GRENE-TEA Model Intercomparison Project (GTMIP) Stage 1: Experiment protocol

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1. Introduction

Overall target of the activity

The goals of the modeling group in the terrestrial ecosystem research project of the GRENE Arctic Climate Change Research Project (GRENE-TEA) are to a) feed to the coupled global climate model (CGCM) research project for the possible improvement of the physical and ecological processes for the Arctic terrestrial modeling (excl. glaciers and ice sheets) in the extant terrestrial schemes in the CGCMs , and b) lay the foundations of the future-generation Arctic terrestrial model development. To achieve these goals the GTM (modeling group in GRENE-TEA) group is to conduct a model intercomparison project (GTMIP) among the participating models, in which we will utilize the GRENE-TEA site observations data (stage 1) and CGCMs outputs (stage 2) for driving and validating the models. The GTMIP is designated to 1) enhance communications and understanding of the "mind and hands" between the modeling researchers and field scientists, 2) assess the uncertainty and variations stemmed from the extant model implementation/designation, and the variability due to climatic and historical conditions among the Arctic sites, and 3) feed such information and evaluations to the future-generation Arctic terrestrial model development.

The GTMIP consists of two stages: one dimensional, historical GRENE-TEA site evaluations (stage 1) and circumpolar evaluations using projected climate change data from GCM outputs (stage 2). This protocol is for the Stage 1 of the project, which evaluates the TPMs for the physical and the biogeochemical processes by site simulations for recent three decades, driven and validated by the GRENE-TEA site observations data that is compiled through a tight collaboration between field and modelling group of GRENE-TEA.

Background

The pan-Arctic ecosystem is characterized by low mean temperature, snow cover, seasonal frozen ground and permafrost with a large carbon reservoir, covered by various biomes (plant types) ranging from deciduous and evergreen forests to tundra. To investigate the climate change impact in this region, a number of studies using observed data analysis as well as numerical modelling studies were carried out (e.g. Zhang et al., 2005; Brown and Robinson, 2011; Brutel-Vuilmet et al., 2013; Koven et al., 2011, 2013; Slater and Lawrence, 2013). Various schemes for numerical modelling have been developed to treat physical and biogeochemical processes on and below the land surface, and interactions with the overlying atmosphere as a component of the atmosphere ocean coupled global climate models (AOGCMs), or Earth System models (ESMs). Among those, snowpack, ground freezing/thawing and carbon exchange processes are the most important processes in the terrestrial process model (TPM) applied in the pan-Arctic region.

Since the 1990s, a number of model intercomparison projects (MIPs) have been carried out, focusing on the performance of the TPMs, AOGCMs and ESMs; such as PILPS (Project for Intercomparison of Land-Surface Parameterization Schemes; Henderson-Sellers, 1993), SnowMIP (Snow Models Intercomparison Project; Etchevers et al. 2004; Essery et al. 2009), Potsdam NPP MIP (Potsdam Net Primary Production Model Intercomparison Project; Cramer et al., 1999), C4MIP (Coupled Climate–Carbon Cycle Model Intercomparison Project; Friedlingstein et al. 2006), CMIP5 (Coupled Model Intercomparison Project; Taylor et al. 2012), and MsTMIP (Multi-scale synthesis and Terrestrial Model Intercomparison Project; Huntzinger et al., 2013) among others.

Based on the outcomes from these MIPs, the TPMs have improved their performances. However, as past MIPs are carried out for the global scale or in the subarctic region using the gridded outputs from the models, an intercomparison dedicated to Arctic region processes that include both physical and biogeochemical aspects for site-level are still limited (e.g. Ekisi et al., 2014; Rawlins et al., 2015). A mission of the modelling group in the terrestrial research project of the GRENE Arctic Climate Change Research Project (GRENE-TEA) is to a) feed to the AOGCM research community the possible improvements regarding the physical and biogeochemical processes for the Arctic terrestrial modelling (excl. glaciers and ice sheets) in the extant terrestrial schemes in the AOGCMs, and b) lay the foundations of the future-generation Arctic terrestrial model development. This model intercomparison project (GTMIP) is planned and conducted, as an activity to achieve these goals. It is also designated to enhance communications and understanding of the "mind and hands" between the modelling and empirical scientists, as well as to assess the uncertainty and variations stemmed from the model implementation/designation, and the variability due to climatic and historical conditions among the pan-Arctic sites.

2. Experiment design

2.1 Targeted processes

The following five categories (from “a)” to “e)” below) were selected as the key processes to assess the performance of the extant TPMs in pan-Arctic region, evaluate the variations among the models and the mechanisms behind their strength and weakness, and draw information and guidance to improve for the next generation of TPMs. The five categories consist a) exchange of energy and water between atmosphere and land, b) snowpack, c) phenology, d) ground freezing/ thawing and active layer, and e) carbon budget.

The scientific questions at the Stage 1 are: How well do the TPMs reproduce target metrics (shown in B in Table 1, but not limited to) in terms of agreement with the observations? How do the reproductions vary among the models? If the reproductions are good or poor in some models, which processes in TPMs are responsible and why?

Table1: The key processes categories and target processes

A: Key processes categories	B: Target processes and metrics
Energy and water budget	Partition of energy and water at surface, canopy, and subsurface, albedo
Snowpack (snow cover ratio, snow depth/snow water equivalent)	Snow water equivalent, snow density, snow cover duration (length and dates)
Phenology	Annual maximum leaf area index, growing season (length and dates)
Ground freezing/thawing, active layer	Active layer thickness (in permafrost) or maximum seasonal frozen depth, trumpet curve, ice content ratio
Carbon budget	Net primary production, heterotrophic and autotrophic respiration, net ecosystem production, stored carbon mass in different pools

2.2. Spatial domain

The stage 1 of GTMIP will use the forcing data obtained at the GRENE-TEA observation sites (Fig.1), provided and compiled by the field scientists in charge of the sites. Besides the direct comparison of the model outputs to evaluate the inter-sites and inter-model variations, it is aimed to give a good opportunity for the modelers and field scientists working together to substantiate the mutual understanding (Field-Model collaboration).

Fig.1: Location map of GRENE-TEA sites

We will conduct the experiment at six pan-Arctic observation sites listed below (Table 2) owing to the availability of data to drive and validate the model, and of parameters and supporting information to specify the site. The location, dominant vegetation type, soil, climate, fraction of photosynthetically active radiation (fPAR), leaf area index (LAI), data available for model validation, and reference for observation data at target sites are shown in Table 2.

Table 2: The information of sites

(a): Fairbanks (FB: Poker Flat Research Range), Alaska, USA

Location	65°07’24” N, 147°29’15.” W
Altitude	210 m
Dominant vegetation type	Black spruce forest
Soil	0-14cm layer: moss 14-25cm: undecomposed organic layer 25-39cm: decomposed organic layer 39cm- : silt soil Active layer thickness: 43cm in 2013
Climate	Mean annual air temperature: -2.8 °C (2011) Annual precipitation: 312 mm (2011)
fPAR and LAI[1)]	fPAR: 0.03 (Jan), 0.05 (Feb), 0.05 (Mar), 0.13 (Apr), 0.39 (May), 0.69 (Jun), 0.69 (Jul), 0.69 (Aug), 0.43 (Sep), 0.23 (Oct), 0.06 (Nov), 0.00 (Dec) LAI: 0.05 (Jan), 0.09 (Feb), 0.09 (Mar), 0.23 (Apr), 0.99 (May), 2.26 (Jun), 2.32 (Jul), 1.90 (Aug), 0.80 (Sep), 0.49 (Oct), 0.10 (Nov), 0.01 (Dec.)
Data available for model validation	Snow depth, ground temperature (-0.05, -0.1, -0.2, -0.4, -1.0m), soil moisture (-0.05, -0.1, -0.2, -0.4m), leaf area index, albedo, FPAR (Fraction of photosynthetically active radiation), upward short and long wave radiation, energy and carbon fluxes
Reference	Nakai et al., 2013

(b): Kevo (KV: Kevo Research Station), Finland

Location	69°45' 25”N, 27°00' 37”E
Altitude	100m
Dominant vegetation type	Pine forest
Soil	0-20cm: humus soil 20－50cm: sandy silt
Climate	Mean annual air temperature: -1.6 °C Annual precipitation: 415 mm
fPAR and LAI[1)]	fPAR: 0.03 (Jan), 0.06 (Feb), 0.08 (Mar), 0.11 (Apr), 0.51 (May), 0.56 (Jun), 0.69 (Jul), 0.76 (Aug), 0.68 (Sep), 0.45 (Oct), 0.10 (Nov), 0.02 (Dec) LAI: 0.05 (Jan), 0.10 (Feb), 0.14 (Mar), 0.21 (Apr), 1.13 (May), 1.63

	(Jun), 2.52 (Jul), 2.78 (Aug), 1.66 (Sep), 1.18 (Oct), 0.21 (Nov), 0.05 (Dec.)
Data available for model validation	Snow depth, snow (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7m) and ground temperature (-0.1, -0.2, -0.3, -0.35m), soil moisture (-0.1, -0.2, -0.3m), albedo, upward short and long wave radiation
Reference	Sato et al., 2001

(c): Tiksi (TK), Sakha Republic, Russian Federation

Location	71°35’21”N, 128°46’27”E
Altitude	40 m
Dominant vegetation type	Non-tussock sedge, dwarf-shrubs, and moss tundra
Soil	0-1cm: partially decomposed litter 1-15cm: loam 15-70cm: silt with gravel Active layer thickness: 70cm
Climate	Mean annual air temperature: -13.5 °C Annual precipitation: 331 mm
fPAR and LAI[1)]	fPAR: 0.00 (Jan), 0.00 (Feb), 0.00 (Mar), 0.00 (Apr), 0.03 (May), 0.29 (Jun), 0.45 (Jul), 0.47 (Aug), 0.28 (Sep), 0.04 (Oct), 0.00 (Nov), 0.00 (Dec) LAI: 0.00 (Jan), 0.00 (Feb), 0.00 (Mar), 0.00 (Apr), 0.05 (May), 0.52 (Jun), 0.88 (Jul), 0.73 (Aug), 0.49 (Sep), 0.07 (Oct), 0.00 (Nov), 0.00 (Dec.)
Data available for model validation	Snow depth, ground temperature (-0.1, -0.2, -0.3, -0.47, -1, -2, -3, -5, -10, -20, -30m), soil moisture (0, -0.05, -0.15, -0.3m), albedo, upward short and long wave radiation
Reference	Kodama et al., 2007; Watanabe et al., 2000

(d): Yakutsk (YK: Spasskaya Pad), Sakha Republic, Russian Federation

Location	62°15’18”N, 129°37’6”E
Altitude	220 m
Dominant vegetation type	Larch forest
Soil	0-20cm: organic layer Upper mineral layer: sandy loam Lower mineral layer: silty loam (More than 80% of root: within a soil depth of 20 cm)

	Active layer thickness: 1.2m
Climate	Mean annual air temperature: -10.2 °C Annual precipitation: 188 mm
fPAR and LAI[1)]	fPAR: 0.00 (Jan), 0.00 (Feb), 0.00 (Mar), 0.05 (Apr), 0.28 (May), 0.46 (Jun), 0.42 (Jul), 0.21 (Aug), 0.03 (Sep), 0.00 (Oct), 0.00 (Nov), 0.02 (Dec) 0.00 LAI: 0.00 (Jan), 0.00 (Feb), 0.00 (Mar), 0.00 (Apr), 0.07 (May), 0.58 (Jun), 1.05 (Jul), 0.81 (Aug), 0.28 (Sep), 0.04 (Oct), 0.00 (Nov), 0.00 (Dec.)
Data available for model validation	Snow depth, ground temperature (-0.1, -0.2, -0.4, -0.6, -0.8, -1.2), soil moisture (-0.1, -02, -0.4, -0.6, -0.8m), albedo, FPAR, upward short and long wave radiation, energy and carbon fluxes
Reference	Ohta et al., 2001, 2008, 2014; Kotani et al., 2013; Lopez et al., 2007

(e): Chokurdakh (CH: Kodack/Krybaya) , Sakha Republic, Russian Federation

Location	70°33’48”N, 148°15’51”E
Altitude	9 m
Dominant vegetation type	Tussock wetland/shrubs/sparse larch trees
Soil	Clay loam, silty clay loam Active layer thickness: 0.4-0.7m
Climate	Mean annual air temperature: -13.4 °C Annual precipitation: 196 mm
fPAR and LAI[1)]	fPAR: 0.00 (Jan), 0.00 (Feb), 0.00 (Mar), 0.00 (Apr), 0.00 (May), 0.01 (Jun), 0.18 (Jul), 0.45 (Aug), 0.48 (Sep), 0.26 (Oct), 0.07 (Nov), 0.02 (Dec) LAI: 0.00 (Jan), 0.00 (Feb), 0.00 (Mar), 0.00 (Apr), 0.02 (May), 0.32 (Jun), 0.91 (Jul), 0.79 (Aug), 0.41 (Sep), 0.15 (Oct), 0.00 (Nov), 0.00 (Dec.)
Data available for model validation	Ground temperature (-0.01, -0.05, -0.1, -0.2, -0.3, -0.4, -0.5, -0.75, -1.0, -1.5, -2.0, -2.5, -3.0, -4.0, -5.0, -5.5, -7.0, -10.0 m), soil moisture (-0.035, -0.145, -0.335, -0.535m), albedo, upward short and long wave radiation, energy and carbon fluxes
Reference	Iwahana et al., 2014

(f): Tura (TR), Russian Federation

Location	64°12’32”N, 100°27’49”E

Altitude	250 m
Dominant vegetation type	Larch forest
Soil	10-20cm organic layer Cryosol Active layer thickness: 1m
Climate	Mean annual air temperature: -8.9 °C Annual precipitation: 360 mm
fPAR and LAI[1)]	fPAR: 0.00 (Jan), 0.00 (Feb), 0.00 (Mar), 0.01 (Apr), 0.20 (May), 0.48 (Jun), 0.52 (Jul), 0.49 (Aug), 0.29 (Sep), 0.10 (Oct), 0.00 (Nov), 0.00 (Dec) LAI: 0.00 (Jan), 0.00 (Feb), 0.00 (Mar), 0.01 (Apr), 0.46 (May), 1.28 (Jun), 1.43 (Jul), 1.17 (Aug), 0.48 (Sep), 0.17 (Oct), 0.00 (Nov), 0.00 (Dec.)
Data available for model validation	Ground temperature (-0.05, -0.1, -0.2, -0.4, -0.5), soil moisture (-0.05, -0.1, -0.2, -0.4, -0.5), albedo, FPAR, upward short and long wave radiation, energy and carbon fluxes
Reference	Nakai et al., 2008

1) Average value extracted from 1km grid MODIS satellite from 2001 to 2011
(Sasai et al., 2011)

2.3. Temporal Domain

The target temporal coverage for stage 1 is from 1980 to 2013, providing at least 30 years of data to enable the climatological analysis. The target temporal coverage may be extended up to 50 years to enable the comparison with the tree-ring data taken at GRENE-TEA sites

2.4. Driving Data Sets

The target period of the stage 1 is set from 1980 to 2013, which can provide at least 30 years of data to enable climatological analyses. We provide the following driving data for the stage 1 experiment: surface air temperature, precipitation, specific humidity, air pressure, wind speed, incident short wave and long wave radiation.

For this stage (site simulations), forcing and validation data have been prepared, taking maximum advantage of the observation data taken at GRENE-TEA sites (Fairbanks (FB) in Alaska, Tiksi (TK), Yakutsk (YK), Chokurdakh (CH), and Tura (TR) in Russia, and Kevo (KV) in Finland; **Fig. 1**), to evaluate the inter-model and inter-site variations for 1980-2013. Backbone of the continuous forcing data (called “level 0” or L0; Saito et al., 2014a) was constructed from a reanalysis data to avoid limited coverage and/or missing or lack of the consistency inherent to observational data, with bias-corrected with the monthly CRU (for temperature; Harris et al., 2014) and GPCP (for precipitation; Adler et al., 2003) datasets at the respective nearest grid to the sites. The ERA-interim reanalysis data (Dee et al., 2011) was chosen from four products (i.e. NCEP/NCAR, NCEP-DOE, JRA55, ERA-interim) because it showed the smallest bias relative to the monthly CRU and GPCP in terms of 2m air temperature and precipitation in the pan-Arctic region (north of 60 degree).

Then, assimilation of the observed data was applied to reflect the local characteristics to derive the primary driving data, “level 1” data (L1; Saito et al., 2014b), and, in addition, the level 1 hybrid data (L1H) by replaced by the observed data when available. The L1 dataset was provided for the four sites (FB, KV, TK and YK) due to availability of the observed data for validations. Further detail of method to create the L0 and L1 data, and their basic statistics, are described in Sueyoshi et al. (2015).

The 20-year detrended meteorological driving dataset was provided for spin up, especially for biogeochemical models to set up initial soil carbon conditions, without being affected by warming trend and/or ENSO (El Niño Southern Oscillation). This dataset is based on the L1 data for the period of 1980-1999 (Saito et al., 2015). The monthly value of fPAR and LAI dataset at GRENE-TEA sites, created based on MODIS satellite data (MOD15A2, MYD15A2), were also provided for such models that need these data for driving (Saito et al., 2014c).

The driving data sets are provided basically in the ASCII fixed length record files, and are available through Arctic Data Archive System (ADS; https://ads.nipr.ac.jp/gtmip/gtmip.html), along with the simulation protocol.

2.5 Parameters for boundary condition

The stage 1 consists of two sub stages: 1A and 1B. The stage 1A, aiming to evaluate the inter-model variations in baseline performance at each site, requests the participants to use the parameters in default settings for the provided boundary conditions such as land cover type. In contrast, the stage 1B allows tuning for best reproduction of the observed so that the variations and sensitivity in parameter values among sites can be evaluated.

2.6. Initial condition and model spin-ups

We set the date of initial condition on 1 September, 1979 so that a simulation can start with a no-snow condition. The initial data for the boundary condition of the model will be available, as most of station has the observation data for the soil temperature and soil moisture profiles. However, each model can use its own method for initialization.

The spin up process may also differ by models. However, we recommend to spin up until the steady state of main variables (see section 2.5) is achieved. For example, Takata (2002) defined the threshold of a steady state as

$$\frac{X_n - X_{n-1}}{X_n} < 10^{-2},$$

where X is a physical variable (e.g. fluxes, ground temperature, soil moisture, or ice content) in equation (1). Subscript n denotes an annual mean of the n-th year.

For biogeochemical cycle models, we recommend to spin up at least 2000 years using the detrended meteorological driving data (also provided through ADS) and pre-industrial atmospheric CO2 concentration (e.g. 280 ppmv for around 1750) until the soil carbon reaches equilibrium; then the atmospheric CO2 concentration should be increased to the current level (e.g. 340 ppmv) in 200 years or so (the period being dependent on the models). For the submission period (1979 to 2013), use of the historical atmospheric CO2 concentration is recommended for such models as to be driven by time-variant CO2 concentration.

2.7. Variables

We request the participants to submit us those variables listed in Table3 in the ASCII format with the CSV type files.

The variables to submit are categorized into the six groups: 0) model driving, 1) energy and water budget, 2) snow dynamics, 3) vegetation, 4) subsurface hydrological and thermal states, and 5) carbon budget. The priority for each variable, classed to three levels, was set according to the necessity and availability for evaluation of the model performance. In addition, participants are requested to inform the status of the variables in his/her/their model (i.e., model driving, prescribed parameter, prognostic, diagnostic, and not applicable) through the provided questionnaire to identify the characteristics of the model.

Although the temporal resolution of a variable should depend on a model, we request to submit the variables with the minimum temporal resolution available for the model. For the models that outputs daily output, the day time should be defined by the local time (FB: UTC-10, KV: UTC+2, TK: UTC+9, YK: UTC+9, CH: UTC+10, TR: UTC+7). Those models, which use the no-leap calendar (365 days for all years), is requested to drop the day of February 29th.

Table3: The lists of variables to submit

The status in this table is requested to put in the number of status (1: model driving, 2: prescribed parameter, 3: prognostic variable, 4: diagnostic variable, 5: not applicable) for each variable according to each model treatment. The time step in this table is requested to put the time step (e.g. 30 min., daily) of output from each model.

(a): Model driving

Variable	Priority	Definition	Units	Direction (+)	status	Time step
Pr	1	Total precipitation	kg/m^2/s	Downward		
Psn	1	Snowfall	kg/m^2/s	Downward		
Tair	1	Air temperature at reference height	K	-		
Psurf	1	Surface pressure	hPa	-		
Wind	1	Wind speed at reference height	m/s	-		
SWdown	1	Surface incident short wave radiation	W/m^2	Downward		
LWdown	1	Surface incident long wave radiation	W/m^2	Downward		
Qair	1	Specific humidity at reference height	kg/kg	-		
PAR_in	2	Surface incident photosynthetically active radiation	mol/m^2/s	Downward		
CO2air	2	CO_2 concentration at reference height	ppmv	-		

(b): Energy and water budgets

Variable	priority	Definition	Units	Direction (+)	status	Time step
SWup_total	1	Total outgoing short wave radiation (total over snow-free and snow-covered canopy, snow-free and snow-covered ground)	W/m^2	Upward		
LWup_total	1	Total outgoing long wave radiation (same as SWup_total)	W/m^2	Upward		
Qh_total	1	Total sensible heat flux (same as SWup_total)	W/m^2	Upward		
Qle_total	1	Total latent heat flux (same as SWup_total)	W/m^2	Upward		

Qg_total	1	Total ground heat flux (total over snow-free and snow-covered ground)	W/m^2	Downward		
ET_total	1	Total evapotranspiration (i.e., Et_veg + E_soil + Ei + Ei_snw)	$kg/m^2/s$	Upward		
Qs	1	Surface runoff	$kg/m^2/s$	-		
Qsb	1	Subsurface runoff	$kg/m^2/s$	-		
alpha_sw	1	Total shortwave albedo	-	-		
Et_veg	1	Total transpiration of vegetation (e.g. forest transpiration + forest floor transpiration)	$kg/m^2/s$	Upward		
E_soil	1	Soil evaporation from snow-free ground	$kg/m^2/s$	Upward		
Ei	2	Canopy interception evaporation on snow-free canopy	$kg/m^2/s$	Upward		
Ei_snw	2	Canopy interception evaporation on snow-covered canopy	$kg/m^2/s$	Upward		
Sub_snow	1	Sublimation from the ground snow pack	$kg/m^2/s$	Upward		
SWup_can	2	Outgoing short wave radiation on snow-free canopy	W/m^2	Upward		
LWup_can	2	Outgoing long wave radiation on snow-free canopy	W/m^2	Upward		
Qh_can	2	Sensible heat flux on snow-free canopy	W/m^2	Upward		
Qle_can	2	Total latent heat flux on snow-free canopy	W/m^2	Upward		
SWup_gnd	2	Outgoing short wave radiation on snow-free ground	W/m^2	Upward		
LWup_gnd	2	Outgoing long wave radiation	W/m^2	Upward		

		on snow-free ground				
Qh_gnd	2	Sensible heat flux on snow-free ground	W/m^2	Upward		
Qle_gnd	2	Total latent heat flux on snow-free ground	W/m^2	Upward		
Qg_gnd	2	Total ground heat flux on snow-free ground	W/m^2	Downward		
SWup_can_snw	2	Outgoing short wave radiation on snow-covered canopy	W/m^2	Upward		
LWup_can_snw	2	Outgoing long wave radiation on snow-covered canopy	W/m^2	Upward		
Qh_can_snw	2	Sensible heat flux on snow-covered canopy	W/m^2	Upward		
Qle_can_snw	2	Total latent heat flux on snow-covered canopy	W/m^2	Upward		
SWup_snw	2	Outgoing short wave radiation on snow-covered ground	W/m^2	Upward		
LWup_snw	2	Outgoing long wave radiation on snow-covered ground	W/m^2	Upward		
Qh_snw	2	Sensible heat flux on snow-covered ground	W/m^2	Upward		
Qle_snw	2	Total latent heat flux on snow-covered ground	W/m^2	Upward		
Qg_snw	2	Total ground heat flux on snow-covered ground	W/m^2	Downward		
fPAR	2	Absorbed fraction incoming PAR on canopy	-	-		

(c): Snowpack

Variable	priority	Definition	Units	Direction (+)	status	Time step
SnowT_*layer*	1	Snow temperature at surface and in each user-defined snow layer (m)	K	-		

SWE	1	Total snow water equivalent	kg/m^2	-		
SnowDepth	1	Total snow depth	m	-		
Rho_sn_bulk	1	Bulk density of snow	kg/m^3	-		
Rho_sn_*layer*	1	Density of snow in each user-defined snow layer (m)	kg/m^3	-		
Wsn_liq_*layer*	1	Liquid water content of snow in each user-defined snow layer (m)	kg/m^2	-		
Alpha_sn	1	albedo of snow	-	-		
Ksn_*layer*	1	thermal conductivity of snow in each user-defined snow layer (m)	W/m/K	-		
Fcompact_sn	2	Compaction rate of snow (snow density change due to compaction)	$kg/s•m^3$	-		
SIF	2	Snow impurity factor (which expresses the effects of black carbon and mineral dust as a single parameter: composite mass absorption cross sections of snow impurities per unit snow mass)	-	-		

(d): Vegetation/ Phenology

Variable	priority	Definition	Units	Direction (+)	status	Time step
AvgSurfT	1	Average of all vegetation, bare soil and snow skin temperatures	K	-		
VegT_*layer*	1	Vegetation canopy temperature in user-defined canopy layer (m)	K	-		
W_can_liquid_*layer*, W_can_solid_*layer*,	2	Canopy water in user-defined canopy	kg/m^2	-		

W_can_total_*layer*		layer in the liquid and solid phases				
LAI_total	1	Total leaf area index	m^2/m^2	-		
LAI_up_can	1	Leaf area index of upper canopy	m^2/m^2	-		
LAI_forest_floor	1	Leaf area index of forest floor	m^2/m^2			
Ce, Ch, Cd	1	Exchange coefficient of leaf (vapor, heat, momentum)	-	-		
r_a	1	Aerodynamic resistance between canopy air space and reference height	s/m			
VgH	1	Vegetation height	m	-		
VgB	1	Canopy base height	m	-		
Root_frac_*layer*	1	Root fraction in each user-defined soil layer (The cumulative root fraction from the surface to the bottom depth with root in the soil should be 1.0)	-	-		
Alpha_leaf	2	Leaf albedo (VIS, NIR)	-	-		
T_leaf	2	Leaf transmissivity (VIS, NIR)	-	-		
VC	2	Vegetation coverage	-	-		
gc	2	Canopy conductance	m/s	-		
fBurn	3	Burnt area fraction	-	-		
fPFT	3	Fraction of plant functional types (PFT) or dominant PFT, which is based on the classification in each model (e.g. high latitude deciduous forest and	-	-		

		woodland, tundra)				

(e): Subsurface hydrological and thermal states

Variable	priority	Definition	Units	Direction (+)	status	Time step
Tg_*depth*	1	Ground temperature at surface and in each user-defined soil layer (m)	K	-		
Wg_*depth*	1	Volumetric soil water content including the liquid, vapor and solid phases of water in each user-defined soil layer (m)	m^3/m^3	-		
Wg_frac_*depth*	1	Fraction of saturation of soil water content in each user-defined soil layer (m) (wilting=0, saturation=1)	-	-		
Wg_frozfrac_*depth*	1	Fraction of soil moisture mass in the solid phase in each user-defined soil layer (m)	-			
kg_*depth*	1	Soil thermal conductivity in each user-defined soil layer (m)	J/K/m/s			
Cg_*depth*	1	Soil heat capacity in each user-defined soil layer (m)	$J/K/m^3$			
Theta_s_*depth*	1	Porosity of soil in each user-defined soil layer (m)	-			
K_s_*depth*	1	Saturation hydraulic conductivity of soil in each user-defined soil	m/s			

		layer (m)				
Psi_s_*depth*	1	Saturation matric potential in each user-defined soil layer (m)	m			
b, n, alpha_*depth*	1	Empirical factor for soil retention curve in each user-defined soil layer (m)	-			

(f): Carbon budget

Variable	priority	Definition	Units	Direction(+)	status	Time step
GPP	1	Gross Primary Production on land	$kgC/m^2/s$	Downward		
NPP	1	Net Primary Production on land (=GPP – Ra)	$kgC/m^2/s$	Downward		
Ra	1	Autotrophic (plant) respiration on land	$kgC/m^2/s$	Upward		
Rh	1	Heterotrophic Respiration on land	$kgC/m^2/s$	Upward		
TotCarLitSoil	1	Total soil organic carbon	kgC/m^2	-		
NEP	1	Net ecosystem productivity (=NPP - Rh)	$kgC/m^2/s$	Downward		
Pmax or Vcmax	1	Maximum photosynthesis rate or maximum rate of Rubisco carboxylase activity	$mol/m^2/s$	-		
Q10	1	Temperature sensitivity in soil respiration	-	-		
NBP	2	Net Biome production (=NEP - other efflux from the land by natural or anthropogenic disturbances)	$kgC/m^2/s$	Downward		
cLeaf	2	Carbon mass in leaves	kgC/m^2	-		
cStemCRoot	2	Carbon mass in stems and coarse roots	kgC/m^2	-		

cFRoot	2	Carbon mass in fine roots	kgC/m^2	-		
cOtherLiving	2	Carbon mass in other living compartments	kgC/m^2	-		
cLitter	2	Carbon mass in litter pool	kgC/m^2	-		
cSoilMineral	2	Carbon mass in soil mineral	kgC/m^2	-		
cOtherDead	2	Carbon mass in other forms	kgC/m^2	-		
CO2fire	3	CO2 emission from fire	$kgC/m^2/s$	Upward		
Carbon_alloc	3	Carbon allocation ratio to each organ of vegetation (leaf, stem and root)	-	-		
M	3	Mortality/Senescence ratio (ratio of mortality and senescence of each organ (leaf, stem and root) per unit time)	-	-		

The template file for output submission is provided through ADS. The file naming convention for submitting the result of each model is defined as follows.
[Model-ID]_[stage-ID]_[forcing ID]_[station-ID]_[yymmdd (date of submission)].csv,
where stage_ID is either "1a" or "1b", forcing_ID is "L0", "L1" or "L1H", and station_ID is shown in Table 4.

Table 4: File naming convention for submitting the result of each model
Model name is for current participating model.

Model-name	Model-ID	Stage-name	Stage-ID	Forcing-data set	Forcing-ID	Station-name	Station-ID
2LM	2LM	Stage 1.0A	1.0A	Level 0.2	Lv0.2	Fairbanks	FB
FROST	FROST	Stage 1.0B	1.0B	Level 1.0	Lv1.0	Kevo	KV
SMAP	SMAP	------------	--------	-----------	-----------	Tiksi	TK
SNOWPACK	SNOWPACK	------------	--------	-----------	-----------	Yakutsk	YK
HAL	HAL	------------	--------	-----------	-----------	Chokurdakh	CH
MATSIRO-ssnowd	MATsnow	------------	--------	-----------	-----------	Tura	TR
MATSIRO-	MAT4	------------	--------	-----------	-----------	-----------	--------

MIROC4							
MATSIRO-Permafrost	MATpf	-------------	--------	------------	------------	------------	--------
MATSIRO-MIROC5	MAT5	-------------	--------	------------	------------	------------	--------
SPAC-multilayer	SPAC	-------------	--------	------------	------------	------------	--------
LPJ	LPJ	-------------	--------	------------	------------	------------	--------
BEAMS	BEAMS	-------------	--------	------------	------------	------------	--------
PB-SDM	PBSDM	-------------	--------	------------	------------	------------	--------
STEM1	STEM1	-------------	--------	------------	------------	------------	--------
VISIT	VISIT	-------------	--------	------------	------------	------------	--------
CHANGE	CHANGE	-------------	--------	------------	------------	------------	--------
SEIB-DGVM-MIROC	SEIB-M	-------------	--------	------------	------------	------------	--------
SEIB-DGVM-Noah	SEIB-N	-------------	--------	------------	------------	------------	--------
JULES	JULES	-------------	--------	------------	------------	------------	--------
Biome-BGC	B-BGC	-------------	--------	------------	------------	------------	--------

To identify the characteristics of the model, we would like to ask the participants to answer the questionnaire provided through ADS.

2.8. Metrics

We proposed the scoring metrics shown in Table 5 to evaluate the terrestrial model performance in pan-Arctic region. The metrics are divided into five categories (energy and water budget, snowpack, phenology, subsurface hydrological and thermal states, carbon budget). These metrics are closely related to the processes of snowpack, frozen soil and biogeochemical processes in cryosphere.

Table 5: The lists of metrics for model performance evaluation

(a): Energy and water budget

Variable	Definition	Units	Direction (+)	Time step
Rn_season, Rn_annual	Seasonally and annually averaged net radiation	W/m^2	Downward	seasonal annual
Qh_season, Qh_annual	Seasonally and annually averaged sensible heat flux	W/m^2	Upward	seasonal annual

Qle_season, Qle_annual	Seasonally and annually averaged latent heat flux	W/m^2	Upward	seasonal annual
ET_season, ET_annual	Seasonally and annually averaged total evapotranspiration	mm/day	Upward	seasonal annual
Qs_season, Qs_annual	Seasonally and annually averaged surface runoff	mm/day	Out of soil column	seasonal annual
Qsb_season, Qsb_annual	Seasonally and annually averaged subsurface runoff	mm/day	Out of soil column	seasonal annual
Et_veg_season, Et_veg_annual	Seasonally and annually averaged transpiration of vegetation	mm/day	Upward	seasonal annual
E_soil_season, E_soil_annual	Seasonally and annually averaged soil evaporation	mm/day	Upward	seasonal annual
Wg_frac_season Wg_frac_annual	Seasonally and annually averaged fraction of saturation of soil water content (wilting=0, saturation=1)	-	-	seasonal annual
deltaWg_season, deltaWg_annual	Seasonally and annually averaged change of stored soil moisture	mm/day	-	seasonal annual
alpha_season, alpha_annual	Seasonally and annually averaged shortwave albedo	-	-	seasonal annual
E_can_season, E_can_annual	Seasonally and annually averaged canopy interception evaporation	mm/day	Upward	seasonal annual

(b): Snowpack

Variable	Definition	Units	Direction (+)	Time step
SWE_max Date_SWE_max	Annual maximum snow water equivalent and the date reached	kg/m^2 day	-	annual
SnD_max Date_SnD_max	Annual maximum snow depth and the date reached	m day	-	annual
SnowDuration Date_start_snow_cover	Annual duration of snow cover and the date of snow cover start/end	day	-	annual
Sub_snow_season, Sub_snow_annual	Seasonally and annually averaged total sublimation from the ground snow pack	mm/day	Upward	annual

(c): Phenology

Variable	Definition	Units	Direction (+)	Time step
LAI_max	Annual maximum leaf area index	m^2/m^2	-	annual
GlowSeasonLentgh	Growing season length and the date of start/end of growing season	day	-	annual

(d): Subsurface hydrological and thermal states

Variable	Definition	Units	Direction (+)	Time step
ALT or ThawDepth_max	Active layer thickness (permafrost region) or annual maximum thawing depth (seasonal frozen ground) and the date reached	m	-	annual
FrozenDepth_max	Annual maximum frozen depth and the date reached	m	-	annual
Tg_range_*depth*	Annual range of soil temperature in pre-defined soil layer	K	-	annual
Wg_frozfrac_max_*depth*	Annual maximum fraction of soil moisture mass in the solid phase in pre-defined soil layer	-	-	annual

(e): Carbon budget

Variable	Definition	Units	Direction (+)	Time step
NPP_annual, NPP_growing	Annual and growing season net primary production on land	$kgC/m^2/year$ $kgC/m^2/duration$	Downward	annual growing season
GPP_annual, GPP_growing	Annual and growing season gross primary production	$kgC/m^2/year$ $kgC/m^2/duration$	Downward	annual growing season
Rh_annual Rh_growing	Annual and growing season heterotrophic respiration on land	$kgC/m^2/year$ $kgC/m^2/duration$	Upward	annual growing season
Ra_annual Ra_growing	Annual and growing season autotrophic (plant) respiration on land	$kgC/m^2/year$ $kgC/m^2/duration$	Upward	annual growing season
Re_annual Re_growing	Annual and growing season ecosystem	$kgC/m^2/year$ $kgC/m^2/duration$	Upward	Annual growing

	respiration on land			season
NEP_annual NEP_growing	Annual and growing season net ecosystem productivity (=NPP-Rh) on land	$kgC/m^2/year$ $kgC/m^2/duration$	Downward	Annual growing season
cLeaf_annual	Stored carbon mass in leaves	kgC/m^2	-	annual
cStemCRoot_annual	Stored carbon mass in stems and coarse roots	kgC/m^2	-	annual
cFRoot_annual	Stored carbon mass in fine roots	kgC/m^2	-	annual
cOtherLiving_annual	Stored carbon mass in other living compartments	kgC/m^2	-	annual
cLitter_annual	Stored carbon mass in litter pool	gC/m^2	-	annual
cSoilMineral_annual	Stored carbon mass in soil mineral	gC/m^2	-	annual

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