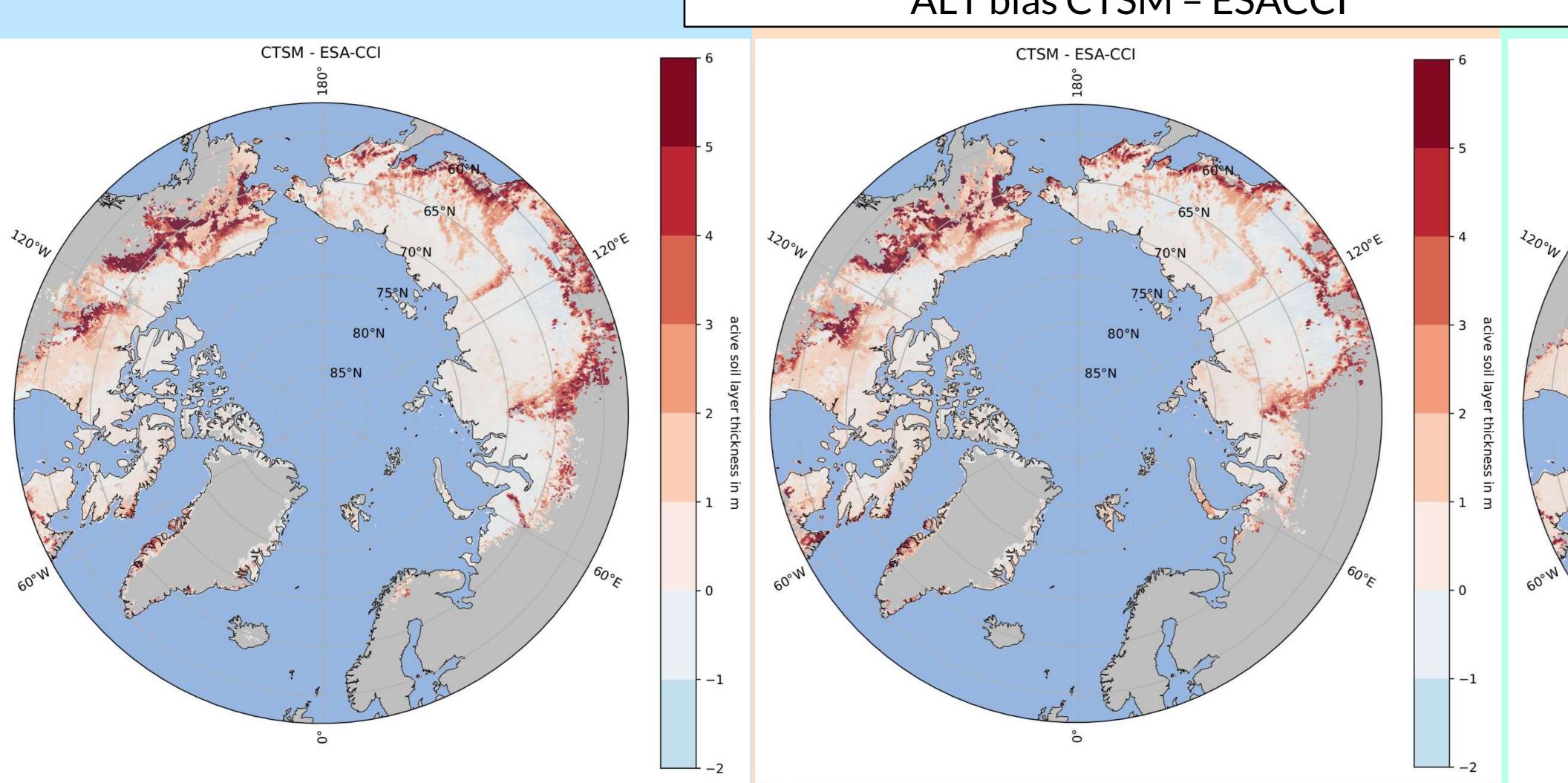
Soil temperature bias at -5 m CTSM – ESACCI





Soil temperature bias at -10 m CTSM – ESACCI

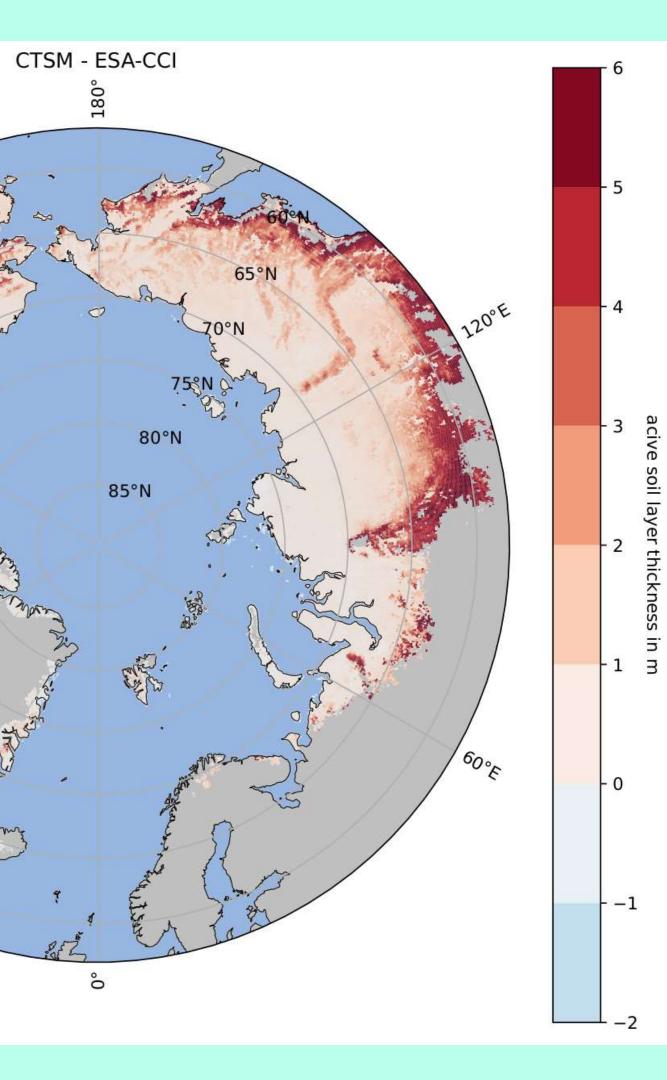




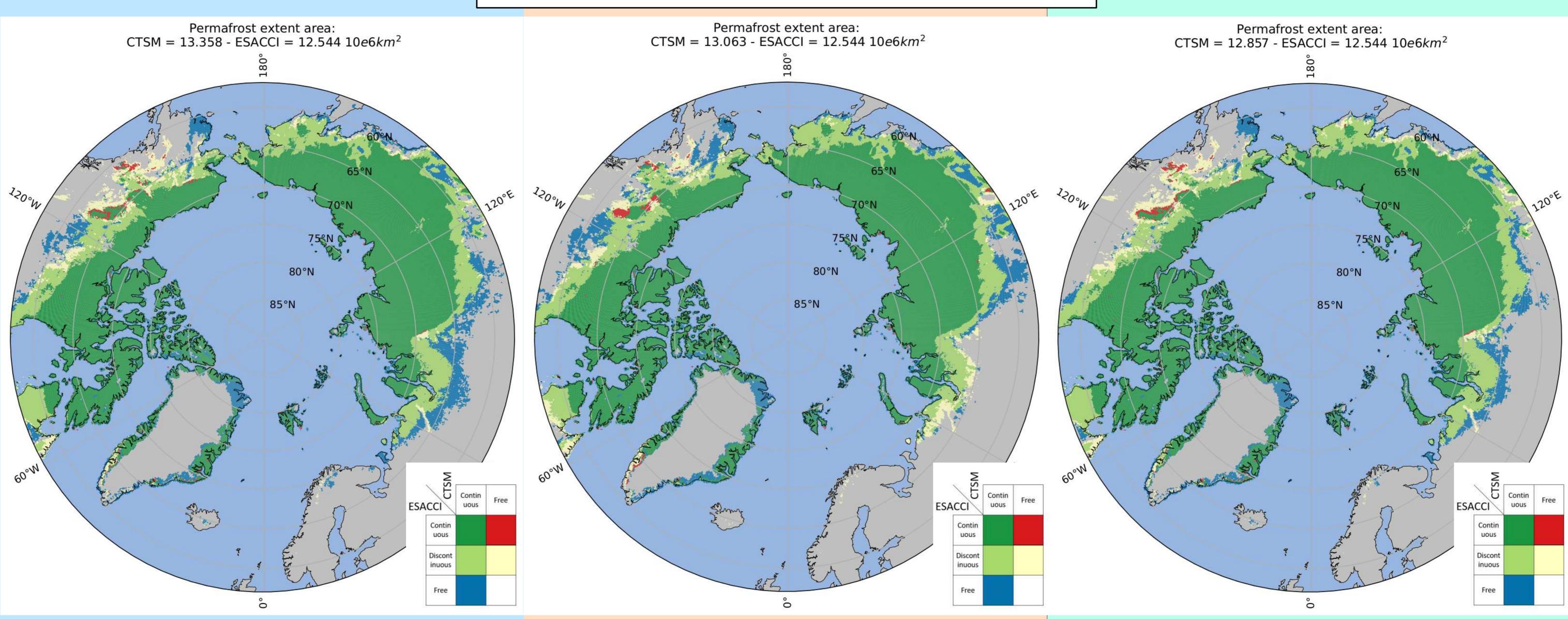
Run 002 GSWP3 Default soil 1980-2014

ALT bias CTSM – ESACCI

Run 005 ERA5 New soil 1980-2021



And the second



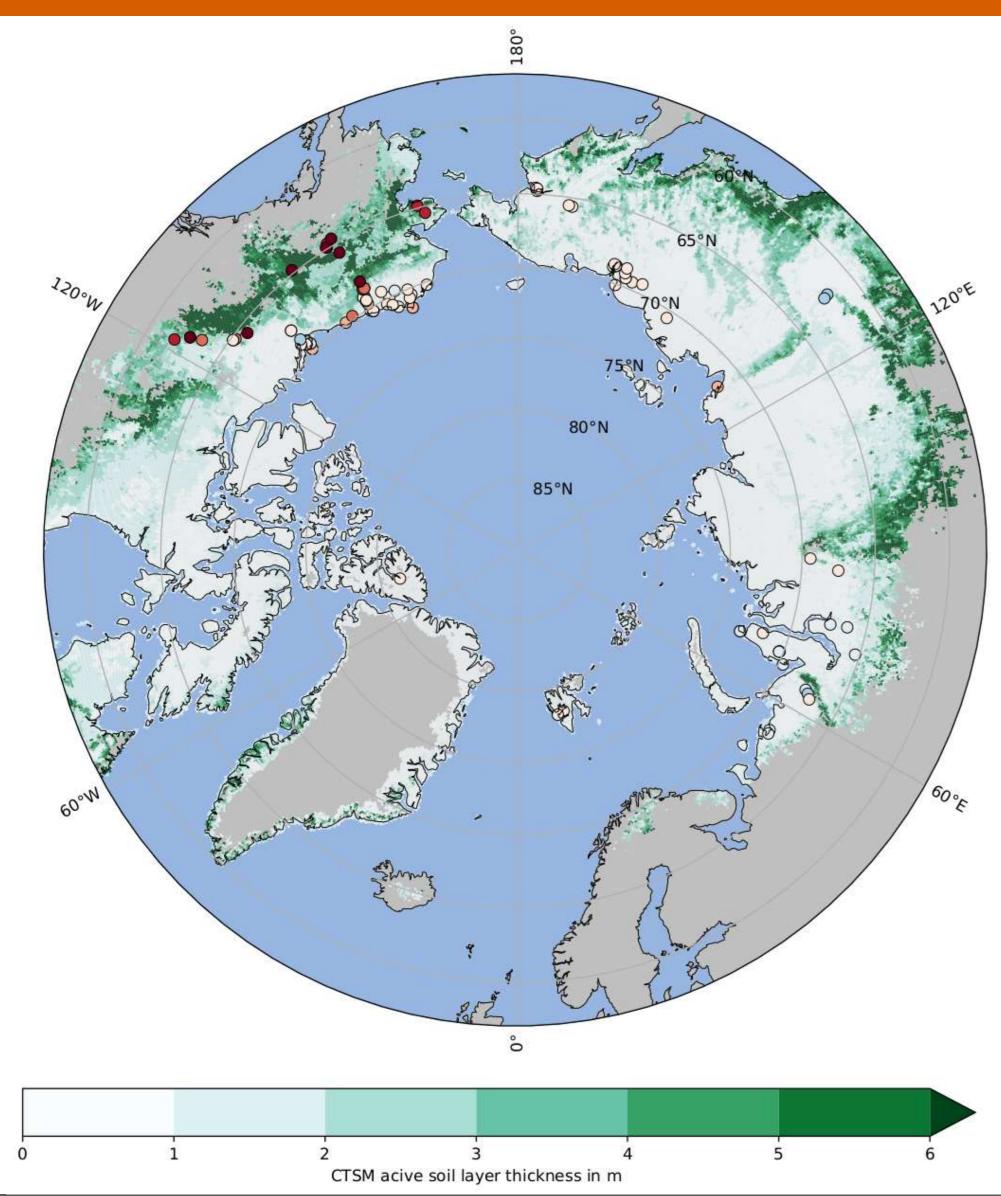
Run 002 GSWP3 Default soil 1980-2014

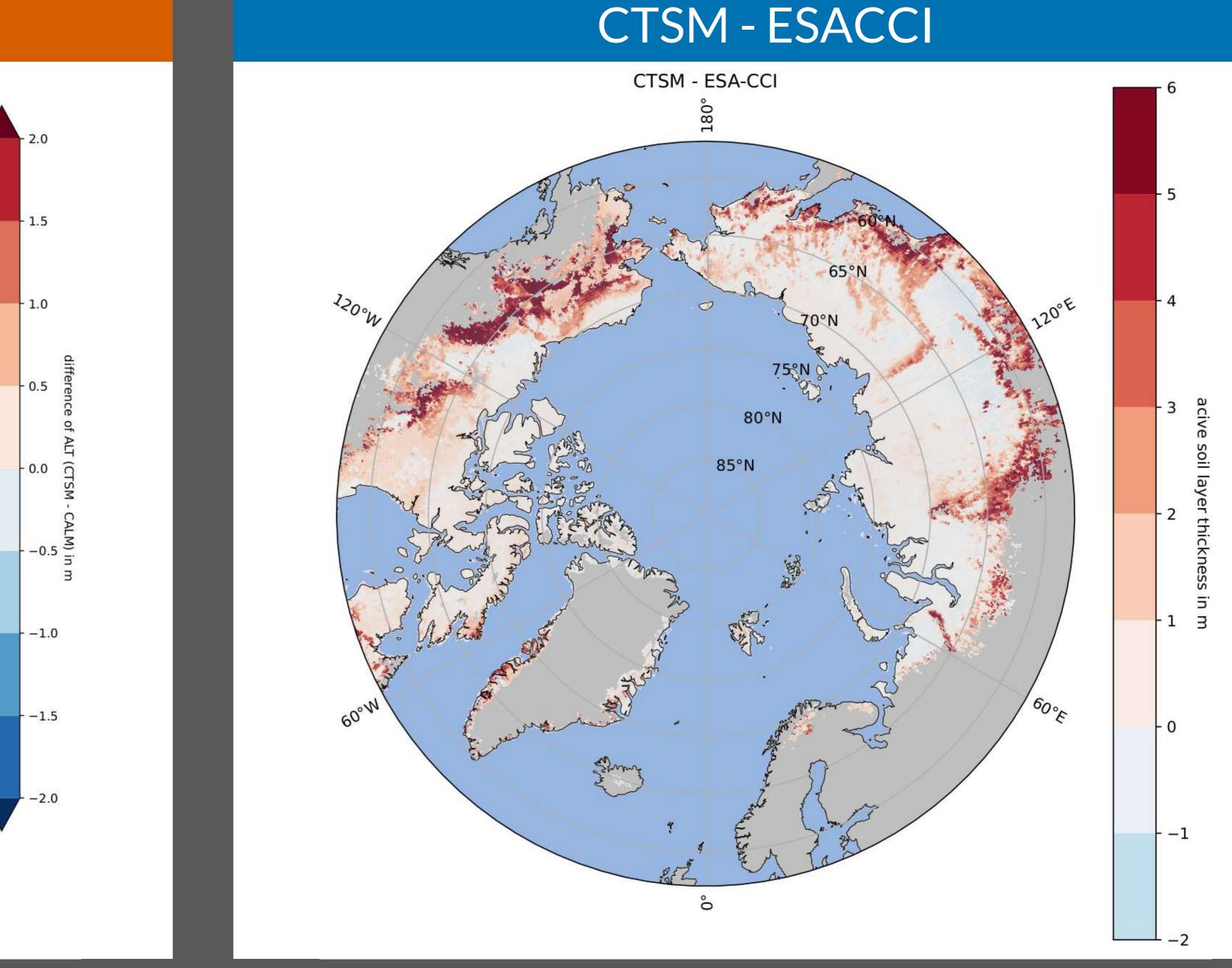
PFR extent CTSM – ESACCI

CALM ESACCI

Active Layer Thickness

CTSM - CALM

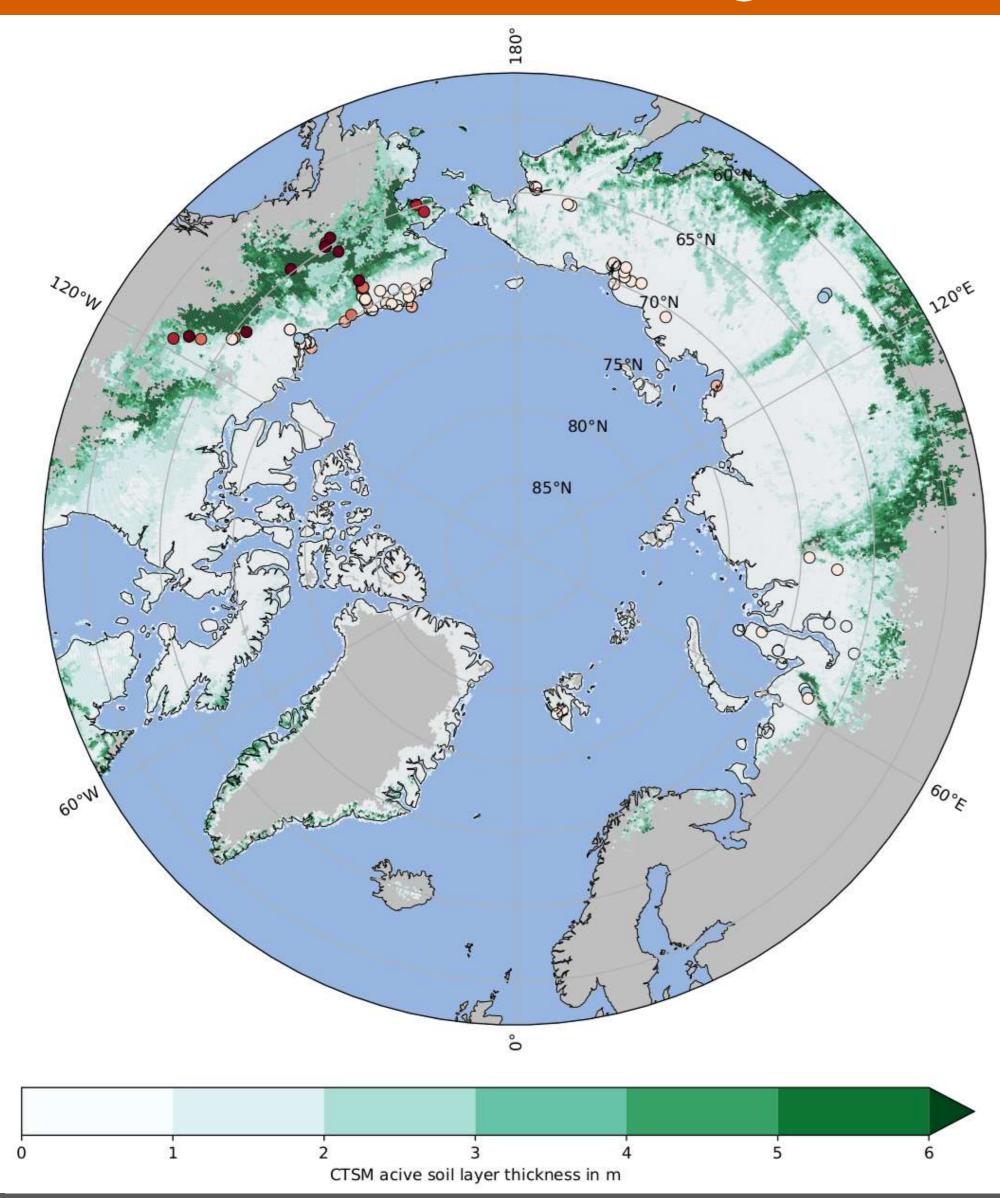


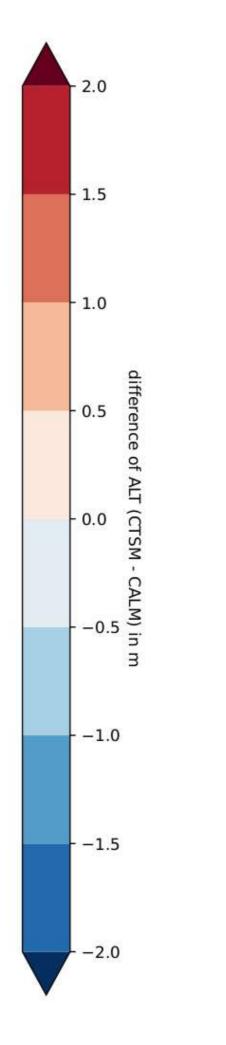


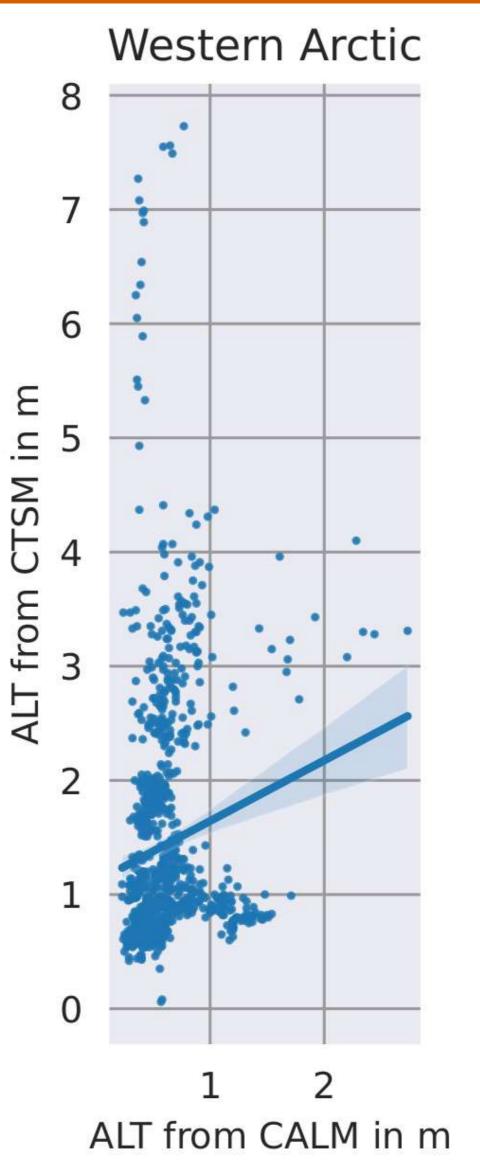


Active Layer Thickness

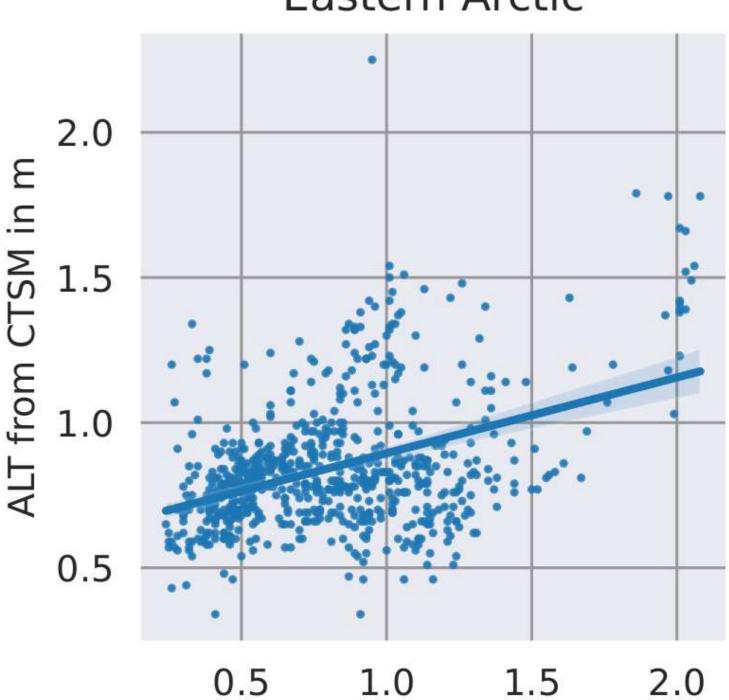
Period average







Not period average

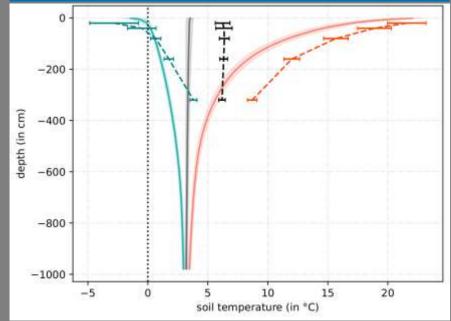


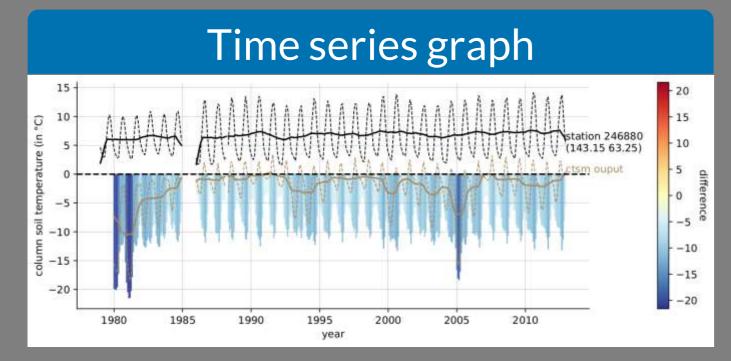
Eastern Arctic

2.0 1.0 1.5 ALT from CALM in m

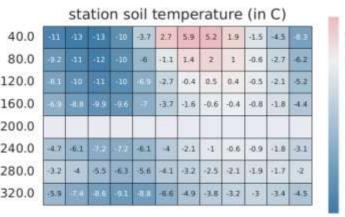
554 in-situ stations

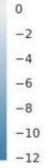
Trumpet curves

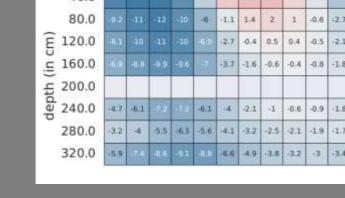




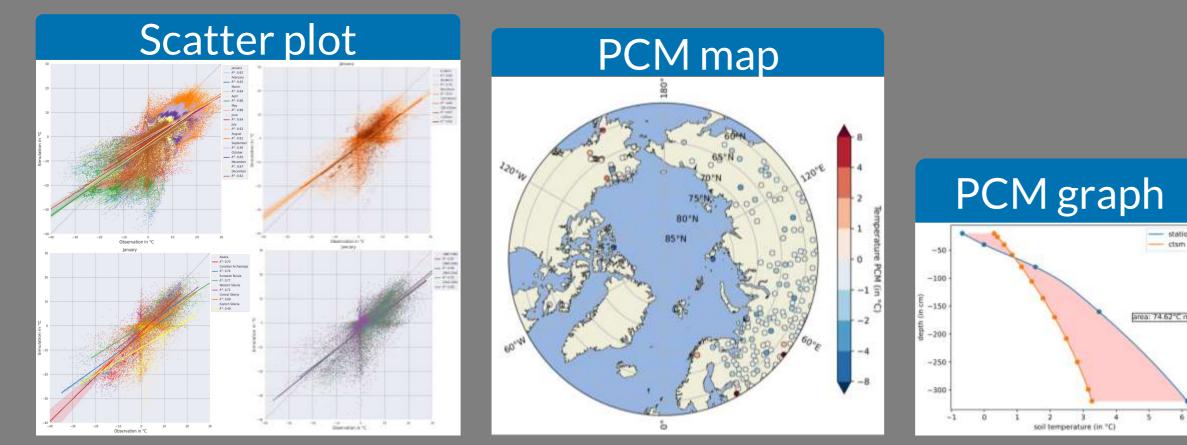










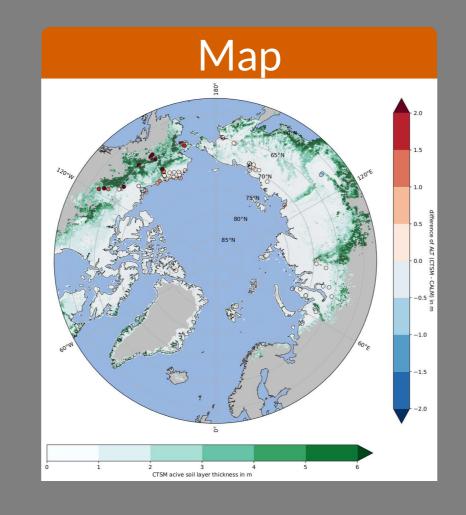


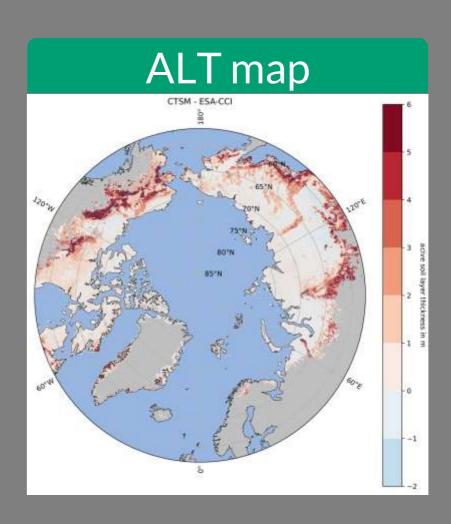
Observation products



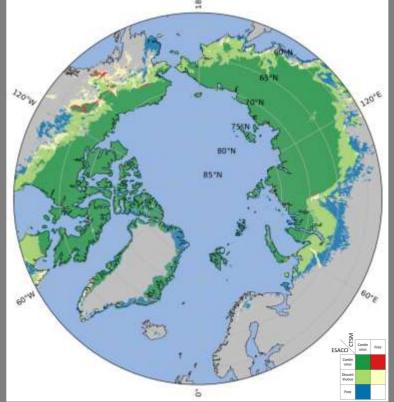
CALM network

ESACCI products









____ station

area: 74.62°C m

2 3 4 soil temperature (in "C)

