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*Supplement of*

## **ORCHIDEE-MICT (v8.4.1), a land surface model for the high latitudes: model description and validation**

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## Soil thermal parameters

	$\theta_{\text{sat}}$ (or porosity) ( $\text{m}^3 \text{m}^{-3}$ )	$\lambda_{\text{dry}}$ ( $\text{W m}^{-1} \text{K}^{-1}$ )	$\lambda_{\text{solid}}$ ( $\text{W m}^{-1} \text{K}^{-1}$ )	$c_{\text{dry}}$ ( $10^6 \text{J K}^{-1} \text{m}^{-3}$ )
sand	0.43	0.22	6.91	1.47
loamy sand	0.41	0.23	6.04	1.41
sandy loam	0.41	0.23	4.49	1.34
silt loam	0.45	0.20	2.80	1.27
silt	0.46	0.20	3.30	1.21
loam	0.43	0.22	3.43	1.21
sandy clay loam	0.39	0.25	4.49	1.18
silty clay loam	0.43	0.22	3.30	1.32
clay loam	0.41	0.23	3.21	1.23
sandy clay	0.38	0.26	4.03	1.18
silty clay	0.36	0.28	3.30	1.15
clay	0.38	0.26	2.80	1.09
pure organic soil	0.92	0.05	0.25	2.50

$\theta_{\text{sat}}$ : volumetric moisture content at saturation (porosity);  $\lambda_{\text{dry}}$ : dry soil thermal conductivity, calculated by the empirical equation:

$$\lambda_{\text{dry}} = \frac{0.135\rho + 64.7}{2700 - 0.947\rho} \text{ with } \rho = 2700(1 - \theta_{\text{sat}})$$

$\lambda_{\text{solid}}$ : thermal conductivity of soil solids;  $c_{\text{dry}}$ : dry soil heat capacity.

**Table S1.** Soil thermal parameters for mineral soil (including 12 USDA soil textures) and organic soil used in Eq. 4.

## 5 Soil hydraulic parameters

	$\theta_r$ ( $\text{m}^3 \text{m}^{-3}$ )	$\alpha$	$n$	$\theta_{fc}$ ( $\text{m}^3 \text{m}^{-3}$ )	$\theta_{wp}$ ( $\text{m}^3 \text{m}^{-3}$ )
sand <sup>a</sup>	0.045	1.45	2.68	0.049	0.045
loamy sand <sup>a</sup>	0.057	1.24	2.28	0.071	0.057
sandy loam <sup>a</sup>	0.065	0.75	1.89	0.122	0.066
silt loam	0.067	0.20	1.41	0.240	0.104
silt	0.034	0.16	1.37	0.258	0.090
loam	0.078	0.36	1.56	0.165	0.088
sandy clay loam	0.100	0.59	1.48	0.169	0.111
silty clay loam	0.089	0.10	1.23	0.338	0.197
clay loam	0.095	0.19	1.31	0.270	0.150
sandy clay	0.100	0.27	1.23	0.267	0.170
silty clay	0.070	0.05	1.09	0.337	0.266
clay	0.068	0.08	1.09	0.347	0.271

**Table S2.** Coefficients in the van Genuchten equation (Eq. 11) and derived field capacity ( $\theta_{fc}$ ) and permanent wilting point ( $\theta_{wp}$ ) for the 12 USDA soil textures. <sup>a</sup>: for the three sandy soils, field capacity corresponds to  $\psi = -10 \text{ kPa}$  instead of  $-33 \text{ kPa}$ .

## Number of ignitions in the SPITFIRE module in ORCHIDEE-MICT

Region	BONA	TENA	CEAM	NHSA	SHSA	EURO	MIDE	NHAF	SHAF	BOAS	CEAS	SEAS	EQAS	AUST
Ratio	2.09	0.04	1.02	0.62	0.67	1.20	2.85	56.24	31.67	3.39	1.68	12.64	99.80	3.56

**Table S3.** Region-specific values used to scale the simulated number of ignitions in the SPITFIRE module in ORCHIDEE-MICT. Refer to <http://www.globalfiredata.org/data.html> for the acronyms of different regions.

## 5 Selected northern watersheds for discharge and water balance evaluation

Station name	Basin name	Longitude (°E)	Latitude (°N)	Basin area (km <sup>2</sup> )	Q <sub>mean</sub> GRDC (m <sup>3</sup> s <sup>-1</sup> )	Naturalized Q <sub>mean</sub> (m <sup>3</sup> s <sup>-1</sup> )	Permafrost area (%)
Pilot station	Yukon	-162.88	61.93	831390	6553	-	87
Arctic Red River	Mackenzie	-133.75	67.46	1660000	9044	-	42
Volgograd Power Plant	Volga	44.59	48.81	1360000	8246	-	-
Salekhard	Ob	66.53	66.57	2949998	12960	13005	4
Igarka	Yenisei	86.50	67.48	2440000	19400	19234	42
Kusur	Lena	127.65	70.70	2430000	17550	17426	90
Kolymaskaya	Kolyma	158.72	68.73	526000	3252	-	100

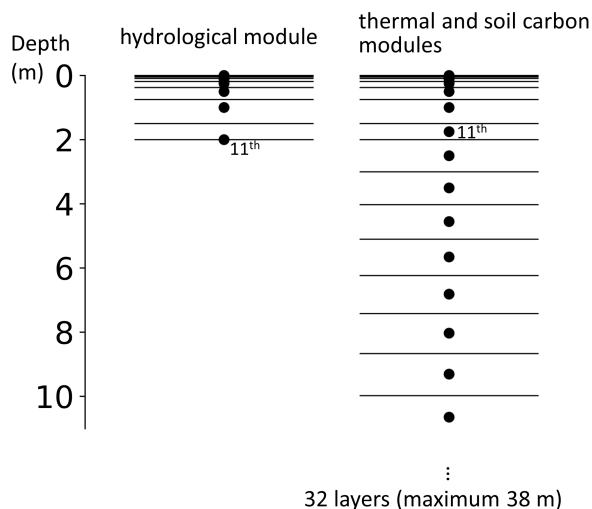
**Table S4.** List of the gauge stations of the seven major Arctic rivers studied. Q<sub>mean</sub> is the mean annual discharge from the two databases, averaged over the period 1981-2007. Permafrost coverage (continuous + discontinuous permafrost) is calculated using data from Brown et al. (1998) over the entire basin considered (Holmes et al., 2012).

## Relationships between river discharge bias in Spring and pre-melt SWE bias

Basin name	Pre-melt SWE bias (m <sup>3</sup> s <sup>-1</sup> ) [average Feb.-Mar.]		Spring flow bias (m <sup>3</sup> s <sup>-1</sup> ) [sum Apr.-Jun.]		Spring flow bias explained by the pre-melt SWE bias (%)	
	GSWP3	CRUNCEP	GSWP3	CRUNCEP	GSWP3	CRUNCEP
1: Yukon	+1825	-6420	+13180	-18900	14	34
2: Mackenzie	+2700	-3200	+38350	+1880	7	-170
3: Volga	+9140	+2615	+57360	+30030	16	9
4: Ob	+11825	-3510	+64960	+30730	18	-11
5: Yenisei	+6235	-4730	+6430	-46470	97	10
6: Lena	-530	-9515	+18160	-39550	-3	24
7: Kolyma	+560	-2580	+4430	-11175	13	23

**Table S5.** SWE bias during the pre-melt season (average between February and March) and the bias of discharge in spring (total discharge between April and June) (both in m<sup>3</sup> s<sup>-1</sup>) with the two forcings in each basin, over the period 1981-2007. The two last columns are the contribution of the pre-melt SWE bias to the spring discharge bias (in %). Bias is defined here exactly like in Fig. 22.

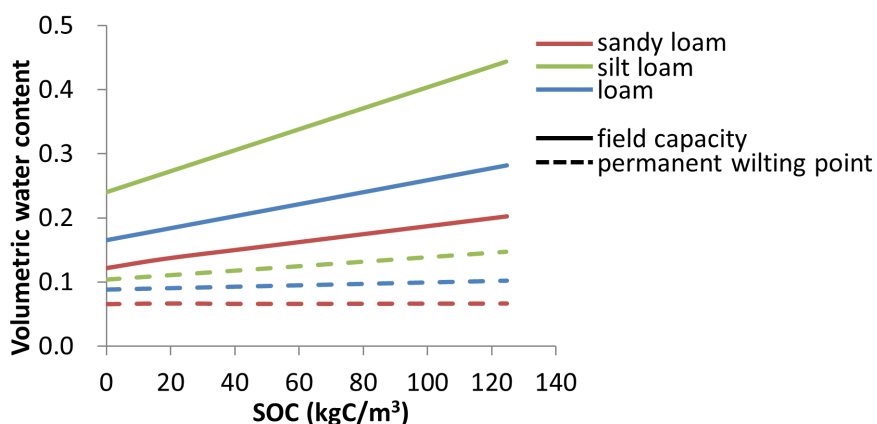
## Soil vertical discretization in ORCHIDEE-MICT



**Figure S1.** Soil vertical discretization in ORCHIDEE-MICT. Solid lines and black dots represent the interfaces and nodes of each layer respectively. The soil hydrological module has 11 layers to 2 meters; the soil thermal and soil carbon modules have 32 layers to 38 meters, in which the first 11 layers are identical to that in hydrology, except that the nodes of the 1st and 11th layer in hydrology lie at the interface.

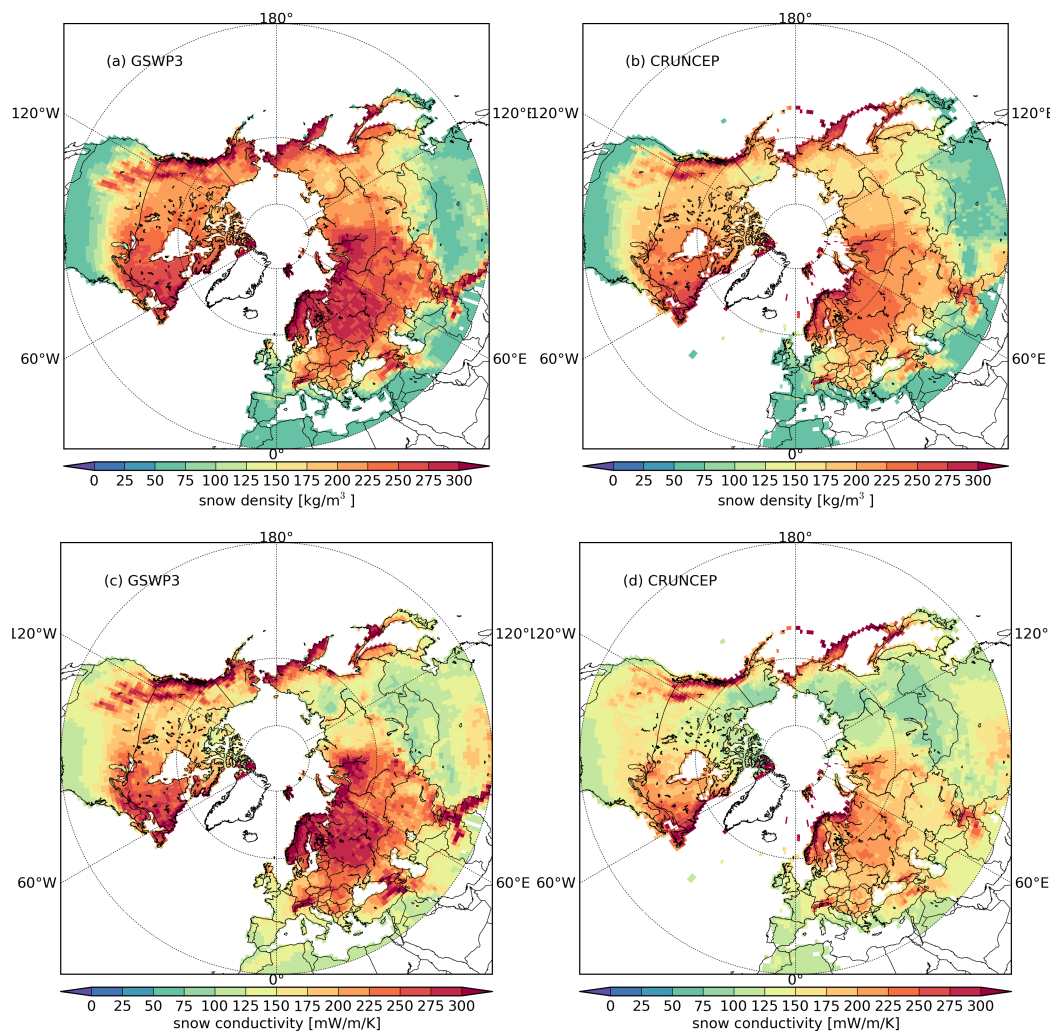
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## Soil moisture content as a function of soil organic carbon



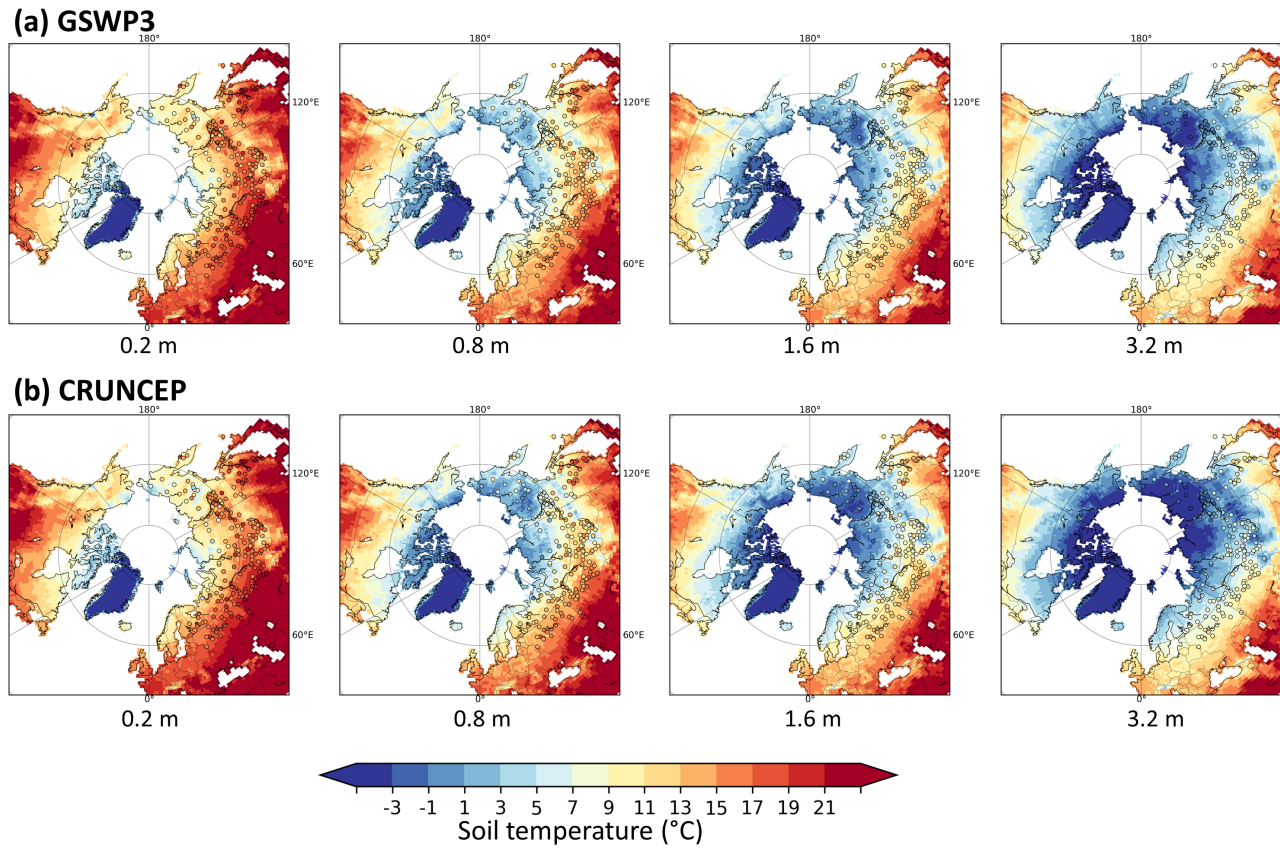
**Figure S2.** Parameterization of soil moisture content at field capacity ( $\theta_{fc}$ ) and permanent wilting point ( $\theta_{wp}$ ) as a function of soil organic carbon, for three representative soil textures in the northern high latitudes. The difference between  $\theta_{fc}$  and  $\theta_{wp}$  represents the water holding capacity of the soil as a function of SOC.

## Snow density and conductivity



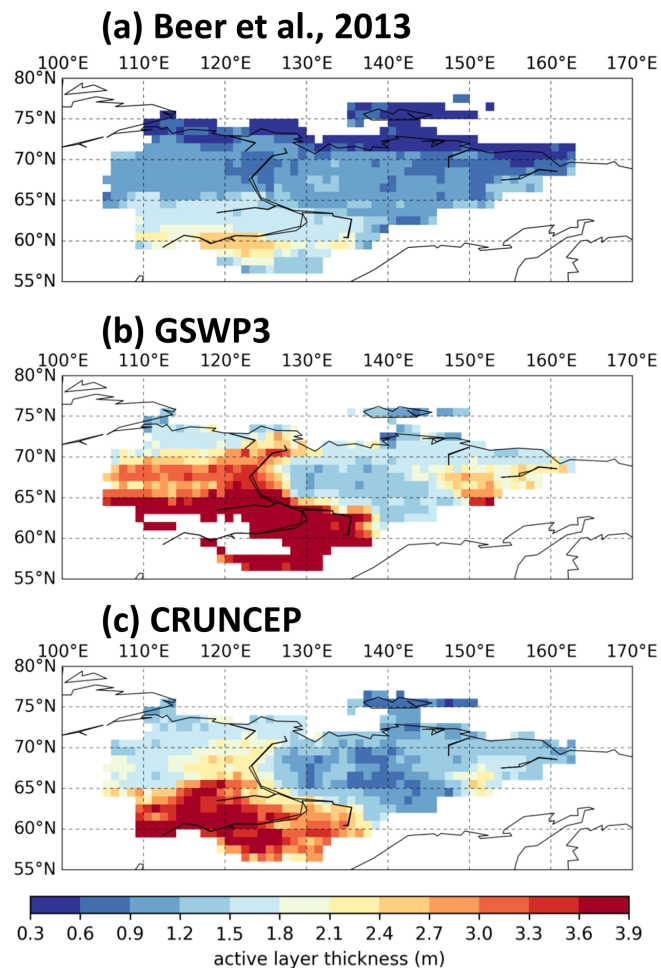
**Figure S3.** (a,b) Mean snow density ( $\text{kg m}^{-3}$ ) and (c,d) snow conductivity ( $\text{mW m}^{-1} \text{K}^{-1}$ ) computed over the three snow layers, averaged over the period 1981-2007. Results from the (a,c) GSWP3 and (b,d) CRUNCEP-forced simulation.

## Maximum monthly soil temperature

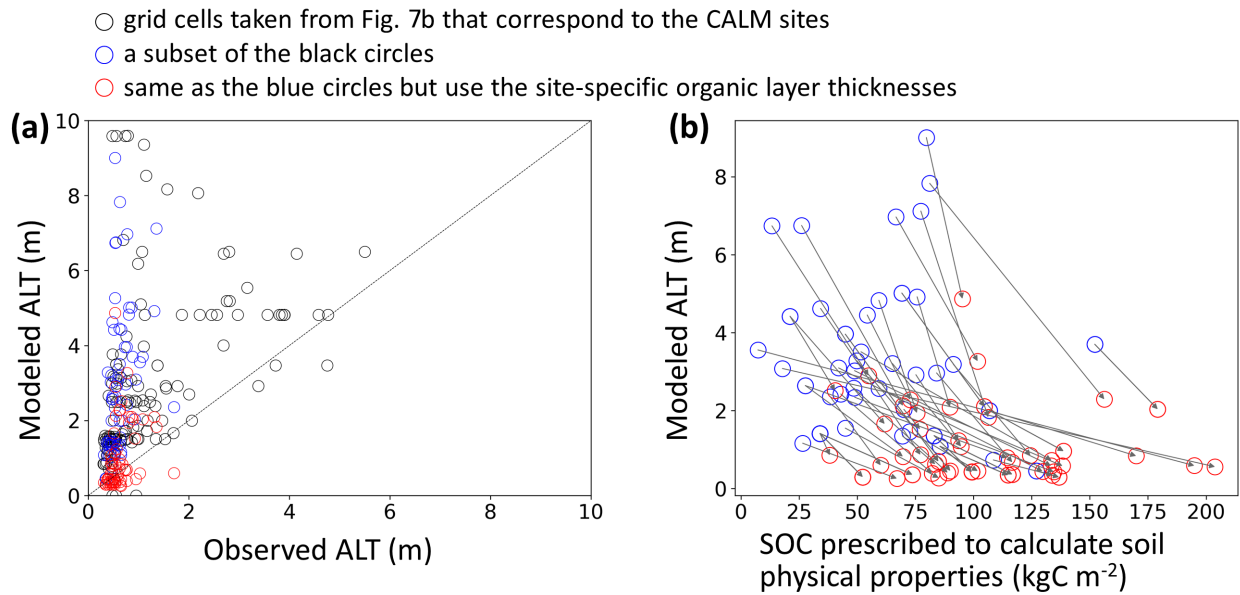


**Figure S4.** Maximum monthly soil temperature at different depths in **(a)** GSWP3 and **(b)** CRUNCEP-forced simulation (background maps), compared to the site observations (color filled circles), averaged over the period 1981-2000.

## Active layer thickness



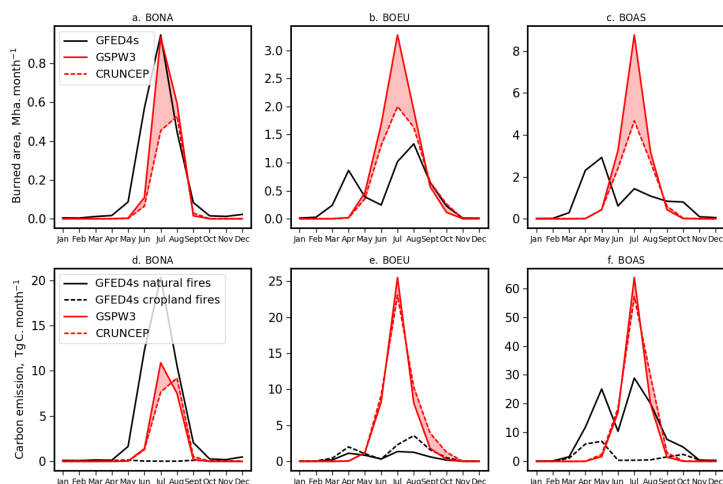
**Figure S5.** (a) Active layer thickness (ALT) of Yakutia, East Siberia, upscaled based on the map of landscapes and permafrost conditions in Yakutia by Beer et al. (2013). (b,c) Modeled ALT for the same region with GSWP3 and CRUNCEP, averaged over the period 1960-1987 to be consistent with Beer et al. (2013).



**Figure S6.** (a) Scatter plot of modeled ALT forced by CRUNCEP compared with observed ALT from the CALM network, averaged over the period 1990-2007. The black circles represent the grid cells taken from the regional simulation (shown in Fig. 7b). The blue circles represent a subset of the CALM sites for which we performed additional runs using site-specific organic layer thicknesses, with the result shown by the red circles. (b) Illustration for the difference of the additional site simulations. Each grey arrow connects the same site, pointing from the blue circles using soil carbon content from NCSCD (upscaled at  $1^\circ$  by  $1^\circ$  resolution) to calculate soil physical properties, to the red circles using the organic layer thickness provided by the sites. See text for further information.

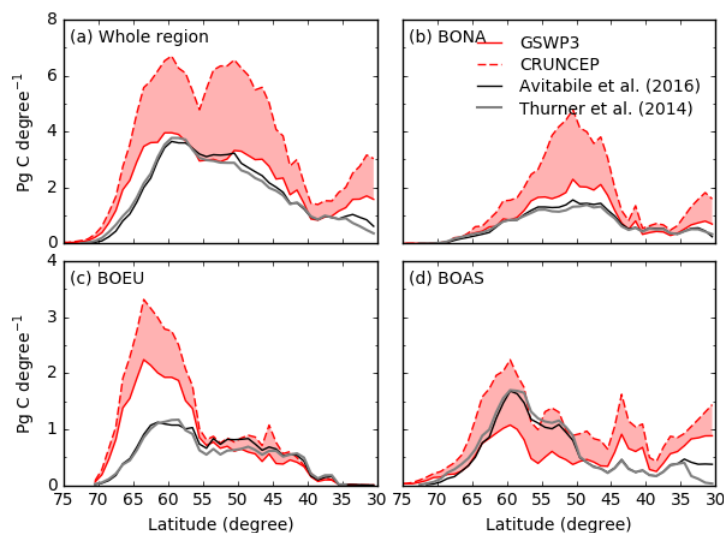


## Seasonal cycle of burned area and fire carbon emissions



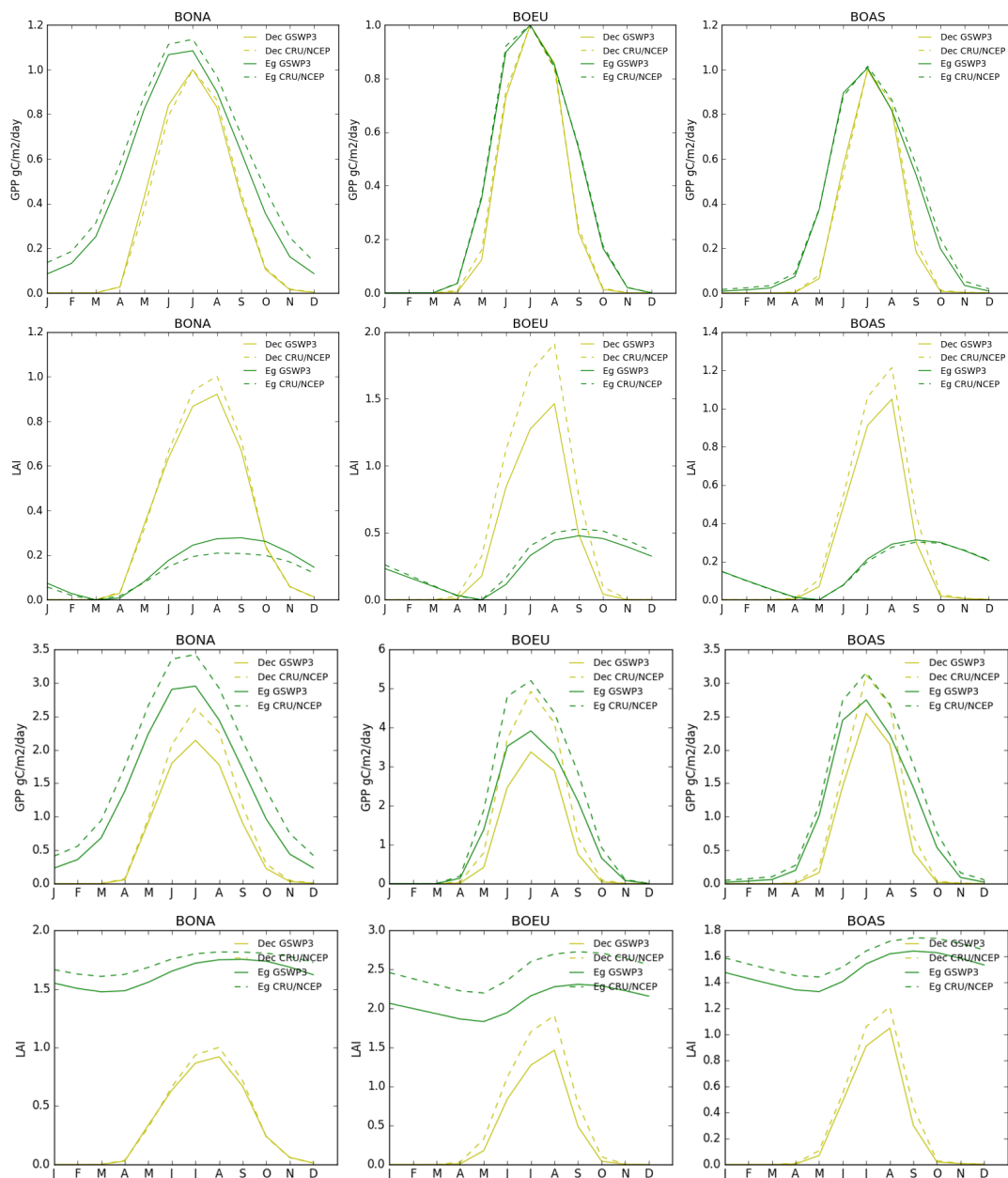
**Figure S7.** Monthly mean seasonal (a-c) fire burned area ( $\text{Mha month}^{-1}$ ) and (d-f) carbon emissions to the atmosphere ( $\text{TgC month}^{-1}$ ) from the GFED4s dataset and the two simulations, averaged over the period 1997–2007. For carbon emissions, cropland and natural fires are represented separately.

## Latitudinal distribution of fire carbon emissions



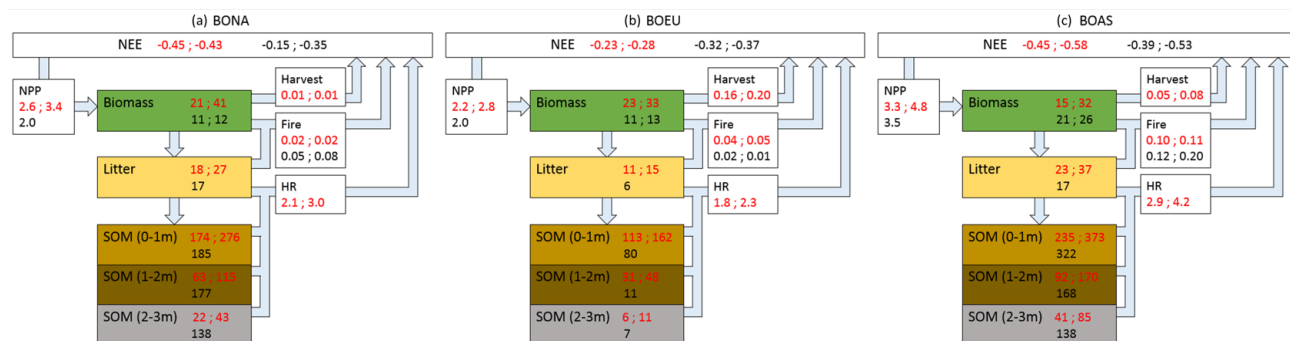
**Figure S8.** Latitudinal distribution of total annual forest biomass carbon stocks ( $\text{PgC degree}^{-1}$ ) in the GSWP3 and CRUNCEP-forced simulations, compared to observations by Avitabile et al. (2016) and Thurner et al. (2014) for (a) the whole model domain. High-latitude sub-regions of (b) BONA, (c) BOEU and (d) BOAS have been extended to  $30^{\circ}\text{N}$  here compared to their shapes in Fig. 2a.

## LAI and GPP seasonality between deciduous and evergreen forests



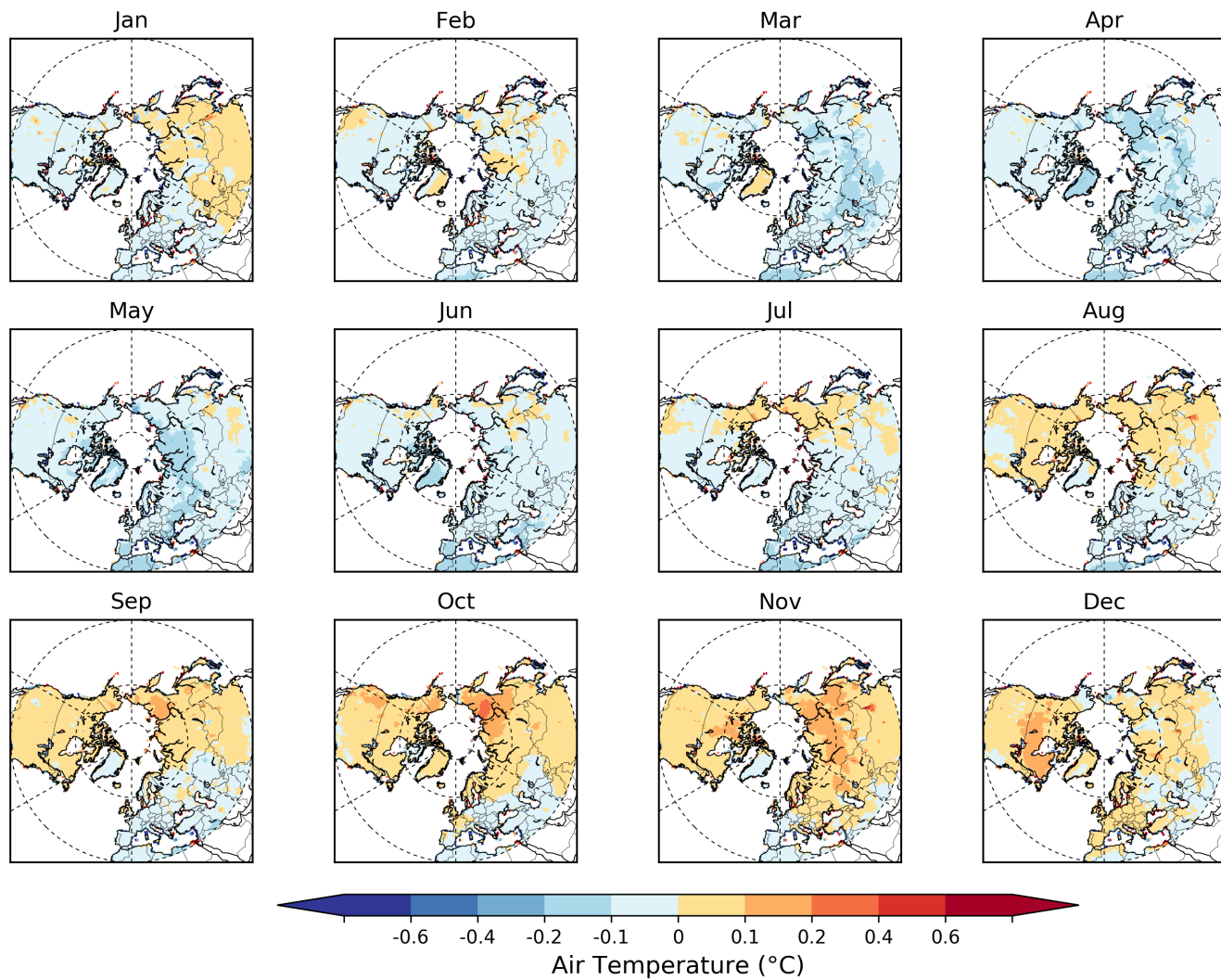
**Figure S9.** Monthly mean seasonal (**first and third panels**) GPP ( $\text{gC m}^{-2} \text{day}^{-1}$ ) and (**second and fourth panels**) LAI (-) for deciduous (light green) and conifer forests (dark green), over the three high-latitude sub-regions (shown in Fig. 2a), averaged over the period 2000-2007. The lower panel shows absolute values and the upper one values scaled for a better comparison.

## Land carbon fluxes and pools modeled and derived from observations

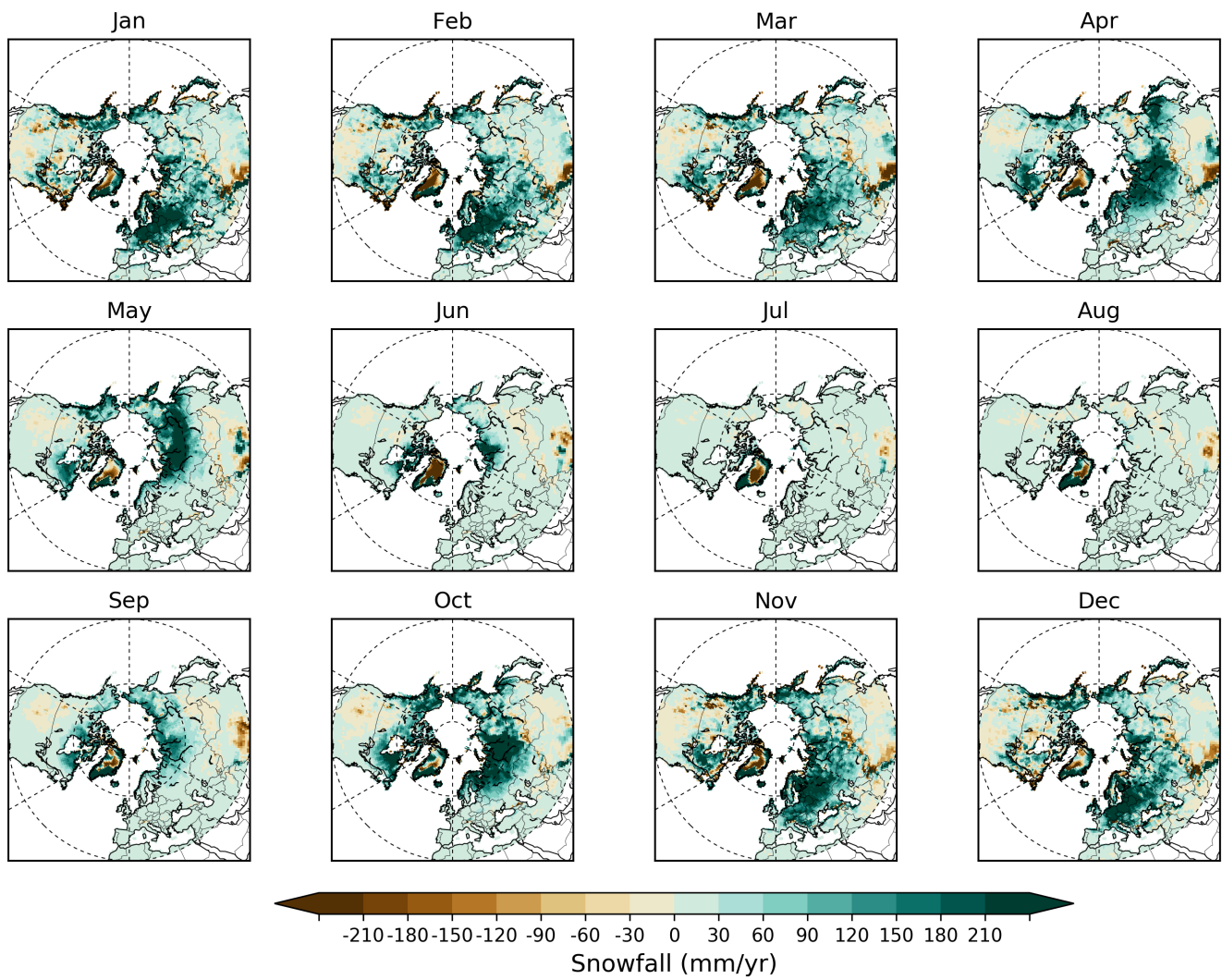


**Figure S10.** Annual mean land carbon fluxes ( $\text{PgCyr}^{-1}$ ) and pool sizes ( $\text{PgC}$ ) over the three high-latitude sub-regions (shown in Fig. 2a) **(a)** BONA, **(b)** BOEU and **(c)** BOAS, averaged over the period 2000-2007. The red numbers are the model results forced by (left) GSWP3 and (right) CRUNCEP. The black numbers are from observation-based estimates used in the text : NPP from MODIS (NTSG), fire emissions from (left) GFED4s and (right) GFAS datasets, harvest fluxes include crop harvest and wood product decay in the model (for simplicity the change in wood product pools is not represented), NEE from the two atmospheric inversions (left) Jena CarboScope and (right) CAMS, biomass from (left) Avitabile et al. (2016) and (right) Turner et al. (2014), litter from Pan et al. (2011), soil carbon from NCSCD (Hugelius et al., 2013) in permafrost regions and HWSD in non-permafrost regions.

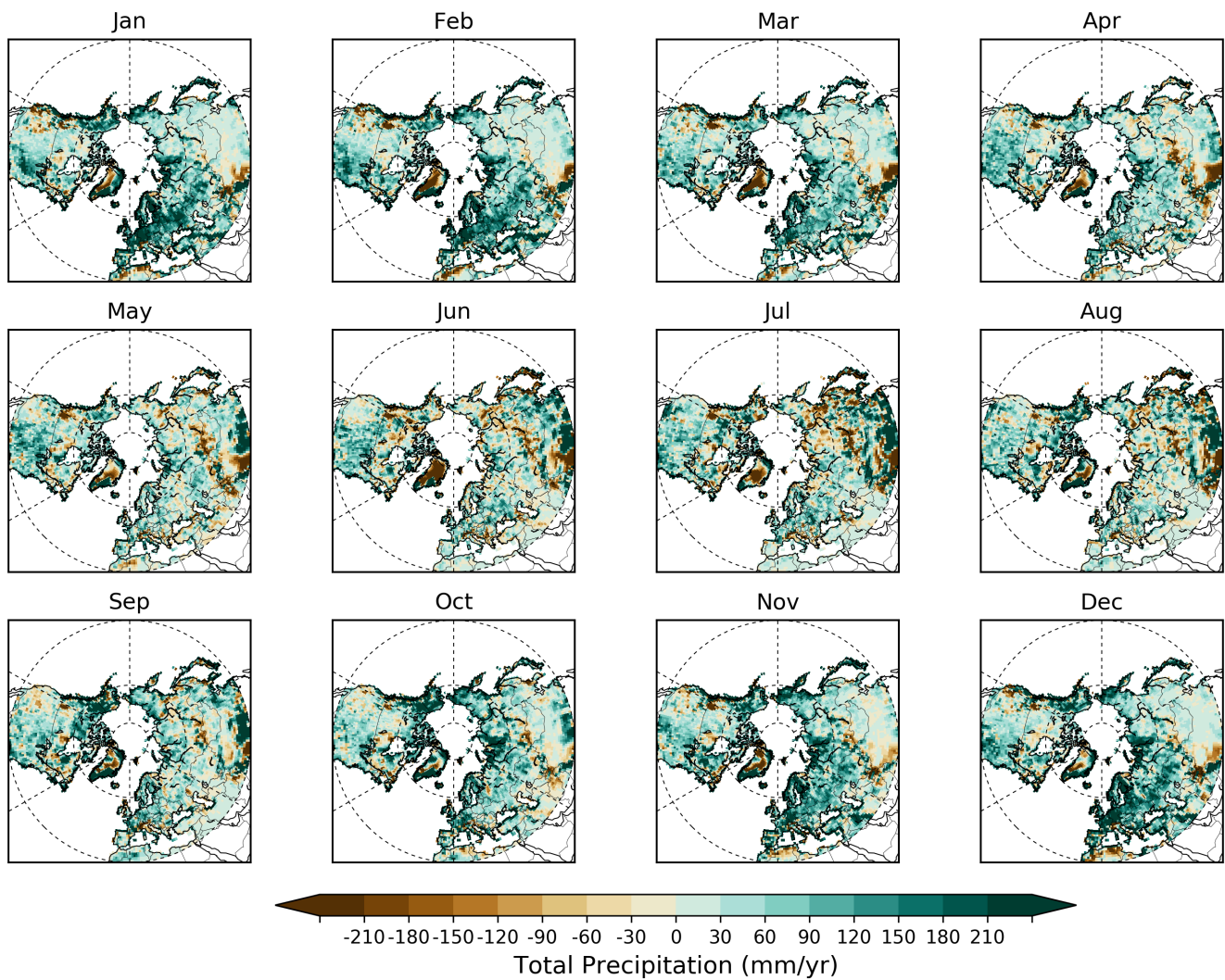
Differences of atmospheric variables between GSWP3 and CRUNCEP forcings (GSWP3 minus CRUNCEP)



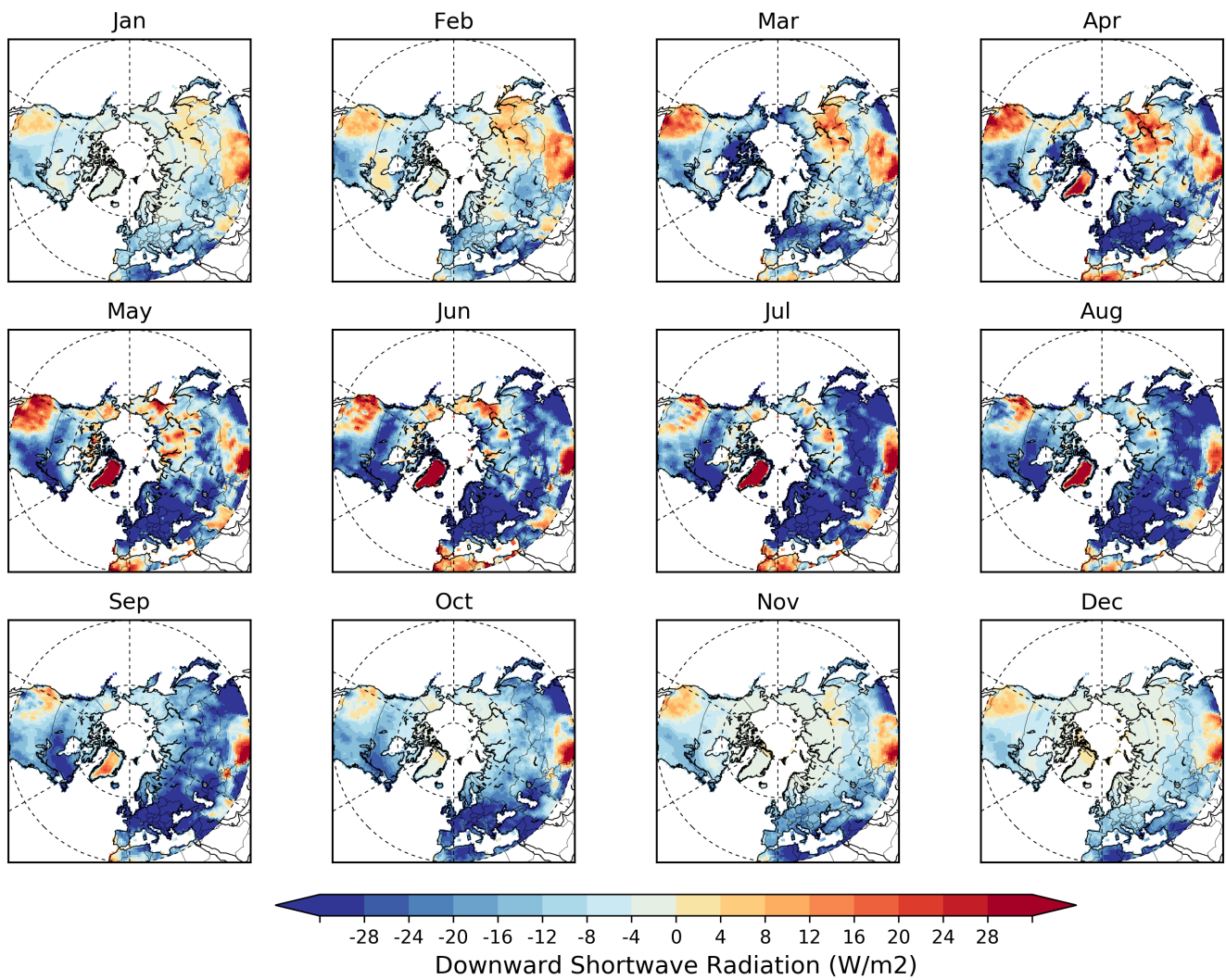
**Figure S11.** Difference in monthly air temperature (°C) between GSWP3 and CRUNCEP (GSWP3 minus CRUNCEP), averaged over the period 1981-2007.



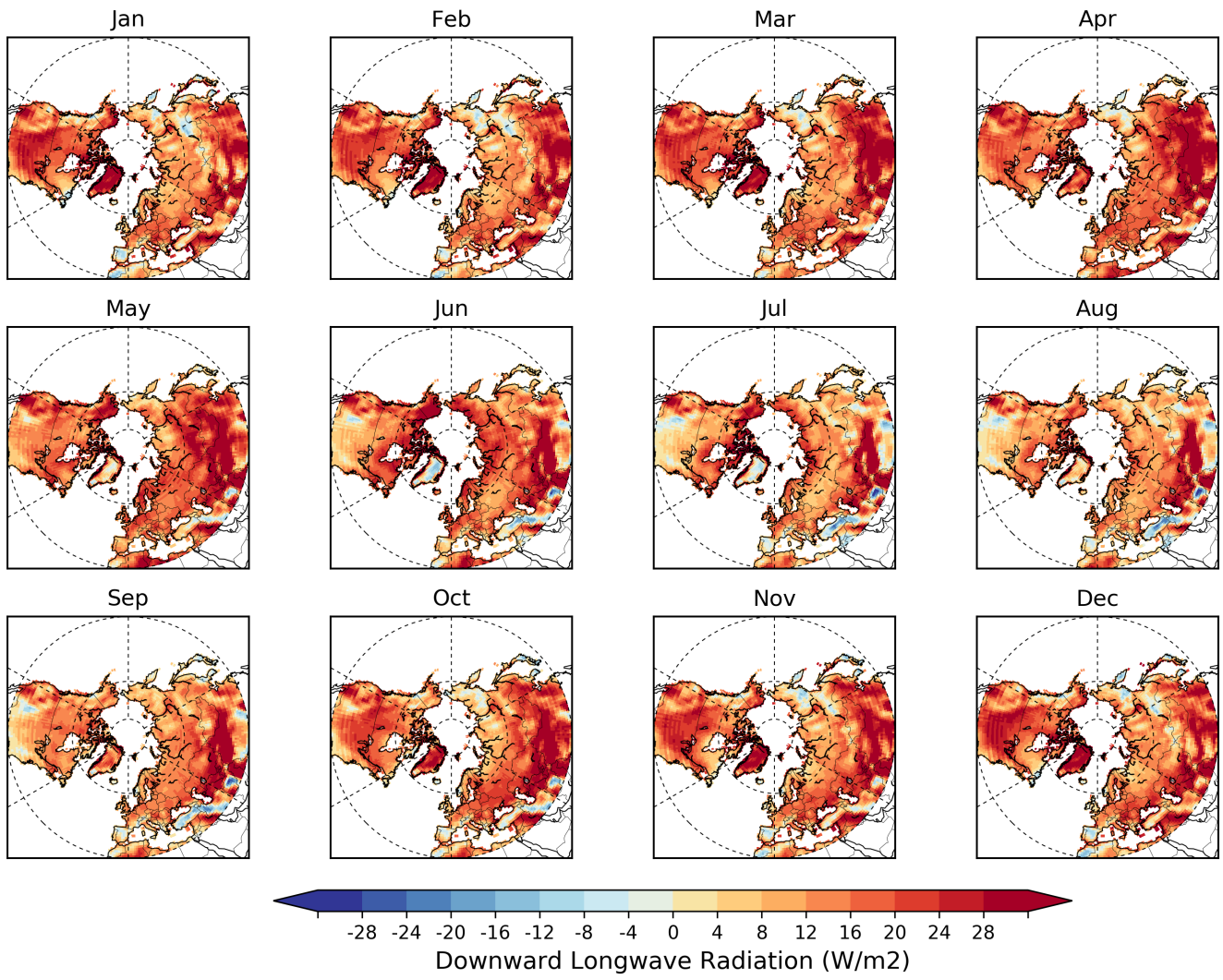
**Figure S12.** Same as Fig. S11 but for snowfall ( $\text{mm yr}^{-1}$ )



**Figure S13.** Same as Fig. S11 but for total precipitation ( $\text{mm yr}^{-1}$ )

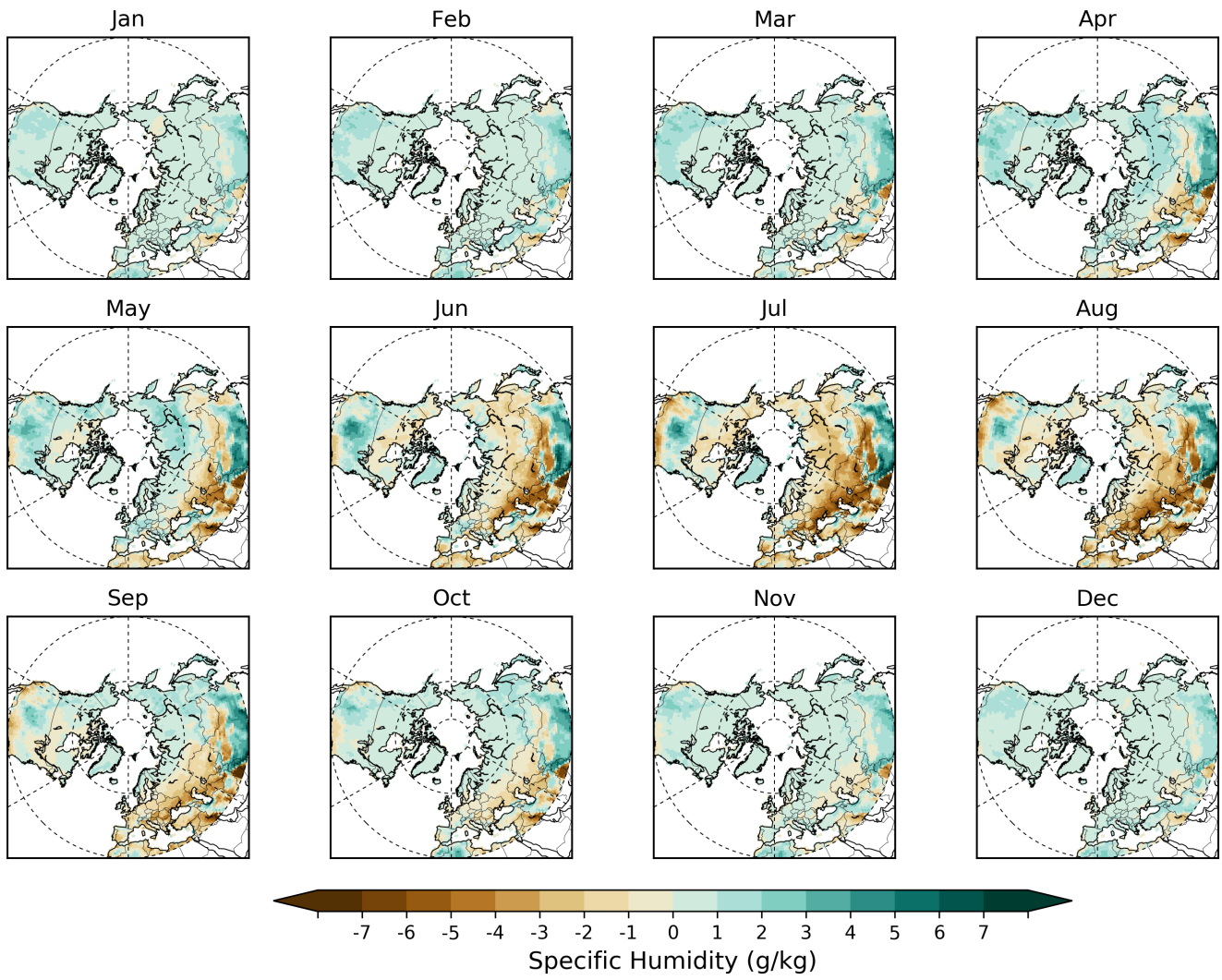


**Figure S14.** Same as Fig. S11 but for downward shortwave radiation ( $\text{W m}^{-2}$ )

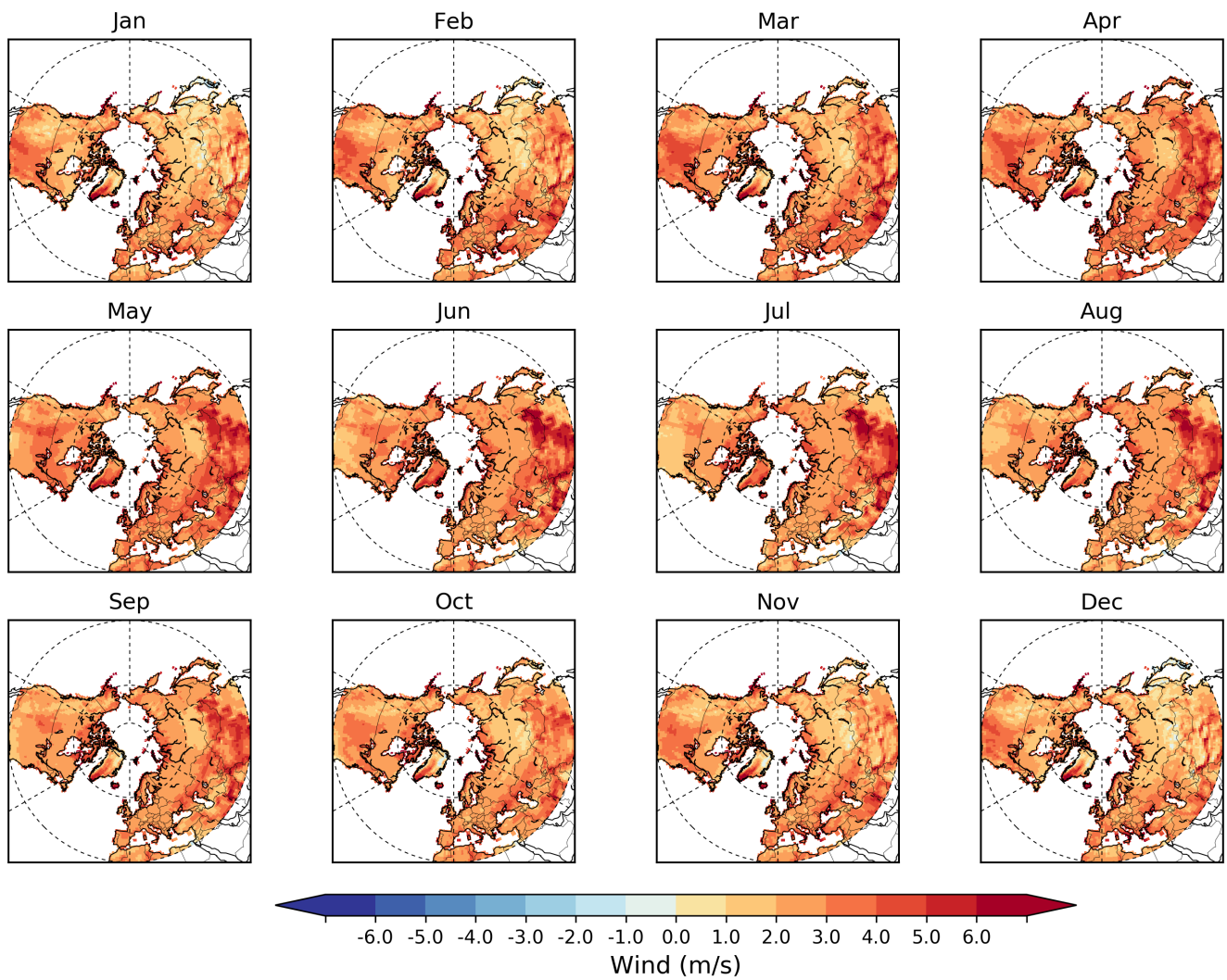


**Figure S15.** Same as Fig. S11 but for downward longwave radiation ( $\text{W m}^{-2}$ )

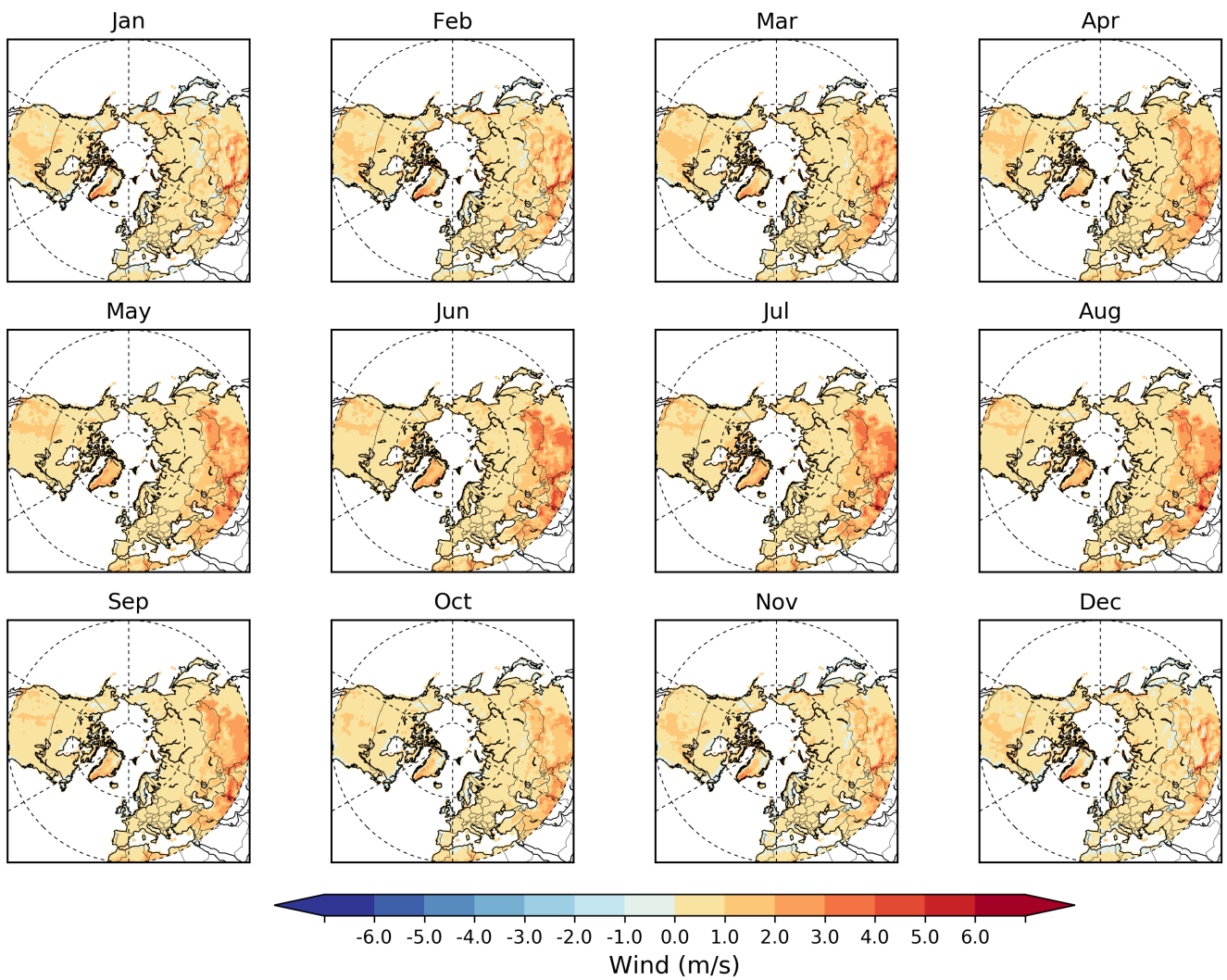




**Figure S16.** Same as Fig. S11 but for specific air humidity ( $\text{gkg}^{-1}$ )



**Figure S17.** Same as Fig. S11 but for wind speed at 10 m ( $\text{m s}^{-1}$ )



**Figure S18.** Same as Fig. S11 but for wind speed at 2 m in ORCHIDEE outputs ( $\text{m s}^{-1}$ )

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