

Dear editor,

We would like to thank the reviewers for their constructive comments on our paper. We addressed all their comments and replied to them point by point below.

A marked-up manuscript version showing the changes made during the revision process is also attached below.

We hope that the manuscript is now acceptable for publication in Geoscientific Model Development.

Kind regards,
Matteo Willeit and Andrey Ganopolski

Response to reviewer #1

The authors developed a comprehensive land model of intermediate complexity for long-term simulations and paleoclimate studies. The model descriptions provided enough details for readers to understand the model, and the overall global offline model evaluations using a variety of datasets demonstrated the adequate performance of the model. This manuscript can be accepted after addressing the following concerns.

Specific comments/suggestions:

L186: Does eq. (5) converges to eq. (4) (bare soil) when canopies (e.g., LAI+SAI approach zero) disappear? It is also unclear how the stomatal resistance r_s is dependent on LAI in the model formulations Eqs. (33), (69), (70).

The dependence of r_s on LAI is implicit in the dependence of g_{can} on carbon assimilation, which depends on the absorbed photosynthetically active radiation, which in turn depends on LAI (Eq. (63)). What was not mentioned in the text was that g_{min} , the minimum canopy conductance, depends on LAI (and soil moisture). This has now been added to the text.

If LAI tends to zero then r_s tends to infinity and therefore the first term on the rhs of Eq. (5) tends to zero. The canopy evaporation term (last term in Eq. (5)) also tends to zero when LAI tends to zero. The only term remaining when LAI+SAI approach zero is the term representing evaporation from the ground below the canopy (second term on the rhs). In the original formulation of Eq. (5) this term does not converge to Eq. (4) when LAI+SAI are becoming small because the undercanopy resistance $r_{a,can}$ remains finite. This has been changed by introducing a simple LAI+SAI dependence in the $r_{a,can}$ formulation (Eq. (30)):

$$r_{a,can} = \frac{L_{ai} + S_{ai}}{C_{can}u_*}$$

There only difference that remains between Eq. (5) and Eq. (4) in the limit LAI+SAI approaching zero is the use of two different temperatures (skin and ground) in the computation of the saturated specific humidity. However, when vegetation is disappearing, the difference between the skin temperature and the top soil layer temperature becomes negligible.

L432: The effects of snow metamorphism and snow melting on snow density are neglected in the model. Is this the main reason for the model's deficiency in the snow simulation (e.g., Figs. 13-15)?

The model performance in simulating total snow mass is comparable to the performance of state-of-the-art CMIP5 models, which also tend to melt snow too late in spring compared to the GlobSnow dataset (see Figure 5 in Shi and Wang (2015) and http://www.earsel.org/SIG/Snow-Ice/files/oral_ws2014/Luojus_2014_EARSeL_CMIP5.pdf). This is now discussed in the text.

The main limitation of our model is probably that it includes a single snow layer, which makes it in general more inert to fast changes in atmospheric conditions.

L753: While the equilibrium spin-up mode is fine, the authors should at least test it against the actual spin-up for "at least 10,000 years" (say, 50,000 years). If global testing is too time-consuming, the authors could pick up a few model boxes over different climate regimes for the test.

The idea of introducing an equilibrium spin-up mode in the model was mainly to have a very efficient way to bring the model to a quasi-equilibrium state to allow fast testing and tuning of the model. For all practical applications the spin-up mode is of limited use since an additional transient model simulation is anyway required to bring the model in equilibrium with the fast seasonal processes. Also, because the model integrates one year in approximately one second, a proper transient spinup of 10,000 years can be achieved in only a few hours. In the simulations presented in the paper we therefore slightly changed the experimental setup by removing the equilibrium spinup phase and substituting it with a 30,000 years transient spinup simulation.

L834: For biogeochemistry, the authors should compare the model LAI with MODIS LAI (e.g., the seasonal cycle over different latitudes with limited crop coverages). After all, MODIS LAI is one of the most reliable vegetation datasets.

We added a comparison of modelled LAI with MODIS LAI as suggested by the reviewer. We included a figure comparing annual maximum LAI and a figure comparing the zonal mean seasonal LAI variations for different latitudinal bands.

L845: The value of comparing potential vegetation from one model to another in Fig. 19 seems to be limited. It may be more useful to do a comparison similar to that in Zeng et al. (2008, e.g., their Fig. 10).

In addition to Figure 19 we included also a figure similar to Fig. (10) in Zeng et al. (2008) in the revised version of the paper. In the new figure modelled PFT coverage as a function of annual precipitation is compared to MODIS land cover data.

L762 (Section 8: Evaluation): The authors did an excellent job in using comprehensive datasets in model evaluations. However, most of the discussions were quite qualitative. The authors should compute some simple quantities (e.g., root mean square difference, correlation coefficient, mean bias, : : :) for some of the comparisons for two purposes: to back up the qualitative statements, and for other groups to compare their models' performance against the PALADYN v1.0 model in the future. For instance, there seems to be years with opposite anomaly signs in Fig. 18 (L840), and the authors should at least compute the simple correlation coefficient to quantify the agreement.

As suggested by the reviewer we computed root mean square differences and correlations for some of the model-data comparisons (in particular for global maps of different quantities) and reported the values directly on the figures to allow the reader to get a quick quantitative measure of model performance.

Additionally, the discussion of the evaluation results has been extended to include more quantitative analyses.

Minor comments:

L52: It is appropriate to cite Dai et al. (2013) here

It is not clear how a citation to Dai et al. (2003) would fit into the mentioned sentence. Dai et al. (2003) give an overview of the CLM land surface model, which uses the Ball model to link leaf photosynthesis and stomatal conductance. The Ball model is cited in the sentence, but CLM is just one of many models using the Ball model and we think that a citation to these is not appropriate here.

L418: Where and when does “frozen water runoff” occur?

Frozen water runoff occurs if the snow water equivalent of the snow layer exceeds 1000 kg/m², as mentioned in the text. In practice in the model simulation for the 20th century it is limited to areas around Greenland, where annual snow accumulation exceeds snow melt.

L815: Another reason is the assumption of global uniform soil porosity in the model.

This is now mentioned in the text.

L820: The agreement of wetland areas between the model and multi-satellite data is not very good in spatial distribution (Fig. 11). Please comment.

The paragraph where wetland extent is evaluated has been extended including further discussion: “The mean annual simulated wetland area is 3.2 mln km². Maximum monthly wetland extent is reasonably well captured by the model (Fig. 11). Compared to the multi-satellite product from GIEMS (Prigent et al., 2007; Papa et al., 2010) the model simulates larger wetland extent in tropical forest areas and northern peatland areas. However, if compared to other wetland products based on data other than from satellite, GIEMS is underestimating wetlands below dense forests (e.g. the Amazon forest (Melack and Hess, 2010)) and in peatland regions of northern Canada and Eastern Siberia (Stocker et al., 2014). In south-east Asia, the GIEMS wetland extent also includes extensive rice cultivation areas, which are not represented in the model. The modelled seasonal variation in global wetland area is in very good agreement with GIEMS (Fig. 12).”

L852: Explain “flux weighted discrimination”

Has been replaced by: “GPP-weighted isotopic discrimination during photosynthesis”.

Table 5: Canopy diffuse snow-free albedos (0.005 for vis and 0.154 for nir) for needleleaf trees seem to be too small. In addition, does the model consider evergreen versus deciduous trees for LAI_{min} = 1 and LAI_{max} = 9 (broadleaf) or 7 (needleleaf)?

The diffuse canopy albedo values are taken from Houldcroft et al. (2009) and are based on MODIS data. The values seem also to be in agreement with site level observations reported by Betts and Ball (1997).

All PFT specific parameters listed in Table 5 are the same for evergreen and deciduous trees.

References:

- Dai, Y., and 11 coauthors, 2003: *The Common Land Model*. *Bull. Amer. Meteor. Soc.*, **84**, 1013-1023.
- Zeng, X. D., X. Zeng, and M. Barlage, 2008: *Growing temperate shrubs over arid and semiarid regions in the Community Land Model—Dynamic Global Vegetation*

References:

- Shi, H. X., & Wang, C. H. (2015). Projected 21st century changes in snow water equivalent over Northern Hemisphere landmasses from the CMIP5 model ensemble. *Cryosphere*, *9*(5), 1943–1953. <http://doi.org/10.5194/tc-9-1943-2015>

Houldcroft, C. J., Grey, W. M. F., Barnsley, M., Taylor, C. M., Los, S. O., & North, P. R. J. (2009). New Vegetation Albedo Parameters and Global Fields of Soil Background Albedo Derived from MODIS for Use in a Climate Model. *Journal of Hydrometeorology*, *10*(1), 183–198. <http://doi.org/10.1175/2008JHM1021.1>

Betts, A. K., & Ball, J. H. (1997). Albedo over the boreal forest. *Journal of Geophysical Research*, *102*(D24), 28901. <http://doi.org/10.1029/96JD03876>

Response to reviewer #2

General comments

In this manuscript, the authors presented a new integrated terrestrial model, PALADYN, which includes major physical and biogeochemical processes at an intermediate complexity. The model was developed on the basis of previous models such as LPJ and TRIFFID but includes several recent findings such as new stomatal conductance model. Although many terrestrial models for similar purposes have been developed, this model has several unique and intriguing features. In particular, inclusion of peatland and permafrost carbon dynamics will allow the model to simulate long-term (e.g., glacial time scale) simulations as proposed by the authors. This manuscript includes more than hundred equations, many tables, and schematic diagrams to fully describe the model. To demonstrate the model performance, the authors compared major terrestrial variables with contemporary observational datasets. Overall, these results show good performance of the model, but the authors provided only very brief explanations. Although I agree that scientific insights are not necessarily included into the manuscript, I recommend clarifying the characteristics of the PALADYN model, especially in comparison with other models. Therefore, I conclude that the manuscript needs minor revision before acceptance for publication. Please look my specific comments for details.

The model evaluation section has been extended to include a more in depth and quantitative analysis of the model performance, including also discussions of the model performance relative to state-of-the-art land surface models, where appropriate. To back up the qualitative analyses of model performance we additionally computed some quantitative metrics like correlation and root mean square error for a number of modelled quantities. These values are directly included in the figures to allow the reader to get a quick quantitative measure of model performance.

Specific comments

Line 103: It seems that the model don't have a separate type for crops. Do you have an idea to include croplands to account for agriculture?

We are not planning to include crops in the model. A representation of agriculture is out of the scope of the model, which is mainly designed to represent natural processes.

Line 171: In Eq.(2), the symbol sigma seems to represent Stefan-Boltzman constant, but no definition was provided.

Sigma is the Stefan-Boltzmann constant and is defined in Table 1. For clarity now this is stated also after Eq. (2).

Line 286: Vegetation height h_v is later estimated by Eq. (81). It is helpful for readers to explain this at this point.

We added a reference to Eq. (81) as suggested.

Line 397: In Eq. (42), what kind of phenomenon does the last turnover term represent? Stem flow?

The last term in Eq. (42) crudely parameterizes all canopy water removal terms excluding evaporation. It therefore includes e.g. stem flow, dripping from the leaves and water removal by wind.

Line 456: It seems that Figure 2 does not include the surface runoff R_w . Can you include R_w into Figure 2?

R_w has been included into Figure 2 and several other variables in Figure 2 have been renamed to match the variable names used in the equations.

Line 566: Is this the single-sided (or projected) specific leaf area?

Yes, SLA is the one-sided leaf area per leaf carbon mass. This is now explicitly stated in the text.

Line 606: The statement is at least partially incorrect. In East Siberia, a broad area of forest is dominated by larch, a deciduous needleleaf species.

The sentence was probably not clear enough and has been reformulated. Since the model has only a single PFT to represent deciduous and evergreen needleleaf trees, both deciduous and evergreen trees share the same PFT-specific parameters (including the specific leaf area, SLA). In the model, deciduous needleleaf trees would be competitive in East Siberia if their SLA would be higher (as would be appropriate according e.g. to the TRY database) than the value of 6 m²/kgC used in the model for needleleaf trees. By assuming that needleleaf trees are evergreen independently of the climatic conditions, we allow some needleleaf forest to grow e.g. in east Siberia, where it would not grow otherwise.

Line 745: How did you determine the stable and radiocarbon isotope ratios of the atmospheric CO₂? As you know, it has been changed by the Suess effect.

So far, regarding carbon isotopes, in the paper we have shown only the isotopic discrimination during photosynthesis, which does not depend on the isotope ratios of atmospheric CO₂. The issue of stable and radiocarbon isotope ratios of the atmospheric CO₂ will be discussed in a future paper where carbon isotopes will be evaluated in more detail.

Line 772: "Manua" should be replaced by "Mauna".

Corrected.

Line 821: In terms of wetland extent, the model estimate seems to underestimate in Southeast Asia. I guess that the GIEMS data includes a substantial fraction of paddy fields. Is it correct?

Yes, the wetlands in Southeast Asia in GIEMS include a substantial fraction from rice cultivations. The paragraph comparing the modelled wetland extent with GIEMS has been expanded in the paper and this issue is now discussed. (see also response to reviewer#1)

Line 852: Can you say something about the simulated discrimination in relation to C₃ and C₄ plant distribution? Do you confirm that distribution and functional contribution of C₃ and C₄ plants were reasonably simulated?

In the revised version of the manuscript we added some discussion of the simulated discrimination shown in Fig. (21). As shown in Fig. (22) the model reproduces the difference in discrimination between C3 and C4 plants. This, together with the modelled C4/C3 grass distribution, explains the low discrimination values in subtropical areas, particularly in Africa, in agreement with other modelling studies (e.g. Scholze et al. (2003)).

References:

Scholze, M., Kaplan, J. O., Knorr, W., & Heimann, M. (2003). Climate and interannual variability of the atmosphere-biosphere $^{13}\text{CO}_2$ flux. *Geophysical Research Letters*, *30*(2), 1097.
<http://doi.org/10.1029/2002GL015631>

PALADYN v1.0, a comprehensive land surface-vegetation-carbon cycle model of intermediate complexity

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Abstract. PALADYN is presented, a new comprehensive and computationally efficient land surface–vegetation–carbon cycle model designed to be used in Earth system models of intermediate complexity for long-term simulations and paleoclimate studies.

The model treats in a consistent manner the interaction between atmosphere, terrestrial vegetation
5 and soil through the fluxes of energy, water and carbon. Energy, water and carbon are conserved. ~~The~~
~~model~~ PALADYN explicitly treats permafrost, both in physical processes and as important carbon
pool. ~~The model~~ It distinguishes 9 surface types of which, namely 5 are different vegetation types,
bare soil, land ice, lake and ocean shelf. Including the ocean shelf allows to treat continuous changes
in sea level and shelf area associated with glacial cycles. Over each surface type the model solves
10 the surface energy balance and computes the fluxes of sensible, latent and ground heat and upward
shortwave and longwave radiation. ~~It~~ The model includes a single snow layer.

Vegetation and bare soil share a single soil column. The soil is vertically discretized into 5 layers
where prognostic equations for temperature, water and carbon are consistently solved. Phase changes
of water in the soil are explicitly considered. A surface hydrology module computes precipitation
15 interception by vegetation, surface runoff and soil infiltration. The soil water equation is based on
Darcy’s law. Given soil water content, the wetland fraction is computed based on a topographic
index. The temperature profile is also computed in the upper part of ice sheets and in the ocean shelf
soil.

Photosynthesis is computed using a light use efficiency model. Carbon assimilation by vegetation
20 is coupled to the transpiration of water through stomatal conductance. ~~The model~~ PALADYN in-
cludes a dynamic vegetation module with 5 plant functional types competing for the gridcell share
with their respective net primary productivity.

The model [PALADYN](#) distinguishes between mineral soil carbon, peat carbon, buried carbon and shelf carbon. Each soil carbon 'type' has its own soil carbon pools generally represented by a litter, a fast and a slow carbon pool in each soil layer. Carbon can be redistributed between the layers by vertical diffusion [and advection](#). For the vegetated macro surface type, decomposition is a function of soil temperature and soil moisture. Carbon in permanently frozen layers is assigned a long turnover time which effectively locks carbon in permafrost. Carbon buried below ice sheets and on flooded ocean shelves is treated differently. The model also includes a dynamic peat module.

PALADYN includes carbon isotopes ^{13}C and ^{14}C , which are tracked through all carbon pools. Isotopic discrimination is modelled only during photosynthesis.

A simple methane module is implemented to represent methane emissions from anaerobic carbon decomposition in wetlands (including peatlands) and flooded ocean shelf.

The model description is accompanied by a thorough model evaluation in offline mode for the present day and the historical period.

1 Introduction

Land surface models (LSMs) represent an essential component of Earth system models ([ESMs](#)) of different complexity. Currently LSMs simulate the interaction between atmosphere, vegetation, land surface and upper soil through the fluxes of energy, water and carbon. Modern LSMs are the result of a gradual convergence of initially separate modeling approaches: climate, carbon cycle and vegetation dynamics models (e.g. Pitman, 2003; Sellers et al., 1997).

In the earlier climate models very simple land surface schemes with bucket hydrology and without explicit vegetation representation were used (Manabe, 1969). The 2nd generation LSMs (Sellers et al., 1997) simulated soil temperature and moisture in several layers and the water and energy exchange between the land surface and the atmosphere were mediated by vegetation represented as a big leaf (e.g. Deardorff, 1978), BATS (Dickinson et al., 1986) and SiB (Sellers et al., 1986)). This step was required because biological processes play a major role in controlling evapotranspiration. In 2nd generation LSMs the behaviour of leaf stomata, which controls the rate of transpiration of water from plants, was represented based on empirical relations with climate (e.g. Jarvis, 1976). The 3rd generation of LSMs included additionally a mechanistic representation of photosynthesis (Farquhar et al.; Collatz et al., 1991) which could then directly be related to stomatal conductance used to compute transpiration (Ball et al., 1987; Leuning, 1995).

Terrestrial biogeochemical models followed a separate line of development. These models were designed to simulate the exchanges of carbon between the atmosphere and terrestrial ecosystems for a given climate and geographic vegetation distribution (e.g. Raich et al., 1991; Melillo et al., 1993; Running and Coughlan, 1988; Running and Gower, 1991; Foley, 1994).

Equilibrium biogeography models were developed alongside terrestrial carbon cycle models to simulate the global vegetation distribution for given climatic conditions (Woodward, 1987; Prentice et al., 1992; Haxeltine and Prentice, 1996b; Neilson, 1995). However, equilibrium models do not
60 simulate the processes of plant growth, competition and mortality that govern the dynamics of vegetation changes. Global dynamic vegetation models have been developed for this purpose (Haxeltine and Prentice, 1996b; Sitch et al., 2003; Cox, 2001; Friend et al., 1997; Foley et al., 1996; Woodward et al., 1998; Brovkin et al., 1997).

Since it was shown that climate-vegetation feedbacks may be important, the first attempts to incorporate interactive vegetation into climate models were made (Henderson-Sellers, 1993; Claussen,
65 1994). While during the 1990s and 2000s climate models and then Earth system models (ESMs) based on coupled general circulation models (GCMs) remained too expensive to perform long-term simulations, a new class of models - Earth system models of intermediate complexity (EMICS, Claussen et al. (2002)) - emerged. The EMIC CLIMBER-2 (Petoukhov et al., 2000; Ganopolski et al., 2001) was one of the first Earth system models which included both terrestrial carbon cycle
70 and vegetation dynamics based on VECODE (Brovkin et al., 1997, 2002) and has been also used to estimate the strength of the climate-vegetation feedback (Willeit et al., 2014b) and the carbon cycle feedback (Willeit et al., 2014a). Later, similar and more comprehensive vegetation models were incorporated in both complex and intermediate complexity ESMs (e.g. Cox, 2001; Brovkin et al.,
75 2009; Arora and Boer, 2006; Krinner et al., 2005; Sato et al., 2007).

A limitation of previous land surface modeling approaches is that different model components are not necessarily consistent because initially they were developed as stand-alone models. Additionally, initially LSMs have been developed with the intention to capture the processes which are important for climate change projections on the time scales of centuries, thus missing processes which might
80 play an important role on longer time scales. This was fully justified by the fact that complex ESMs were and are still too computationally expensive to be used on much longer time scales, such as for simulations of glacial cycles. Only recently some existing models have been adapted to include slower processes, for example peat carbon dynamics (Wania et al., 2009; Kleinen et al., 2012; Spahni et al., 2013; Stocker et al., 2014). However, the simulation of processes with long time scales, such
85 as peat carbon accumulation or inert permafrost carbon dynamics, require necessarily a transient modelling approach, which is made feasible only by a fast model.

Here we present a new land ~~surface~~-model primarily designed for paleoclimate applications, and therefore named PAleo LAnd DYNAmics model (PALADYN), although also applicable to many other types of studies, including multi-ensemble future projections. The model has been designed
90 to represent the land processes which are thought to be important both on short and very long time scales. The physical and biochemical processes are consistently coupled with each other. The model is intended to be used in the next generation of the CLIMBER EMIC and to substitute VECODE. CLIMBER employs a statistical dynamical atmosphere model. This type of model does not explicitly

simulate weather and therefore PALADYN is designed to simulate climatological mean seasonal
95 cycle. Typical ~~application~~ applications of such model ~~is~~ are simulations of Earth system dynamics
on astronomical and geological time scales. This is why particular attention is given to the selection
of the proper complexity of the different processes which are represented in order to capture the
main feedbacks in the system but at the same time maintain the model computationally efficient.
We expect that PALADYN can also be used in other EMICs since most of them still employ rather
100 simplistic LSMs.

2 Model overview

PALADYN is designed to operate on coarse resolution required for long-term simulations. Here we
test the model on a $5 \times 5^\circ$ ~~horizontal~~ horizontal resolution.

In each grid cell the model distinguishes 9 surface types (5 vegetation types, bare soil, ice sheets,
105 lakes and ocean shelf) (Fig. 1a). All surface type fractions can change over time. The fraction of
vegetation types and bare soil is computed by the dynamic vegetation module. The model is also able
to handle changes in the fraction of ice sheet and ocean shelf, when given as input. This is necessary
to simulate glacial cycles. So far lakes are implemented in the model only as a placeholder.

Over each surface type, except ocean shelf, the model solves the surface energy balance and com-
110 putes the fluxes of sensible, latent and ground heat and upward shortwave and longwave radiation.

Vegetation and bare soil share a single soil column (Fig. 1b) where temperature, moisture and
carbon are discretized in 5 vertical layers reaching down to a depth of 3.9 m. The top soil layer is
20 cm thick. A single snow layer with prognostic temperature and density is included in the model on
top of the soil column. A 1d-heat diffusion equation is solved to compute snow and soil temperature
115 with the ground heat flux as top boundary condition. Snowmelt and phase changes of water in the soil
are explicitly considered. A surface hydrology module computes rainfall intercepted by vegetation,
surface runoff and infiltration. Infiltration provides the top boundary condition for the solution of
soil water equation based on Darcy's law. Given soil water content the wetland fraction is computed
following a simplified TOPMODEL approach (Niu et al., 2005).

120 For the ice sheet fraction, the temperature of the snow layer and of the top 3.9 m of ice below is
computed in the same way as for the soil, but phase changes in the ice are inhibited. The temperature
of the soil below the shelf water is needed to calculate the decomposition rate of shelf carbon. It is
computed from a 1-d diffusion equation with the shelf water temperature prescribed as top boundary
condition and assuming that the soil is saturated with liquid and/or frozen water. Phase changes are
125 accounted for.

Photosynthesis is computed following Sitch et al. (2003) and Haxeltine and Prentice (1996a, b).
Carbon assimilation by vegetation is coupled to the transpiration of water vapor through stomatal
conductance. PALADYN includes a dynamic vegetation module based on TRIFFID (Cox, 2001)

with 5 plant functional types competing for the gridcell share with their respective net primary
130 production.

PALADYN includes a representation of soil carbon processes, including slow processes that are
thought to be relevant over multimillennial time scales associated with glacial-interglacial transitions,
when the appearance and disappearance of continental ice sheets, changes in sea level and land area
can potentially strongly affect the land carbon cycle. PALADYN therefore includes processes with
135 a long time scale, such as accumulation of carbon in peatlands, inert carbon locked in perennially
frozen ground and carbon buried below ice sheets. It also accounts for changes in land area due to
sea level variations and isostatic adjustment of the lithosphere to the ice sheet loading. During periods
of low sea level the model allows vegetation to grow on exposed ocean shelves. When sea level is
rising the exposed shelf becomes flooded and the vegetation dies.

140 The soil of the vegetated grid cell part, the soil below the ice sheet and soil below the shelf
water ~~has its~~ have their own carbon pools (Fig. 1c) represented in general by a litter, a fast and
a slow carbon pool in each soil layer. Carbon can be redistributed between the layers by vertical
diffusion and advection. For the vegetated part, decomposition of organic matter is a function of
soil temperature and soil moisture. Carbon in permanently frozen layers is assigned a long turnover
145 time which effectively locks carbon in permafrost. Carbon buried below ice sheets and carbon on the
flooded ocean shelf ~~are treated separately~~ is treated separately, but is not discussed in detail in this
paper.

A representation of peatland dynamics is also included in PALADYN. In inundated areas, peat is
formed by accumulating carbon at the surface in the seasonally anoxically decomposing acrotelm.
150 When the acrotelm carbon exceeds a critical value, carbon is transferred to the catotelm below the
water table.

PALADYN also includes carbon isotopes ^{13}C and ^{14}C , which are tracked through all carbon pools.
Isotopic discrimination is modelled only during photosynthesis.

A simple methane module is implemented to represent methane emissions from anaerobic carbon
155 decomposition in wetlands (including peatlands) and flooded ocean shelf.

The processes represented in PALADYN are illustrated in Fig. 2 and Fig. 3.

All physical model components and photosynthesis are integrated with an implicit timestepping
scheme with a time step of one day. Dynamic vegetation and soil carbon processes are integrated
with an implicit timestepping scheme with a time step of one month.

160 The model is written in ~~FORTRAN90~~ FORTRAN and uses the NCIO package (Robinson and
Perrette, 2015) to handle input and output of data.

This paper describes the model representation of processes over ice free land. Processes related to
changes in land-ice-ocean mask, buried and ocean shelf carbon will be described in a forthcoming
paper.

165 3 Surface energy balance and fluxes

The surface energy balance equation at the land surface is written as:

$$(1 - \alpha)SW^\downarrow + \epsilon LW^\downarrow - LW^\uparrow - H - LE - G = 0, \quad (1)$$

where α is surface albedo, SW^\downarrow is the incoming shortwave radiation, ϵ is the surface emissivity for longwave radiation, LW^\downarrow and LW^\uparrow are the incoming and outgoing longwave radiation at the surface, H is the sensible heat flux, LE is the latent heat flux and G the ground heat flux. Equation (1) is then solved for the skin temperature, T_* , using the formulations for the energy fluxes described next. All symbols are defined in Table 1.

The surface emitted longwave radiation is given by the Stefan-Boltzmann law with a surface type dependent emissivity ϵ (section 3.2) to account for the fact that the surface is not a perfect black body:

$$LW^\uparrow = \epsilon \sigma T_*^4. \quad (2)$$

σ is the Stefan-Boltzmann constant. The sensible heat flux is computed from the temperature gradient between the surface and a reference height above the surface and an aerodynamic resistance, r_a (section 3.3), using the bulk aerodynamic formula:

$$180 \quad H = \frac{\rho_a C_p}{r_a} (T_* - T_a), \quad (3)$$

where ρ_a is air density, C_p is the specific heat of air, r_a is the aerodynamic resistance and T_a is the temperature of the air at a reference level z_{ref} .

Similarly, the latent heat flux over unvegetated surfaces is expressed in terms of the specific humidity gradient between the surface and a reference atmospheric level with the addition of a factor β_s (section 3.4) representing a possible limitation in the moisture supply:

$$185 \quad LE = L \frac{\rho_a}{r_a} \beta_s (q_{\text{sat}}(T_*) - q_a). \quad (4)$$

L is the latent heat of vaporisation, q_{sat} is the specific humidity at saturation and q_a is the specific humidity of air. Over vegetation the latent heat flux consists of contributions from transpiration of water vapour through leaf stomata during photosynthesis, soil/snow evaporation and sublimation from below the canopy and evaporation ~~of rainfall~~ and sublimation of precipitation intercepted by the canopy:

$$LE = L \frac{\rho_a}{r_a + r_s} (q_{\text{sat}}(T_*) - q_a) + L \frac{\rho_a}{r_a + r_{a,\text{can}}} \beta_s (q_{\text{sat}}(T_{s,1}) - q_a) + LE_{\text{can}}. \quad (5)$$

$r_{a,\text{can}}$ is the aerodynamic resistance between the soil surface and the vegetation canopy (section 3.3) and r_s is the canopy resistance to water vapor flux through the leaf stomata as described in detail in section 3.4). $T_{s,1}$ is the temperature of the top soil layer, or the snow layer temperature if snow

is present. Canopy evaporation and sublimation, E_{can} , is computed using the skin temperature from the previous time step as described in section 5.1.

The ground heat flux is represented by conduction of heat between the skin and the center of the snow layer or top soil layer:

$$200 \quad G = 2\lambda_{s,1} \frac{T_{\star} - T_{s,1}}{\Delta z_1}. \quad (6)$$

$\lambda_{s,1}$ is the heat conductivity and Δz_1 is the thickness of the snow layer or top soil layer.

The prognostic terms in T_{\star} in the formulation of the surface energy fluxes are then linearized using Taylor series expansion assuming that the temperature at the new time step, $T_{\star,n+1} = T_{\star,n} + \Delta T_{\star}$ with $\Delta T_{\star} \ll T_{\star}$:

$$205 \quad T_{\star,n+1}^4 = T_{\star,n}^4 + 4T_{\star,n}^3 (T_{\star,n+1} - T_{\star,n}), \quad (7)$$

$$q_{\text{sat}}(T_{\star,n+1}) = q_{\text{sat}}(T_{\star}) + \left. \frac{dq_{\text{sat}}}{dT_{\star}} \right|_{T_{\star}=T_{\star,n}} (T_{\star,n+1} - T_{\star,n}). \quad (8)$$

Equation (1) can then be solved explicitly for the skin temperature at the new time step, $T_{\star,n+1}$, separately for each surface type.

210 If snow is present and the skin temperature is above freezing the surface energy fluxes are diagnosed first with the skin temperature greater than 0°C and then with skin temperature set to 0°C . The difference between the sum of the energy fluxes is then ~~used to melt part of~~ added to the energy available to melt the snow layer.

Given the new skin temperatures, the ground heat flux G and its derivative with respect to top soil or snow temperature ($\partial G / \partial T_{s,1}$) are diagnosed and used as input for the ~~1d~~ soil heat diffusion equation. After the top-soil/snow temperature has been updated as described in section 4, it is used to compute the total ground heat flux $G_{\text{new}} = G + \partial G / \partial T_{s,1} \Delta T_{s,1}$. Skin temperature is then updated using G_{new} and all remaining surface energy and water fluxes are diagnosed.

220 In the next sections the surface parameters needed for the solution of the surface energy balance equation are described.

3.1 Surface albedo

PALADYN distinguishes between direct beam and diffuse albedo in the visible and infrared spectral bands. For ice sheets and bare soil the surface albedo is computed as a weighted mean of snowfree (α_{snfree}) and snow (α_{sn}) albedoes:

$$225 \quad \alpha = f_{\text{sn}} \alpha_{\text{sn}} + (1 - f_{\text{sn}}) \alpha_{\text{snfree}}, \quad \text{bare soil, ice sheets.} \quad (9)$$

The snowfree soil albedo in the visible and near infrared band ~~are is~~ prescribed from (Dazlich and Los, 2009). The fraction considered to be snow covered depends on snow height (h_{sn}) and snowfree

roughness length (z_0^{snfree}) of the surface (Section 3.3) following Oleson et al. (2004):

$$f_{\text{sn}} = \frac{h_{\text{sn}}}{h_{\text{sn}} + 10z_0^{\text{snfree}}}. \quad (10)$$

230 The albedo of grass and shrubs is computed by additionally separating the snowfree albedo into bare soil and canopy albedo through a sky view factor f_{sv} :

$$\alpha = f_{\text{sn}}\alpha_{\text{sn}} + (1 - f_{\text{sn}})(1 - f_{\text{sv}})\alpha_{\text{snfree}}^{\text{can}} + (1 - f_{\text{sn}})f_{\text{sv}}\alpha_{\text{soil}}, \quad \text{grass, shrubs.} \quad (11)$$

The sky view factor is a function of the leaf area index (L_{ai}), the stem area index (S_{ai}) and an extinction coefficient k_{ext} (Table 2) (e.g. Otto et al., 2011):

$$235 \quad f_{\text{sv}} = \exp[-k_{\text{ext}}(L_{\text{ai}} + S_{\text{ai}})]. \quad (12)$$

The forest albedo is computed as a weighted mean of canopy albedo (α_{can}) and albedo of the ground below the canopy (α_{g}):

$$\alpha = f_{\text{sv}}\alpha_{\text{g}} + (1 - f_{\text{sv}})\alpha_{\text{can}}, \quad \text{forest.} \quad (13)$$

The direct beam sky view factor for forest includes a daily radiation weighed solar zenith angle (μ) dependence following Campbell and Norman (1989):

$$240 \quad f_{\text{sv}}^{\text{dir}} = \exp\left[-k_{\text{ext}} \frac{(L_{\text{ai}} + S_{\text{ai}})}{\cos\mu}\right]. \quad (14)$$

The sky view factor for diffuse radiation is derived by fitting the relation given by Verseghy et al. (1993) and is taken to be:

$$f_{\text{sv}}^{\text{dif}} = \exp\left[-k_{\text{ext}} \frac{(L_{\text{ai}} + S_{\text{ai}})}{\cos 45^\circ}\right]. \quad (15)$$

245 The albedo of the ground below the canopy, α_{g} , is computed as in Eq. (9). α_{can} varies between snowfree canopy albedo and snow-covered canopy albedo depending on the canopy fraction covered by snow:

$$\alpha_{\text{can}} = f_{\text{sn}^{\text{can}}}^{\text{cans}} \alpha_{\text{sn}}^{\text{can}} + (1 - f_{\text{sn}^{\text{can}}}^{\text{cans}}) \alpha_{\text{snfree}}^{\text{can}}. \quad (16)$$

The canopy fraction covered by snow, $f_{\text{sn}}^{\text{can}} f_{\text{can}}^{\text{fs}}$, is described in Section 5.1. For $\alpha_{\text{snfree}}^{\text{can}}$ the PFT specific values derived from MODIS data in Houlcroft et al. (2009) for the TRIFFID PFTs are used and $\alpha_{\text{sn}}^{\text{can}}$ values are taken from Moody et al. (2007) based on MODIS data (Table 5).

Snow albedo is parameterized as a function of the solar zenith angle and a snow ageing factor. The diffuse albedo of freshly fallen snow is set to 0.95 in the visible band and to 0.65 in the near infrared band. The actual albedo of snow for diffuse radiation depends on a snow age factor f_{age} :

$$255 \quad \alpha_{\text{sn}}^{\text{vis,dif}} = \alpha_{\text{sn,fresh}}^{\text{vis,dif}} - 0.05f_{\text{age}}, \quad (17)$$

$$\alpha_{\text{sn}}^{\text{nir,dif}} = \alpha_{\text{sn,fresh}}^{\text{nir,dif}} - 0.25f_{\text{age}}. \quad (18)$$

The snow age factor is intended to represent the effect of snow grain size increase on albedo (Warren and Wiscombe, 1980). For simplicity and to account for the fact that a statistical dynamical atmosphere does not resolve single snowfall events but rather returns a smoothly varying daily snowfall rate, f_{age} is parameterized as a function of skin temperature and snowfall rate as described in Appendix A. If the skin temperature is at melting point, the snow albedo is further reduced by 0.2 to account for the formation of melt ponds.

The direct beam snow albedo is then computed as (Dickinson et al., 1986):

$$\alpha_{\text{sn}}^{\text{dir}} = \alpha_{\text{sn}}^{\text{dif}} + 0.4f_{\mu}(1 - \alpha_{\text{sn}}^{\text{dif}}), \quad (19)$$

where the solar zenith angle factor is slightly modified from Dickinson et al. (1986) to correct for the bias highlighted by Gardner and Sharp (2010):

$$f_{\mu} = 0.5 \left(\frac{3}{1 + 2\cos\mu} - 1 \right). \quad (20)$$

3.2 Surface emissivity

The broadband emissivity (ϵ) used to compute the net longwave radiation at the surface is a surface-type dependent parameter. It is taken to be equal to 0.96 for all vegetation types, 0.9 for bare soil, 0.99 for snow-covered ground and 0.99 for ice (Jin and Liang, 2006; Walters et al., 2014).

3.3 Aerodynamic resistances

The aerodynamic resistance, r_a , is computed for each surface type accounting for atmospheric stability through a bulk Richardson number following BATS (Dickinson et al., 1986). The drag coefficients for neutral stratification are obtained from boundary-layer theory:

$$C_{\text{DN}}^{\text{m}} = \kappa^2 \left[\ln \left(\frac{z_{\text{ref}} - d}{z_{\text{m}}} \right) \right]^2, \quad \text{drag coefficient for momentum} \quad (21)$$

$$C_{\text{DN}}^{\text{h}} = \kappa^2 \left[\ln \left(\frac{z_{\text{ref}} - d}{z_{\text{m}}} \right) \ln \left(\frac{z_{\text{ref}} - d}{z_{\text{h}}} \right) \right], \quad \text{drag coefficient for heat and water.} \quad (22)$$

z_{ref} is a reference height above the surface and d is the zero-plane displacement, the height above the ground at which zero wind speed is achieved, and depends on the surface type. z_{m} is the roughness length for momentum and is computed as the weighted mean of the roughness length of snow (z_0^{sn}) and the roughness length of the snow-free surface (z_0^{snfree}):

$$z_{\text{m}} = f_{\text{sn}} z_0^{\text{sn}} + (1 - f_{\text{sn}}) z_0^{\text{snfree}}. \quad (23)$$

A logarithmic averaging would be more appropriate here (Zeng and Wang, 2007), but for computational efficiency a simple linear weighting is preferred. This simplification does not significantly affect the model results. The snow covered fraction is given by Eq. (10) for all surface types. For vegetated surfaces, z_0^{snfree} is given by a weighted mean of vegetation (z_0^{v}) and bare soil (z_0^{b}) roughness:

$$z_0^{\text{snfree}} = V z_0^{\text{v}} + (1 - V) z_0^{\text{b}}. \quad (24)$$

where the weight V depends on the vegetation state:

$$290 \quad V = \frac{L_{ai} + S_{ai}}{(L_{ai} + S_{ai})_{crit}}, \quad (25)$$

and is limited to be lower than 1. The critical value of $(L_{ai} + S_{ai})_{crit}$ is set to 2. Zeng and Wang (2007) showed that model results are not very sensitive to the formulation of V . z_0^v is taken as 1/10 of the vegetation height (h_v) and the displacement $d = 0.7Vh_v$. Vegetation height h_v varies over time for each PFT and differs between PFTs (see Eq. (82)). For bare soil, snow and ice $d = 0$ and the values of z_0 are given in Table 2.

In general the roughness length for heat and water vapor differs from the roughness length for momentum and is defined by (Garratt, 1994; Milly and Shmakin, 2002):

$$\ln\left(\frac{z_m}{z_h}\right) = 2. \quad (26)$$

z_h is therefore almost an order of magnitude smaller than z_m .

300 Although the surface energy balance equation in PALADYN is solved with a daily time step, which implies that the diurnal cycle in atmospheric stability can not be resolved by the model, the inclusion of a simple Richardson number dependence based on daily mean temperatures in the computation of the drag coefficients significantly improves the simulated surface energy fluxes when the stratification is unstable. The bulk Richardson number is calculated as (Dickinson et al., 1986):

$$305 \quad R_i = g z_{ref} \frac{(1 - T_* / T_a)}{V_a^2 + 1}, \quad (27)$$

where g is the acceleration due to gravity and V_a is the wind speed at the reference level z_{ref} . The drag coefficients for the unstable case ($R_i < 0$) are then adjusted to account for atmospheric stability:

$$C_D^{m/h} = C_{DN}^{m/h} \left(1 + 24.5 \sqrt{-C_{DN}^{m/h} R_i} \right) \quad R_i < 0. \quad (28)$$

Finally, the aerodynamic resistance for sensible and latent heat flux is given by:

$$310 \quad r_a = \frac{1}{C_D^h V_a} \quad (29)$$

The aerodynamic resistance for the transfer of heat and water between the ground and the canopy is parameterized ~~partly following as:~~

$$r_{a,can} = \frac{1}{C_{can} u_*}. \quad (30)$$

315 ~~$u_* = V_a C_D^h \sqrt{C_D^h}$ is the friction velocity and represents the wind speed incident on the leaves. The drag coefficient C_{can} is given by:~~

$$C_{can} = W C_{bare} + (1 - W) C_{dense} \frac{1 - \exp[-(L_{ai} + S_{ai})]}{C_{can} V_a}. \quad (31)$$

The ~~weight W depends on the~~ leaf and stem area index, ~~$W = e^{-(L_{ai} + S_{ai})}$. C_{can} varies between C_{dense} for dense canopy and C_{bare} when W factor insures that $r_{a,can}$ tends to zero when vegetation is vanishing.~~ The values of ~~C_{dense} and C_{bare} are the drag coefficient C_{can} is~~ given in Table 2.

320 3.4 Surface resistance to water vapor fluxes

Additionally to the aerodynamic resistances, the flux of water vapor from the ground or canopy is subject to additional resistances. For evaporation from bare soil this surface resistance is represented in terms of a β_s -factor. Different parameterisations of β_s have been proposed to be used in global climate models (e.g. Mahfouf and Noilhan, 1991). The model [results](#), in particular the geographic distribution and extent of modelled bare soil, [is-are](#) strongly dependent on the formulation of the β_s factor. Thus various surface resistance formulations for bare soil evaporation are implemented in PALADYN with the default β_s depending on top-soil moisture (θ_1) and field capacity (θ_{fc}) following Lee and Pielke (1992):

$$\beta_s = \begin{cases} \frac{1}{4} \left[1 - \cos \left(\pi \frac{\theta_1}{\theta_{fc}} \right) \right]^2 & \theta_1 < \theta_{fc} \\ 1 & \theta_1 \geq \theta_{fc}. \end{cases} \quad (32)$$

330 The resistance for transpiration of water through the leaf stomata is coupled to the uptake of carbon during photosynthesis and is simply the inverse of the canopy conductance calculated by the photosynthesis module (section 6.1) after conversion to units of m s^{-1} :

$$r_s = \frac{1}{g_{\text{can}}}. \quad (33)$$

Evaporation and sublimation from the canopy and sublimation from snow and ice are assumed to occur without surface resistance ($r_s = 0$ and $\beta_s = 1$).

4 Snow and soil temperature

The heat transfer in the snow-soil column is represented by a one-dimensional heat diffusion equation:

$$c \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} \left[\lambda \frac{\partial T_s}{\partial z} \right]. \quad (34)$$

340 Equation [34](#)(34) assumes that the lateral heat transport and vertical heat transport other than by conduction are small and can be neglected. Other models include for example the vertical heat advection by the water penetrating into the soil (e.g. Cox et al., 1999). Equation 34 also assumes that there are no heat sources inside the soil column. Heat generated by organic matter decomposition is an example of internally generated heat (e.g. Khvorostyanov et al., 2008). In Eq. [34](#)(34) c is the volumetric heat capacity and λ is the thermal conductivity of soil/snow. Equation [34](#)(34) is solved with the ground heat flux as top boundary condition and zero heat flux at the bottom of the soil column. Eventually the deep permafrost model of Willeit and Ganopolski (2015) is going to be coupled to PALADYN with the geothermal heat flux as bottom boundary condition. The numerical solution of Eq. [34](#)(34) follows the fully implicit formulation in Oleson et al. (2013). The snow/soil temperature

350 profile is calculated first without phase change and then readjusted for phase change following Ole-
son et al. (2013). If the new temperature of snow or of a soil layer containing frozen water is greater
than 0 °C the excess energy is used to melt snow or frozen soil water. If all snow is melting during
one time step and excess energy is remaining, this energy is added to the top soil layer. If soil tem-
perature drops below 0 °C soil water starts to freeze. Observations show that liquid water exists in
355 the soil at temperatures well below 0 °C because of adsorption forces, capillarity and ground hetero-
geneity (e.g. Williams and Smith, 1989) and the presence of solutes (e.g. Watanabe and Mizoguchi,
2002). To allow liquid water to coexist with ice below 0 °C, a freezing point depression is included
in the model and the maximum liquid water content for soil temperatures T_s below $T_0 = 273.15\text{K}$
is formulated as (e.g. Cox et al., 1999; Niu and Yang, 2006; Ekici et al., 2014):

$$360 \quad w_w^{\max} = \Delta z \rho_w \theta_{\text{sat}} \left[\frac{L_f (T_s - T_0)}{g T_s \psi_{\text{sat}}} \right]^{-1/b}, \quad (35)$$

where Δz is the layer thickness, ρ_w the density of water, θ_{sat} the porosity of the soil, L_f the lat-
ent heat of fusion of water, ψ_{sat} is the matric potential at saturation and b the Clapp-Hornberger
parameter (Section 5.4).

4.1 Snow and soil thermal properties

365 [Snow](#) [In winter, snow](#) plays a crucial role in insulating the ground below from the cold air temper-
atures. A realistic parameterisation of snow thermal properties is therefore fundamental to simulate
frozen soil dynamics. In particular, PALADYN is very sensitive to the parameterisation of snow
thermal conductivity. Hence, several snow thermal conductivity formulations that are all dependent
on snow density are included in the model (Yen, 1981; Jordan, 1991; Riche and Schneebeli, 2013).

370 The default snow thermal conductivity is from (Riche and Schneebeli, 2013):

$$\lambda_{\text{sn}} = \lambda_a - 1.06 \times 10^{-5} \rho_{\text{sn}} + 3 \times 10^{-6} \rho_{\text{sn}}^2. \quad (36)$$

λ_a is the air thermal conductivity and the snow density ρ_{sn} is described in detail in [Sectionsection](#) 5.2.

The volumetric heat capacity of snow depends on snow density and specific heat capacity of ice
(C_i):

$$375 \quad c_{\text{sn}} = C_i \rho_{\text{sn}}. \quad (37)$$

Soil heat capacity is a volume weighted mean of dry soil and liquid and frozen water:

$$c = (1 - \theta_{\text{sat}}) c_s + \theta_w \rho_w C_w + \theta_i \rho_i C_i, \quad (38)$$

where c_s is the volumetric heat capacity of dry soil (Table 3), θ_w and θ_i are the volumetric soil liquid
and frozen water contents, respectively, C_w is the specific heat capacity of water and ρ_i is the density
380 of ice.

Soil heat conductivity is a combination of heat conductivity of water, ice and dry soil following Farouki (1981):

$$\lambda = K\lambda_{\text{sat}} + (1 - K)\lambda_{\text{dry}}, \quad (39)$$

with

$$385 \quad \lambda_{\text{sat}} = \lambda_s^{1-\theta} \lambda_w^{\frac{\theta_w}{\theta} \theta_{\text{sat}}} \lambda_i^{\frac{\theta_i}{\theta} \theta_{\text{sat}}}, \quad (40)$$

where θ is the total (liquid plus frozen) volumetric soil water content. The original logarithmic formulation of the Kersten number (K) is approximated by a linear function of relative soil moisture:

$$K = \begin{cases} \frac{1}{1-0.35} \left(\frac{\theta}{\theta_{\text{sat}}} - 0.35 \right) & T_s \geq 0^\circ C \\ \frac{\theta}{\theta_{\text{sat}}} & T_s < 0^\circ C \end{cases}. \quad (41)$$

390 K is limited to be between 0 and 1. λ_w and λ_i are the thermal conductivities of water and ice, respectively. λ_s and λ_{dry} are globally uniform soil parameters (Table 3). Alternatively the values can be chosen to be dependent on soil texture and soil organic carbon content following as described in Appendix B. The inclusion of variable λ_s and λ_{dry} does not fundamentally affect the main model results, hence for computational efficiency the parameters are taken to be uniform in space and
395 constant in time by default.

5 Hydrology

5.1 Canopy water

Re-evaporation of canopy intercepted water contributes significantly to the total water flux from the surface to the atmosphere (e.g. Dirmeyer et al., 2006). Therefore, PALADYN includes a representation of rain and snow intercepted by vegetation. Rain is assumed to be intercepted only by trees
400 while snow is intercepted by all PFTs. The prognostic equations for canopy liquid water (w_{can}^w) and snow (w_{can}^s) are similar and written in terms of canopy interception, canopy evaporation/sublimation and a canopy water removal term as:

$$\frac{dw_{\text{can}}^{\text{w/s}}}{dt} = I_{\text{can}}^{\text{w/s}} - E_{\text{can}}^{\text{w/s}} - \frac{w_{\text{can}}^{\text{w/s}}}{\tau_{\text{w/s}}}. \quad (42)$$

405 Canopy interception and evaporation are given by:

$$I_{\text{can}}^{\text{w/s}} = \alpha_{\text{int}}^{\text{w/s}} P_{\text{r/s}} (1 - \exp[-k_{\text{ext}}(L_{\text{ai}} + S_{\text{ai}})]), \quad (43)$$

$$E_{\text{can}}^{\text{w/s}} = \frac{\rho_a}{r_a} (q_{\text{sat}}(T_*) - q_a) f_{\text{can}}^{\text{w/s}}. \quad (44)$$

P_r is the rain rate and P_s the snowfall rate. α_{int}^w and α_{int}^s are interception factors (Table 2). The wet canopy fraction f_{can}^w and the snow covered canopy fraction f_{can}^s are assumed to increase linearly

410 with w_{can}^w and w_{can}^s , respectively, up to a maximum water and snow amount that the canopy can hold, $w_{\text{can}}^{\text{max}} = 0.2(L_{\text{ai}} + S_{\text{ai}})$ (e.g Verseghy et al., 1993). τ_w and τ_s are the water and snow canopy removal time scales, respectively (Table 2). Negative canopy evaporation, that is dew deposition, is inhibited. If skin temperature is greater than 0 °C, all snow is removed from the canopy and added to the snow layer on the ground. Finally $E_{\text{can}} = E_{\text{can}}^w + E_{\text{can}}^s$ is diagnosed and used in the solution
 415 of the surface energy balance equation (Eq. (1)). The rate of rain and snow reaching the ground is then derived as:

$$P_{r/s,g} = P_{r/s} - E_{\text{can}}^{w/s} - \frac{dw_{\text{can}}^{w/s}}{dt}. \quad (45)$$

The area weighted $P_{r/s,g}$ over the vegetated and bare soil surface tiles are then used as input to the surface hydrology module.

420 5.2 Snow

The snow water equivalent evolution of the single snow layer is determined by the snowfall rate $P_{s,g}$, the snowmelt rate M_s and sublimation E_s :

$$\frac{dw_{\text{sn}}}{dt} = P_{s,g} - M_s - E_s. \quad (46)$$

To prevent an indefinite accumulation of snow, w_{sn} is limited to be below $w_{\text{sn,crit}} = 1000 \text{ kg m}^{-2}$
 425 and the snow excess is added to 'frozen water runoff'.

The density of snow is important because it determines the thickness of snow and hence influences surface albedo and surface roughness and because it controls the thermal properties of snow (Section 4.1). The parameterisation of snow density is based partly on Anderson (1976) [and](#) Pitman et al. (1991). The density of freshly fallen snow is temperature dependent following Anderson (1976):

$$430 \rho_{\text{sn,fresh}} = \rho_{\text{sn,min}} + 1.7(T_a - T_0 + 15)^{1.5} \quad T_0 - 15 < T_a < T_0 + 2. \quad (47)$$

$\rho_{\text{sn,min}}$ is the minimum snow density (Table 2). The effect of self-loading on snow compaction is taken into account using the relation proposed by Kojima (1967) as implemented in Pitman et al. (1991) and the prognostic equation for snow density accounting also for the density of freshly fallen snow is written as (Pitman et al., 1991):

$$435 \frac{d\rho_{\text{sn}}}{dt} = \frac{0.5g\rho_{\text{sn}}w_{\text{sn}}}{\eta} + P_{s,g} \frac{\rho_{\text{sn,fresh}} - \rho_{\text{sn}}}{w_{\text{sn}}}, \quad (48)$$

where η is the viscosity depending both on the load and temperature:

$$\eta = \eta_0 \exp \left[k_T(T_0 - T_{\text{ssu}}) + k_\rho \rho_{\text{sn}} \right]. \quad (49)$$

The values of the parameters η_0 , k_T and k_ρ are given in Table 2. The effects of snow metamorphism and snow melting on snow density are neglected. Snow thickness is then computed as:

$$440 h_{\text{sn}} = \frac{w_{\text{sn}}}{\rho_{\text{sn}}}. \quad (50)$$

5.3 Surface runoff and infiltration

Subgrid scale surface hydrology is represented using a TOPMODEL approach (Beven and Kirkby, 1979) as implemented in Niu et al. (2005). The fraction of a grid cell that is assumed to be at saturation, f_{sat} , is determined by the grid cell mean water table position (z_{∇}) and the spatially
 445 varying maximum saturated fraction $f_{\text{sat}}^{\text{max}}$ computed by Stocker et al. (2014) from the compound topographic index (CTI) derived from the high resolution ETOPO1 topography as (Niu et al., 2005):

$$f_{\text{sat}} = f_{\text{sat}}^{\text{max}} e^{-f_{\nabla} z_{\nabla}}. \quad (51)$$

f_{∇} is a parameter whose value is given in Table 2. If the surface is snowfree the wetland fraction is
 450 set equal to the saturated fraction ($f_{\text{wet}} = f_{\text{sat}}$), while it is set to zero otherwise. The grid cell mean water table depth is estimated directly from the volumetric water content in the soil column, the peat fraction (f_{peat}) and the water table in peat (z_{∇}^{peat}) as:

$$z_{\nabla} = (1 - f_{\text{peat}}) \left(h_{\text{soil}} - \sum_l \frac{\theta_l}{\theta_{\text{sat},l}} \Delta z_l \right) + f_{\text{peat}} z_{\nabla}^{\text{peat}}. \quad (52)$$

h_{soil} is the soil column depth and the sum is over all soil layers. The peat water table is assumed
 455 to follow the grid cell mean seasonal water table variations but with an amplitude limited to the acrotelm thickness (Section 6.3.1). The maximum soil infiltration rate is then computed from the saturated hydraulic conductivity of the top soil layer ($k_{\text{sat},1}$ (k_{sat})) assuming that infiltration can occur only in the unsaturated part of the grid cell:

$$q_{\text{inf}}^{\text{max}} = k_{\text{sat},1} (1 - f_{\text{sat}}). \quad (53)$$

460 Surface runoff is then calculated assuming that all liquid water that reaches the surface is routed directly to runoff over the saturated fraction of the grid cell and considering that the maximum infiltration rate can not be exceeded:

$$R_w = f_{\text{sat}} (P_{r,g} + M_s) + (1 - f_{\text{sat}}) \cdot \max(0, P_{r,g} + M_s - q_{\text{inf}}^{\text{max}}). \quad (54)$$

The actual soil infiltration rate is then computed as:

$$465 \quad q_{\text{inf}} = P_{r,g} + M_s - R_w. \quad (55)$$

5.4 Soil hydrology

Water in the soil is assumed to be limited to flow in the vertical direction. Making use of the conservation of mass, the change in volumetric water content over time is then given by the vertical divergence of the water flux and a sink term from soil water extraction by evapotranspiration (e):

$$470 \quad \rho_w \Delta z_l \frac{d\theta_{w,l}}{dt} = q_{l-1} - q_l - e_l, \quad (56)$$

where l is the soil layer index. This equation is solved with infiltration (q_{inf}) as top boundary condition and a free drainage bottom boundary condition, i.e. the water flux at the bottom of the soil column (q_{drain}) is set equal to the bottom hydraulic conductivity. The soil water flux q is expressed by Darcy's law:

$$475 \quad q = k \frac{\partial(\psi - z)}{\partial z}, \quad (57)$$

where k is the hydraulic conductivity and ψ is the matric potential. z is the vertical coordinate and is positive downwards from the surface. The numerical solution of Eq. (56) follows the formulation in Oleson et al. (2013).

The hydraulic conductivity and the matric potential are soil hydraulic properties dependent on soil
480 texture and volumetric soil water following Clapp and Hornberger (1978):

$$\psi = \psi_{\text{sat}} \left(\frac{\theta_w}{\theta_{\text{sat}}} \right)^{-b} \quad (58)$$

$$k = k_{\text{sat}} \left(\frac{\theta_w}{\theta_{\text{sat}}} \right)^{2b+3}. \quad (59)$$

Similarly to the discussion on soil thermal parameters in Section 4.1, hydraulic conductivity and matric potential at saturation, k_{sat} and ψ_{sat} , and the Clapp and Hornberger parameter b are set to
485 global uniform values by default (Table 3). However, a soil texture and soil organic matter content dependent formulation of k_{sat} , ψ_{sat} and b is also available (Appendix B).

6 Biogeochemistry and vegetation dynamics

6.1 Photosynthesis

Daily photosynthesis is modelled following the general light use efficiency model described in Hax-
490 eltine and Prentice (1996a, b) as implemented in the LPJ dynamic vegetation model (Sitch et al., 2003), with some modifications. Compared to other models it has the advantage that it computes daily integrated photosynthesis without the need to explicitly resolve the diurnal cycle and therefore saves computing time. It also makes it convenient to be coupled to the physical PALADYN components, which are also integrated with a daily time step. Daily gross photosynthesis is computed from
495 a light limited (J_E) and a Rubisco limited rate (J_C) as:

$$A_g = \frac{J_E + J_C - \sqrt{(J_E + J_C)^2 - 4\theta_r J_E J_C}}{2\theta_r} \beta_{\theta}. \quad (60)$$

$$J_E = c_1 \cdot APAR, \quad (61)$$

$$J_C = c_2 \cdot V_m. \quad (62)$$

500 θ_r is a shape parameter and $APAR$ is the absorbed photosynthetically active radiation computed as:

$$APAR = 0.5SW^{\downarrow} \alpha_a (1 - e^{-k_{\text{ext}} L_{\text{ai}}}) \Delta t (1 - \alpha_{\text{leaf}}) c_q. \quad (63)$$

Half of the downwelling shortwave radiation is assumed to be in the photosynthetically active wavelength range, α_a accounts for reductions in PAR utilisation efficiencies in natural ecosystems, the factor $1 - e^{-k_{\text{ext}} L_{\text{ai}}}$ scales to the canopy, α_{leaf} is the leaf albedo in the PAR range, Δt is the length of day in seconds and c_q is a conversion factor from J m^{-2} to mol m^{-2} . Parameter values are given in Table 4 and more details on the formulation of c_1 and c_2 and the maximum daily rate of net photosynthesis V_m are given in Appendix C.

Leaf respiration, R_d , is scaled to V_m as:

$$R_d = a_{C3/4} V_m \beta_\theta, \quad (64)$$

and daily net assimilation is then calculated as:

$$A_n = A_g - R_d. \quad (65)$$

Daytime net assimilation can then be computed by adding nighttime respiration:

$$A_{\text{nd}} = A_n + \left(1 - \frac{d_h}{24}\right) R_d. \quad (66)$$

β_θ is a soil moisture limiting factor:

$$\beta_\theta = \sum_l \frac{\theta_{w,l} - \theta_{\text{wp}}}{\theta_{\text{fc}} - \theta_{\text{wp}}} r_l, \quad (67)$$

θ_{wp} and θ_{fc} are the soil moisture values at wilting point and field capacity, respectively. r_l is the fraction of roots in layer l (section 6.2.2). If the soil temperature of layer l is below -2°C the corresponding term in Eq. (67) is set to 0.

c_1 and c_2 depend on the intercellular partial pressure of CO_2 (p_i), which is proportional to the atmospheric CO_2 concentration (p_a):

$$p_i = \lambda_c p_a. \quad (68)$$

In LPJ λ_c is computed iteratively from potential and actual evapotranspiration (Sitch et al., 2003). To reduce the computation cost and in light of recent developments, in PALADYN λ_c is derived from the optimal stomatal conductance model (Medlyn et al., 2011), which predicts that stomatal canopy conductance for water vapour g_{can} is given by:

$$g_{\text{can}} = g_{\text{min0}} + \left(1 + \frac{g_1}{\sqrt{VPD}}\right) \frac{A_{\text{nd}}}{c_a}. \quad (69)$$

VPD is the vapor pressure deficit between leaf surface and ambient air. Since CO_2 has to diffuse through the stomata into the leaf interior before being fixed by photosynthesis and at the same time water vapour diffuses through the stomata from the leaf interior to the canopy air, g_{can} and A_{nd} are also related by:

$$g_{\text{can}} = g_{\text{min0}} + 1.6 \frac{A_{\text{nd}}}{c_a - c_i}. \quad (70)$$

g_{\min} is a minimum stomatal conductance (Table 5) and c_a and c_i are the atmospheric and intercellular CO_2 mole fractions and g_0 is a minimum canopy conductance:

$$g_0 = g_{\min}(1 - e^{-k_{\text{ext}}L_{\text{ai}}})\beta_{\theta}. \quad (71)$$

The values of g_{\min} are given in (Table 5). From Eqs. (69) and (70) λ_c can simply be derived (e.g. Medlyn et al., 2011):

$$\lambda_c = 1 - \frac{1.6}{1 + g_1/\sqrt{VPD}}. \quad (72)$$

To a first approximation, the values of g_1 are taken to be constant PFT specific parameters (Table 5) based on the data reported in Lin et al. (2015). As will be shown in section 6.5, based on a simple model, the ratio of c_i and c_a is also the main parameter determining the carbon isotopic discrimination during photosynthesis. Therefore the PFT specific discrimination is used as an additional constraint on g_1 values.

Finally, maintenance respiration and growth respiration are computed and net primary production (NPP) is derived as in Sitch et al. (2003).

6.2 Vegetation dynamics

There are a number of existing dynamic global vegetation models spanning a large range of different approaches of varying complexity. The appropriate model complexity for PALADYN, balancing low computational expenses and a realistic representation of continental-scale vegetation dynamics, is represented by the top-down modelling approach of the TRIFFID dynamic global vegetation model (Cox, 2001; Clark et al., 2011). Another main advantage of this type of model is that it does not require interannual climate variability, which can not be provided by a statistical-dynamical atmosphere model like CLIMBER. The PALADYN dynamic vegetation scheme is therefore based on TRIFFID. The model distinguishes five plant functional types: broadleaved trees, needleleaved trees, C3 and C4 grass and shrubs. Vegetation carbon C_v and fractional area coverage ν of each PFT i are described by a coupled system of first order differential equations based on the Lotka-Volterra approach for modelling competition between species:

$$\frac{dC_{v,i}}{dt} = (1 - \lambda_{NPP,i})NPP_i - \Lambda_{\text{loc},i}, \quad (73)$$

$$\frac{d\nu_i}{dt} = \frac{\lambda_{NPP,i}NPP_i}{C_{v,i}}\nu_{i,*} \left(1 - \sum_j c_{ij}\nu_j \right) - \gamma_{v,i}\nu_{i,*}. \quad (74)$$

$\nu_{i,*} = \max(\nu_i, \nu_{\text{seed}})$, where ν_{seed} is a small seeding fraction used to ensure that a PFT is always seeded (Table 6). λ_{NPP} is a factor determining the partitioning of NPP between increase of vegetation carbon of the existing vegetated area (Eq. (73)) and spreading of the given PFT (Eq. (74)) and

is given by:

$$\lambda_{\text{NPP}} = \begin{cases} 0 & L_{\text{ai,b}} < L_{\text{ai}}^{\text{min}} \\ \frac{L_{\text{ai,b}} - L_{\text{ai}}^{\text{min}}}{L_{\text{ai}}^{\text{max}} - L_{\text{ai}}^{\text{min}}} & L_{\text{ai}}^{\text{min}} \leq L_{\text{ai,b}} \leq L_{\text{ai}}^{\text{max}} \\ 1 & L_{\text{ai,b}} > L_{\text{ai}}^{\text{max}}. \end{cases} \quad (75)$$

565 $L_{\text{ai,b}}$ is the 'balanced' leaf area index that would be reached if the plant was in full leaf and $L_{\text{ai}}^{\text{min}}$ and $L_{\text{ai}}^{\text{max}}$ are PFT specific parameters (Table 5). Λ_{loc} is the local litterfall rate:

$$\Lambda_{\text{loc}} = \Lambda_{\text{l}} + \gamma_{\text{r}}C_{\text{v,r}} + \gamma_{\text{s}}C_{\text{v,s}}. \quad (76)$$

Litterfall from leaf turnover is given by $\Lambda_{\text{l}} = \gamma_{\text{l}}C_{\text{v,l}}$ for evergreen plants and is computed from the phenological status (section 6.2.1) for deciduous plants. The γ s are PFT dependent turnover rates of
570 leaf, root and stem carbon (Table 5). Vegetation carbon C_{v} is directly related to the balanced leaf area index through the relations of leaf ($C_{\text{v,l}}$), root ($C_{\text{v,r}}$) and stem ($C_{\text{v,s}}$) carbon to $L_{\text{ai,b}}$:

$$C_{\text{v,l}} = \frac{L_{\text{ai,b}}}{SLA}, \quad (77)$$

$$C_{\text{v,r}} = \underline{L}C_{\text{v,l}}, \quad (78)$$

$$C_{\text{v,s}} = a_{\text{wl}}L_{\text{ai,b}}^{\frac{5}{3}b_{\text{wl}}}. \quad (79)$$

$$575 \quad C_{\text{v}} = C_{\text{v,l}} + C_{\text{v,r}} + C_{\text{v,s}}. \quad (80)$$

SLA is the specific leaf area (one-sided leaf area per leaf carbon mass) and is PFT dependent following Kattge et al. (2011) (Table 5). a_{wl} is a PFT specific allometric coefficient (Table 5). In TRIFFID a value of $b_{\text{wl}} = 5/3$ is used (Cox, 2001), although Enquist et al. (1998) suggest $b_{\text{wl}} = 4/3$. In PALADYN $b_{\text{wl}} = 1$ is assumed, which greatly simplifies the solution of Eq. (73), and the a_{wl} values
580 are adjusted accordingly to compensate for the change in b_{wl} . The competition coefficients, c_{ij} , represent the impact of vegetation type j on the vegetation type of interest i . TRIFFID is based on a tree-shrub-grass dominance hierarchy with dominant types i limiting the expansion of sub-dominant types j ($c_{ji} = 1$), but not vice-versa ($c_{ij} = 0$). While in TRIFFID the tree types and grass types co-compete with competition coefficients dependent on their relative heights, in PALADYN they
585 compete only based on their NPP ($c_{ij} = 0.5$ and $c_{ji} = 0.5$). Additionally, in PALADYN we implemented a dependence of the competition coefficients on bioclimatic limits, i.e. the coldest month temperature ($T_{\text{cmon}}^{\text{min}/\text{max}}$) and growing degree days (gdd_{min}) as given in Table 5. In a given grid cell, PFTs outside of the bioclimatic limits are not competitive and will be dominated by other PFTs, regardless of the tree-shrub-grass dominance.

590 The last term in Eq. (74) represents vegetation disturbance. In TRIFFID, the disturbance rate γ_{v} is taken to be a constant PFT specific parameter. In reality, on a global scale, disturbance is mainly caused by fire, which shows a strong dependence on climatic conditions and fuel availability (e.g. Thonicke et al., 2010). We therefore introduce a simple parameterisation for fire disturbance based

on top-soil moisture and aboveground biomass loosely following Reick et al. (2013) and Arora and
 595 Boer (2005):

$$\gamma_v = \gamma_{v,\min} + \frac{1}{\tau_{\text{fire}}} \max\left(0, \frac{\theta_{\text{crit}} - \theta_1}{\theta_{\text{crit}}}\right) \max\left(0, \min\left(1, \frac{C_{v,\text{ag}} - C_{v,\text{low}}}{C_{v,\text{high}} - C_{v,\text{low}}}\right)\right). \quad (81)$$

$\gamma_{v,\min}$ is a minimum constant disturbance rate intended to represent disturbances other than fire
 (e.g. windthrow (Reick et al., 2013) and insect outbreaks, among others (e.g. Dale et al., 2001))
 (Table 6). τ_{fire} is a characteristic fire return time scale, θ_{crit} is the critical soil moisture below which
 600 fires can occur and $C_{v,\text{low}}$ and $C_{v,\text{high}}$ are values of aboveground biomass ($C_{v,\text{ag}}$) that define the
 fuel availability limitation function. All parameter values are listed in Table 6.

Vegetation height is ~~computed from stem carbon following~~ assumed to vary linearly with the
 balanced leaf area index:

$$h_v = \frac{C_{v,s}}{0.01 \cdot a_{ws}} \frac{a_{wl}}{C_{v,s}}^{3/5} a_{wh} L_{ai,b}. \quad (82)$$

605 ~~a_{ws} is the ratio of total to respiring stem carbon~~ a_{wh} is a PFT-specific factor that relates vegetation
 height with the balanced leaf area index (Table 5). a_{wh} values are selected to give plant heights in
 accordance with data in Kattge et al. (2011)

The stem area index, S_{ai} , is taken to be 1/10 of $L_{ai,b}$.

The dynamic vegetation model has a monthly time step.

610 6.2.1 Phenology

The phenology of the PFTs is controlled by the coldest month temperature following Sitch et al.
 (2003). If the coldest month temperature falls below a PFT specific value $T_{\text{cmon}}^{\text{phen}}$ (Table 5), then the
 PFT in the gridcell is assumed to be deciduous and L_{ai} is computed from:

$$L_{ai} = \phi L_{ai,b}. \quad (83)$$

615 ϕ increases linearly with the growing degree days (gdd) above a PFT specific base temperature $T_{\text{base}}^{\text{gdd}}$,
 at a PFT specific rate determined by gdd_{crit} :

$$\phi = \frac{gdd}{gdd_{\text{crit}}}. \quad (84)$$

After ϕ reaches its maximum value of 1 it remains constant until the air temperature drops below
 $T_{\text{base}}^{\text{gdd}}$. Then leaf senescence starts when the temperature drops below $T_{\text{base}}^{\text{gdd}}$ and continues until all
 620 leaves are lost to litter at 5 °C below $T_{\text{base}}^{\text{gdd}}$. Raingreen phenology is not represented in the model.

Needleleaf trees are assumed to always be evergreen, ~~because given the low PFT independently of
 the climatic conditions. Given the relatively low~~ specific leaf area of needleleaf trees (Table 5), they
 would not be competitive in very cold regions if they were deciduous. In reality, deciduous needleleaf
 trees have a much higher specific leaf area (Kattge et al., 2011), which allows them to be competitive.

625 However, since evergreen and deciduous needleleaf trees are represented by a single PFT in the model,
 the different traits of evergreen and deciduous trees cannot be distinguished.

6.2.2 Root distribution

The vertical distribution of roots in the soil plays an important role in land surface models. It determines the water that is accessible to by the plants and hence controls the exchange of water between the surface and the atmosphere. Water availability affects also plant productivity and consequently plays an important role in the competition between plant functional types. It also controls the vertical distribution of root litter input to the soil which is an important factor determining vertical soil carbon distribution. In PALADYN we adopt the root distribution scheme proposed by Zeng (2001). The root fraction in each soil layer (r_l) is derived from the cumulative root fraction:

$$r(z) = 1 - 0.5 (e^{-d_{r,1}z} + e^{-d_{r,2}z}). \quad (85)$$

$d_{r,1}$ and $d_{r,2}$ are PFT specific parameters (Table 5).

6.3 Soil carbon

Traditionally, in terrestrial biosphere models soil carbon has been represented in terms of vertically-integrated pools. Only recently vertically discretized soil carbon has started to be included in these models (e.g. Koven et al., 2009; Schaphoff et al., 2013). Vertically integrated models are unable to represent soil carbon dynamics in permafrost areas, where only part of the carbon stored in the soil column is affected by the seasonal thawing of the upper soil. Large quantities of carbon are stored in the permanently frozen soils around the Arctic (Tarnocai et al., 2009; Hugelius et al., 2014; Schuur et al., 2015) and to model the dynamics of this carbon stock it is necessary to include carbon separately in different soil layers. A proper representation of the permafrost carbon pool is important especially for carbon cycle modelling over long time scales.

Therefore, PALADYN has carbon distributed over the different soil layers where temperature and soil water are also computed. Additionally, each grid cell distinguishes between soil carbon in four different soil columns: mineral soil carbon and peat carbon below the vegetated surface tile, buried carbon below ice sheets and shelf carbon below the water on the ocean shelf (Fig. 1c). Each layer generally contains three carbon pools with different decomposability (Fig. 3). For unfrozen mineral soil carbon the three pools are organized into litter, fast and slow carbon following (Sitch et al., 2003). This structure is modified for peatlands, perennially frozen soils and buried carbon.

The generic prognostic equations for litter, fast and slow soil carbon pools are written as:

$$655 \quad \frac{\partial C_{\text{lit}}(z)}{\partial t} = \Lambda(z) - k_{\text{lit}}(z)C_{\text{lit}}(z) + \frac{\partial}{\partial z} \left(D(z) \frac{\partial C_{\text{lit}}}{\partial z} \right) + \frac{\partial}{\partial z} \left(\underbrace{A(z)C_{\text{lit}}}_{\text{advection}} \right) \quad (86)$$

$$\frac{\partial C_{\text{fast}}(z)}{\partial t} = (1 - f_{\text{lit}}^{\text{resp}})f_{\text{lit} \rightarrow \text{fast}}k_{\text{lit}}(z)C_{\text{lit}}(z) - k_{\text{fast}}(z)C_{\text{fast}}(z) + \frac{\partial}{\partial z} \left(D(z) \frac{\partial C_{\text{fast}}}{\partial z} \right) + \frac{\partial}{\partial z} \left(\underbrace{A(z)C_{\text{fast}}}_{\text{advection}} \right) \quad (87)$$

$$\frac{\partial C_{\text{slow}}(z)}{\partial t} = (1 - f_{\text{lit}}^{\text{resp}})f_{\text{lit} \rightarrow \text{slow}}k_{\text{lit}}(z)C_{\text{lit}}(z) - k_{\text{slow}}(z)C_{\text{slow}}(z) + \frac{\partial}{\partial z} \left(D(z) \frac{\partial C_{\text{slow}}}{\partial z} \right) + \frac{\partial}{\partial z} \left(\underbrace{A(z)C_{\text{slow}}}_{\text{advection}} \right). \quad (88)$$

Litter carbon is increased by litterfall $\Lambda(z)$. A fraction $f_{\text{lit}}^{\text{resp}}$ of the decomposed litter carbon goes directly into the atmosphere, while the rest goes partly into the fast carbon pool ($f_{\text{lit} \rightarrow \text{fast}}$) and partly
660 into the slow carbon pool ($f_{\text{lit} \rightarrow \text{slow}}$) (Table 7). Each carbon pool decomposes at a specific rate k , which depends on soil temperature and soil moisture. The vertical redistribution of soil carbon between soil layers is represented as ~~a diffusive~~an advective–diffusive process with diffusivity $D(z)$
and advection velocity $A(z)$.

Over the vegetated grid cell part, the local litter, the litter originating from competition between
665 the PFTs and the litter from large scale disturbances are aggregated to give an average litterfall ($\Lambda_{\text{veg}}(z)$) as in (Cox, 2001). Litter from the roots is added to the different soil layers depending on the root fraction in each layer, while litter from leaves and stem is added to the top soil layer.

When ice sheets are expanding into vegetated areas, a fraction $f_{\text{veg} \rightarrow \text{bur}}$ of the vegetation carbon is assumed to be directly buried below the ice and the remaining is added to the litter pools of the
670 vegetated part:

$$\Lambda_{\text{bur}}(z) = f_{\text{veg} \rightarrow \text{bur}} \overline{C_v}(z) \Delta f_{\text{ice}} \quad (89)$$

$$\Lambda_{\text{veg}}(z) = (1 - f_{\text{veg} \rightarrow \text{bur}}) \overline{C_v}(z) \Delta f_{\text{ice}}. \quad (90)$$

$\overline{C_v}(z)$ is the mean vegetation carbon content of the vegetated grid cell part in the different soil layers. For the purpose of litter computation the aboveground vegetation carbon is considered to be part of
675 the top soil layer. Δf_{ice} is the increase of ice sheet fraction in the grid cell.

When sea level is rising and shelf areas become flooded, the flooded vegetation is assumed to die instantaneously and vegetation carbon is added directly to the shelf litter pool:

$$\Lambda_{\text{shelf}}(z) = \overline{C_v}(z) \Delta f_{\text{shelf}}, \quad (91)$$

where Δf_{shelf} is the increase in shelf fraction.

680 Vertical carbon diffusivity in unfrozen mineral soils is assumed to be determined by bioturbation and $D(z) = D_{\text{bio}}$ following Braakhekke et al. (2011) (Table 7). In permafrost areas the diffusivity represents cryoturbation in the active layer. $D(z)$ is set to a constant value in the active layer and is assumed to linearly decrease below it to a value of zero at a multiple (n_{al}) of the active layer

thickness z_{al} (Koven et al., 2009):

$$685 \quad D(z) = \begin{cases} D_{cryo} & z \leq z_{al} \\ D_{cryo} \left(1 - \frac{z - z_{al}}{(n_{al} - 1)z_{al}}\right) & z_{al} < z \leq n_{al}z_{al}. \end{cases} \quad (92)$$

The value of D_{cryo} is given in Table 7.

To represent the effects of sedimentation on vertical carbon movement in the soil an advection term is also included in Eqs. (86), (87), (88), similar to what has been introduced by Koven et al. (2013) and Zhu et al. (2016)

690 The decomposition rates for mineral soil carbon depend on temperature, liquid water content in the soil layers and inundated fraction of the grid cell:

$$k_x^{min}(z) = (1 - f_{inun})k_{x,10}f_T(z)f_\theta(z) + f_{inun}k_{x,10}f_T(z)f_{\theta,sat}(z), \quad (93)$$

for $x = \text{lit, fast, slow}$. The inundated grid cell fraction is the wetland fraction with the peatland fraction removed, $f_{inun} = f_{wet} - f_{peat}$. $k_{lit,10}$, $k_{fast,10}$ and $k_{slow,10}$ are the litter, fast and slow carbon decomposition rates at 10°C and field capacity and are given in Table 7. The temperature dependence follows a modified Arrhenius equation (Lloyd and Taylor, 1994):

$$695 \quad f_T(z) = \exp \left[308.56 \left(\frac{1}{56.02} - \frac{1}{46.02 + T(z) - T_0} \frac{1}{46.02 + T_s(z) - T_0} \right) \right]. \quad (94)$$

The soil moisture dependence is taken from Porporato et al. (2003) and gives a linear increase of the decomposition rate up to field capacity and a hyperbolic decrease above field capacity:

$$700 \quad f_\theta(z) = \begin{cases} \frac{\theta_w(z)}{\theta_{fc}} & \theta_w(z) \leq \theta_{fc} \\ \frac{\theta_{fc}}{\theta_w(z)} & \theta_w(z) > \theta_{fc}. \end{cases} \quad (95)$$

The soil moisture dependence factor for inundated land, $f_{\theta,sat}$, is simply the value of f_θ at saturation.

PALADYN allows for the possibility to effectively treat the carbon in frozen soils as inert. If inert permafrost carbon is switched on, the decomposition rates in Eq. 93-93 are additionally weighted by a frozen soil factor, f_{inert} :

$$705 \quad k_x^{min}(z) = (1 - f_{inert}(z))k_x^{min}(z) + f_{inert}(z)k_{inert}, \quad (96)$$

for $x = \text{lit, fast, slow}$. All carbon is assumed to be inert if the fraction of frozen water in a layer exceeds $f_{frz,crit}$:

$$f_{inert}(z) = \min \left(1, \frac{1}{f_{frz,crit}} \frac{\theta_i}{\theta_i + \theta_w} \right). \quad (97)$$

710 Therefore in soil layers where at least a fraction $f_{frz,crit}$ of water is frozen all year round, carbon is effectively decomposing at the very low rate k_{inert} .

More details on the parameterisation of carbon dynamics below ice sheets and on the ocean shelf and of permafrost carbon will be given in a future paper dedicated to processes active on glacial-interglacial cycles time scales.

6.3.1 Peatlands

715 Peat carbon is treated slightly differently from the other carbon pools. We follow the approach of
 Kleinen et al. (2012) and distinguish between a surface litter layer and an acrotelm layer where car-
 bon is decomposed partly under oxic and partly under anoxic conditions, depending on the position
 of the water table. Both litter and acrotelm are assumed to be contained in the top soil layer. In the
 layers below, the catotelm, decomposition occurs without oxygen all year round. The prognostic
 720 equations for peat litter, acrotelm and catotelm carbon are:

$$\frac{\partial C_{\text{lit}}^{\text{peat}}}{\partial t} = \Lambda_{\text{peat}} - k_{\text{lit}}^{\text{peat}} C_{\text{lit}}^{\text{peat}} \quad (98)$$

$$\frac{\partial C_{\text{acro}}}{\partial t} = (1 - f_{\text{lit}}^{\text{resp}}) k_{\text{lit}}^{\text{peat}} C_{\text{lit}}^{\text{peat}} - k_{\text{acro} \rightarrow \text{cato}} C_{\text{acro}} - k_{\text{acro}} C_{\text{acro}} \quad (99)$$

$$\frac{\partial C_{\text{cato}}(z)}{\partial t} = k_{\text{acro} \rightarrow \text{cato}} C_{\text{acro}} - k_{\text{cato}}(z) C_{\text{cato}}(z). \quad (100)$$

The transfer from acrotelm to catotelm carbon occurs only once a critical acrotelm carbon content
 725 $C_{\text{acro,crit}} = 5 \text{ kgC m}^{-2}$ is reached, as suggested by (Wania et al., 2009). Typical acrotelm carbon
 densities are around 20 kgC m^{-3} , so this threshold roughly corresponds to assuming that transfer
 to the catotelm starts when the acrotelm reaches a thickness of 25 cm, which is a typical value of
 observed acrotelm thickness. When this threshold is exceeded, acrotelm carbon is transferred to the
 catotelm in the second soil layer. Peat is assumed to grow thicker by accumulating carbon on top and
 730 therefore in the model the catotelm is shifted to lower soil layers once the catotelm carbon density
 $C_{\text{cato,crit}} \rho_{\text{cato}}$ has been exceeded in a given layer. For the same reason the vertical diffusivity of
 peat carbon is set to 0. Litterfall over peatlands is assumed to be the same as over mineral soil, but to
 be added to the top soil layer only: $\Lambda_{\text{peat}} = \sum_z \Lambda_{\text{veg}}(z)$. The decomposition rates for litter, acrotelm
 and catotelm are given by:

$$735 \quad k_{\text{lit}}^{\text{peat}} = k_{\text{lit},10} f_{\text{T}}(1) (f_{\text{oxic}} + (1 - f_{\text{oxic}}) f_{\theta,\text{peat}}) \quad (101)$$

$$k_{\text{acro}} = k_{\text{acro},10} f_{\text{T}}(1) (f_{\text{oxic}} + (1 - f_{\text{oxic}}) f_{\theta,\text{peat}}) \quad (102)$$

$$k_{\text{cato}}(z) = k_{\text{cato},10} f_{\text{T}}(z) f_{\theta,\text{peat}}. \quad (103)$$

Since peatland soil temperature is not separately computed by the model, the temperature factor is
 calculated using the grid cell mean temperature. $f_{\theta,\text{peat}}$ is taken to be equal to 0.3 as in Wania et al.
 740 (2009) and Koven et al. (2013). The values of the reference decomposition rates are given in Table 7.
 The fraction of litter and acrotelm that is respiring in oxic conditions, f_{oxic} , is determined from the
 mean grid cell water table depth z_{∇} and the minimum monthly water table position z_{∇}^{min} assuming
 that the seasonal water table variations in the peatland fraction follow the grid cell mean water table
 and that the amplitude of water table variations in peatland is reduced compared to the grid cell mean
 745 and limited to the acrotelm thickness:

$$f_{\text{oxic}} = \frac{\min(z_{\text{acro}}, \max(0, z_{\nabla} - z_{\nabla}^{\text{min}}))}{z_{\text{acro}}}. \quad (104)$$

Peatland expansion and contraction is modelled partly following Stocker et al. (2014). The grid cell fraction that is wetland for at least 3 months of the year is considered to be potential peatland area $f_{\text{peat}}^{\text{pot}}$. The actual peatland area f_{peat} is simulated as:

$$750 \quad f_{\text{peat},n+1} = \begin{cases} \min((1+r)f_{\text{peat},n}, f_{\text{peat}}^{\text{pot}}) & \frac{dC_{\text{peat}}}{dt} \geq \left. \frac{dC_{\text{peat}}}{dt} \right|_{\text{crit}} \quad \text{or} \quad C_{\text{peat}} \geq C_{\text{peat}}^{\text{crit}} \\ \max((1-r)f_{\text{peat},n}, f_{\text{peat}}^{\text{min}}) & \frac{dC_{\text{peat}}}{dt} < \left. \frac{dC_{\text{peat}}}{dt} \right|_{\text{crit}} \quad \text{and} \quad C_{\text{peat}} < C_{\text{peat}}^{\text{crit}} \end{cases} \quad (105)$$

Peat is expanding if the annual mean rate of carbon uptake (dC_{peat}/dt) is greater than a critical value $dC_{\text{peat}}/dt|_{\text{crit}}$ or if peat carbon exceeds a value $C_{\text{peat}}^{\text{crit}}$, otherwise peatland area is shrinking.

To account for inertia in lateral peatland expansion and contraction, the relative areal change rate is limited to $1\% \text{ yr}^{-1}$ ($r = 0.01 \text{ yr}^{-1}$). When the peat area is changing, carbon is simply redistributed

755 between mineral soil and peat carbon pools layer-by-layer with the following rules: $C_{\text{lit}}^{\text{peat}} \leftrightarrow C_{\text{lit}}$, $C_{\text{acro}} \leftrightarrow C_{\text{fast}}$ and $C_{\text{cato}} \leftrightarrow C_{\text{slow}}$.

6.4 Methane emissions

Methane emissions are simulated as a constant fraction of heterotrophic respiration when respiration occurs under anaerobic conditions, as is the case in wetlands, peatlands and flooded ocean shelves.

760 The fraction of carbon that is respired as methane, $f_{\text{CH}_4:\text{C}}$, is different for wetlands, peatlands and ocean shelf (Table 7).

6.5 Carbon isotopes: ^{13}C and ^{14}C

The stable carbon isotope ^{13}C and radiocarbon ^{14}C are tracked in PALADYN through all carbon pools in vegetation and soil. Discrimination is simulated only during photosynthesis and follows the model

765 outlined in Lloyd and Farquhar (1994). The discrimination factor Δ for C3 and C4 photosynthesis is given by:

$$\Delta = \begin{cases} 4.4 \frac{c_a - c_i}{c_a} + 27 \frac{c_i}{c_a} & \text{C3} \\ 4.4 \frac{c_a - c_i}{c_a} + (-5.7 + 20 \cdot 0.35) \frac{c_i}{c_a} & \text{C4.} \end{cases} \quad (106)$$

Radiocarbon decay is ignored in the vegetation carbon pools because of their fast turnover time relative to the ^{14}C decay rate. In all soil carbon pools radiocarbon has a half life of 5730 years.

770 7 Model spinup

Some of the processes related to vegetation and soil carbon dynamics have very long intrinsic time scales and therefore long simulations of at least 10000 years would be required to get the system into an equilibrium state with prescribed boundary conditions. Even though this is in principle feasible with PALADYN, it is in fact impractical for test and tuning purposes. Therefore the possibility to

775 run the vegetation and carbon cycle modules with an artificially high internal integration time step

of 1000 or more years is implemented in PALADYN. This is possible due to the fully implicit formulation of the model components. In this equilibrium spinup mode the vegetation and carbon cycle modules are called only at the end of each simulation year but using annually cumulated NPP and litterfall and annual mean decomposition rates for soil carbon. Using the equilibrium spinup mode brings the model close to equilibrium already after around 100 years of simulation. 100 years is also the spinup time required to bring the physical state of the land model, particularly permafrost related processes, into equilibrium with climate. The equilibrium spinup mode can however not be applied to processes which are intrinsically out of equilibrium such as peatlands and inert permafrost carbon. To get the present state of these pools a transient simulation over at least one glacial cycle is required.

8 Evaluation

In this section the performance of PALADYN for present day is presented and discussed. The model is designed for large scale applications and therefore the model evaluation is done at a global scale, although in principle it would be possible to run the model in a single column mode forced with site level observations. For the model evaluation an offline transient simulation from 1901 to 2010 is performed. In offline mode PALADYN needs several monthly climate fields as input as listed in Table 9. In addition the annual atmospheric CO₂ concentration has to be provided. For the historical simulation of the past century the WATCH climate forcing (Weedon et al., 2011, 2014) based on ERA-40 (Uppala et al., 2005) and ERA-Interim reanalysis (Dee et al., 2011) combined with GPCP precipitation (Schneider et al., 2014) is used. CO₂ is prescribed from Bereiter et al. (2015) combined with [Manua-Mauna](#) Loa data (Keeling et al., 1976).

Before running the transient experiment, the model is spun up for ~~100 years as described in section 7~~ 30000 years with the mean 1901-1930 climate as forcing and the 1901 CO₂ concentration of 295 ppm. To get a rough estimate of peatland area and carbon, during ~~this equilibrium the first 4000 years of this~~ spinup phase, the peatland module is enabled to allow peatlands to establish. ~~To allow the fast carbon processes to equilibrate, the model is subsequently run for additional 400 years with the dynamic vegetation and soil carbon modules called with a monthly timestep~~ For the rest of the spinup phase peat carbon is kept constant. Finally, the model is run in transient mode for the historical period forced with annually varying climate and CO₂ concentrations. Peatland area is kept constant during this phase but peat carbon is interactive.

Depending on the time interval covered by the different observational data products, the model climatology over the given time period is computed and used to evaluate the different model components, as described next.

8.1 Physical processes

810 The modelled net radiation absorbed at the surface is in good agreement with reanalysis data both for the seasonal cycle and the annual mean (Fig. 4). With the downwelling shortwave and longwave radiation used as forcing, the net surface radiation is determined by the modelled surface emissivity and albedo. The surface albedo for winter and summer is well simulated in the model (Fig. 5).

815 A correct partitioning of the absorbed radiation between sensible, latent and ground heat flux is of fundamental importance for a land model. The modelled sensible heat flux compares well with ERA-Interim reanalysis data except for the tropics, where it is systematically overestimated and for the subtropics, where it is underestimated in the model (Fig. 6). Evapotranspiration, and therefore the latent heat flux, tends to be overestimated by the model everywhere except for the tropics when compared to estimates from Mueller et al. (2013) (Fig. 7). However, it is in good agreement with 820 ERA-Interim. This is to be expected because evapotranspiration strongly depends on surface air conditions which are used to force the model, which are based on ERA-Interim. The discrepancy between model and (model-based) estimates from (Mueller et al., 2013) might therefore reflect a deficiency in the forcing rather than in the model. Modelled annual global land evapotranspiration is 71×10^{15} kg yr⁻¹

825 Evapotranspiration is the sum of transpiration from vegetation, surface evaporation and canopy interception and re-evaporation. The partitioning of total evapotranspiration between the different components is shown in Fig. 8. Transpiration is dominant in the tropics and generally in densely vegetated areas. A significant amount of precipitation is directly re-evaporated back to the atmosphere from plant canopies, particularly in the tropics and over the boreal forest. Surface evaporation 830 is the only process acting in desert regions. Globally, transpiration, surface evaporation and canopy evaporation account for around 50, 30 and 20 % of total evapotranspiration, respectively. This compares favorably with Dirmeyer et al. (2006), who estimated total global evapotranspiration to be partitioned in 48% from transpiration, 36% from soil evaporation, and 16% from canopy interception and re-evaporation using an ensemble of land surface models.

835 As a consequence of the overestimation of evapotranspiration, simulated runoff is underestimated ~~, particularly~~ over northern hemisphere mid-latitudes (Fig. 9). Compared to data from Fekete et al. (2002) the modelled NH runoff from melting snow in spring tends to be less concentrated to May and June and more gradually distributed over the whole summer season. Global annual runoff is 3537×10^{15} kg yr⁻¹ (Table 8).

840 Modelled ~~DJF and JJA~~ December-January-February (DJF) and June-July-August (JJA) soil moisture shows generally a good agreement with estimates from satellite data (Liu et al., 2012; Wagner et al., 2012) in the tropics, while the model tends to simulate a dryer top soil in high northern latitudes (Fig. 10). This is partly a consequence of using a globally uniform soil porosity. However, it has to be mentioned that the satellite data are representative for the soil moisture of the top few cm 845 of soil, while the top model soil layer is 20 cm thick.

The mean annual simulated wetland area is ~~3.23~~ mln km². ~~Maximum~~ Some features of the maximum monthly wetland extent ~~is generally are reasonably~~ well captured by the model ~~, particularly over~~ high northern latitudes (Fig. 11). Compared to the multi-satellite product from GIEMS (Prigent et al., 2007; Papa et al., 2010) the model simulates larger wetland ~~areas extent~~ in tropical forest areas and northern peatland areas. However, if compared to other wetland products based on data other than from satellite, GIEMS is underestimating wetlands below dense forests (e.g. the Amazon forest (Melack and Hess, 2010)) and in peatland regions of northern Canada and Eastern Siberia (Stocker et al., 2014). In south-east Asia, the GIEMS wetland extent also includes extensive rice cultivation areas, which are not represented in the model. The modelled seasonal variation in global wetland
850 area is in very good agreement with GIEMS (Fig. 12).

The NH spring evolution of snow mass is compared to the GlobSnow dataset (Takala et al., 2011; Luoju et al., 2013) in Fig. 13. The spatial distribution of snow is well captured by the model. However, the model tends to melt snow slightly too late in spring, as highlighted also by the seasonal evolution of the total NH snow mass (Fig. 14). The overestimation of snow mass in spring is a
860 feature common to many state-of-the-art Earth system models (Shi and Wang, 2015). The interannual variability of spring snow over the NH is also largely in agreement with the GlobSnow data, suggesting that the model has a ~~reasonably~~ reasonably good sensitivity (Fig. 15).

Modelled permafrost area is ~~16.5~~ around 16 mln km², which compares well with observations (Table 8). The permafrost extent over Siberia and Northern Canada is generally well simulated by
865 the model (Fig. 16). Also the active layer thickness over the Yakutia region is consistent with the data from Beer et al. (2013) (Fig. 16).

8.2 Biogeochemistry

The modelled annual mean gross primary productivity is compared to estimates from Jung et al. (2009), Beer et al. (2010) and Jung et al. (2011) in Fig. 17. Model and data are generally in good
870 agreement, except over the Amazon where the model underestimates GPP. However, experiments using different climate forcings show a much better agreement between modelled and observed GPP over the Amazon basin, similarly to what shown by Lasslop et al. (2014) (not shown). The simulated global annual GPP of ~~126~~ 133 PgC yr⁻¹ is ~~within the~~ in the upper range of current estimates (Table 8).

875 The net global land carbon flux over the time period 1959-2010 is shown in Fig. 18. The model is able to reproduce some of the interannual variability in the net land carbon uptake, indicating that the sensitivities of net primary production and soil respiration to interannual climate variations are reasonably well represented in the model.

880 The modelled potential vegetation distribution for the present day is shown in Fig. 19, where it is compared to potential vegetation estimates from Ramankutty and Foley (1999). In general the model has the tendency to overestimate the areas covered by broadleaf trees in the tropics. The

boreal needleleaf forest is well reproduced by the model, ~~as are the grass and shrub coverages,~~
PALADYN tends to overestimate the shrub coverage, particularly over the NH, while the area covered
by grasslands is lower than in Ramankutty and Foley (1999). Desert area is overestimated over Aus-
885 tralia. ~~Since vegetation cover strongly depends on the amount of precipitation, it is useful to evaluate~~
~~the ability of the model to reproduce the observed PFT distribution as a function of precipitation~~
(Zeng et al., 2008). ~~The modelled bare soil fraction as a function of annual precipitation perfectly~~
~~matches the observed distribution (Fig. 20). As opposed to observations the model tends to simulate~~
~~more grass than shrubs in arid regions. Where annual precipitation exceeds ≈ 500 mm yr⁻¹~~

890 ~~The annual maximum leaf area index is compared to estimates from MODIS (Yuan et al., 2011)~~
~~in Fig. 21. The modelled maximum LAI is generally higher than in MODIS, particularly in the~~
~~Tropics, in high northern latitudes and in arid regions. The seasonality of the leaf area index over~~
~~the Northern Hemisphere is well simulated at latitudes south of 50N, but is largely underestimated~~
~~north of 50N (Fig. 22) compared to MODIS data. This is because the latitudinal belt between 50N~~
895 ~~and 70N is dominated by evergreen needleleaf forests which have no LAI seasonality in the model,~~
~~while MODIS LAI is close to zero almost everywhere in high northern latitudes during winter. The~~
~~reduced LAI seasonality over the boreal forest compared to observations is a common feature of~~
~~many LSMs (Murray-Tortarolo et al., 2013) and is possibly an artifact of poor satellite data quality~~
~~during winter (Yuan et al., 2011)~~

900 Global modelled vegetation carbon is ~~500~~580 PgC, comparable to observations (Table 8). The
geographic distribution of vegetation carbon content is in good agreement with data from Gibbs
(2006) (Fig. 23), ~~but is overestimated in tropical forests and underestimated in arid regions.~~

The annual mean ~~flux-weighted discrimination~~ GPP-weighted isotopic discrimination during photosynthesis
is shown in Fig. 24. ~~As expected, the lowest values are found in regions dominated by C4 grasses in~~
905 ~~subtropical Africa and Australia. The highest discrimination values are found in the tropical forests~~
~~and in high northern latitudes, similar to the results shown in~~ Scholze et al. (2003). Mean discrimi-
nation for each plant functional type is also compared with observations from Kaplan et al. (2002)
in Fig. 25. The model ~~consistently tends to successfully reproduces the observed differences in~~
~~discrimination between different PFTs, although it tends to consistently~~ overestimate the discrim-
910 ination for all PFTs.

Top meter soil carbon from the HSWD dataset (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) is well
reproduced by the model, ~~although the model underestimates carbon in peatland areas of the NH in~~
~~the Tropics~~ (Fig. 26). ~~Top meter soil carbon is also compared to~~ In high northern latitudes the model
carbon content is higher than in the HSWD dataset (Fig. 26) but lower than in the NCSCD soil
915 carbon dataset for the permafrost region (Hugelius et al., 2013b, a; Tarnocai et al., 2009) ~~in~~ (Fig. 27
) ~~The model underestimates carbon in peatland areas of the NH.~~ Northern permafrost areas store
large amounts of carbon at depths greater than 1 m. The NCSCD soil carbon dataset contains esti-
mates of soil carbon down to a depth of 3 m in the permafrost regions. As expected, the model in

the setup used in the presented simulations can not reproduce the large amounts of carbon stored in
920 perennially frozen ground below 1 m because the inert permafrost carbon pool is not included (not
shown). To get the carbon accumulation in permafrost a transient simulation over at least the last
glacial cycle would be required. This is beyond the scope of this work, but will be discussed in a
future paper. Similarly to the discussion on permafrost carbon, a proper estimate of peatland area
and carbon content would also require a long transient simulation. However, an attempt has been
925 made to estimate the peatland area and carbon using the equilibrium spinup described above. The
estimated peatland area from this idealized approach is compared to NCSCD data (Hugelius et al.,
2013b, a; Tarnocai et al., 2009) in Fig. 28.

Total modelled natural methane emissions for the present day are ~~175~~160 TgCH₄ yr⁻¹. From
these, ~~105~~86 TgCH₄ yr⁻¹ are from the tropics and ~~70~~72 TgCH₄ yr⁻¹ from the extratropics. This
930 values compare well with recent estimates of natural methane emissions (Table 8). The spatial dis-
tribution of annual methane emissions is shown in Fig. 29.

9 Conclusions

The PALADYN model presented here represents a new tool to model the land processes which are
relevant for climate and the carbon cycle on time scales from years to millions of years.

935 PALADYN serves as a land surface scheme, soil model, dynamic vegetation model and land
carbon cycle model. It also includes a representation of peatlands and soil carbon pools in frozen
ground. Compared to other land surface models it has the great advantage that all components are
consistently coupled.

PALADYN furthermore includes a representation of the processes related to changes in land-ice-
940 shelf area, making it suitable for simulations over timescales where sea level and ice sheet areas can
not be considered as fixed boundary conditions. PALADYN is therefore designed to be included in
Earth system models of intermediate complexity.

On a single CPU the model in its standard configuration (daily time step, 5x5 degree horizontal
resolution and 5 soil layers) integrates one year in about 1 second (or equivalently about 100,000
945 model years per day), allowing to simulate e.g. one glacial cycle in one day. It is therefore indicated
for paleoclimate applications or to perform large ensembles of simulations to explore uncertainties
and sensitivities.

PALADYN in its offline version has been shown to perform well at reproducing a number of key
characteristics of the present day land surface, soil, vegetation and land carbon cycle and is therefore
950 ready to be included in Earth system models in a coupled setup.

10 Code availability

The model code is available on request from the authors.

Appendix A: Snow age factor

The snow age factor, f_{age} , is parameterized as a function of skin temperature and snowfall rate P_s as:

$$f_{\text{age}} = 1 - \frac{\ln(1 + f_{\text{age}}^T \frac{P_{s,c}}{P_s})}{f_{\text{age}}^T \frac{P_{s,c}}{P_s}}, \quad (\text{A1})$$

$$f_{\text{age}}^T = e^{0.05(T_* - T_0)} + e^{(T_* - T_0)}. \quad (\text{A2})$$

The dependence of f_{age} on temperature and snowfall rate with $P_{s,c} = 2 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ is shown in Fig. A1.

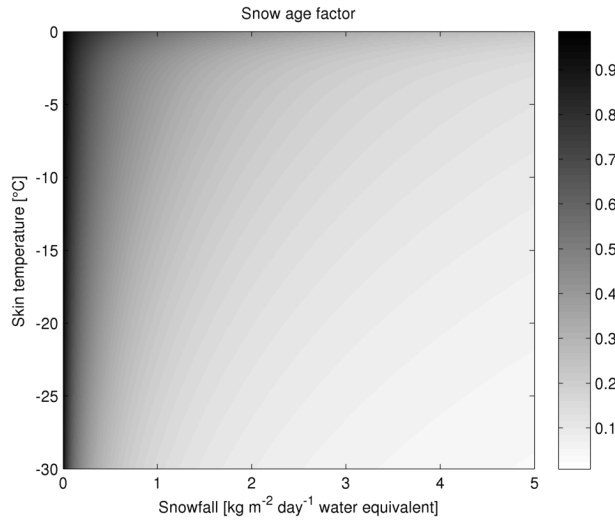


Figure A1. Snow age factor as a function of skin temperature and snowfall rate.

960 Appendix B: Soil thermal and hydraulic properties

Organic matter alters soil thermal and hydraulic properties substantially, in particular because of the much higher porosity of organic soils compared to mineral soils. The importance of accounting for organic matter in land-surface models has been discussed in e.g. Rinke et al. (2008), Lawrence and Slater (2008), Koven et al. (2009), Ekici et al. (2014) and Chadburn et al. (2015). In PALADYN, the fraction of soil that is considered to be organic for the determination of the thermal and hydraulic soil properties is computed in each soil layer from the total carbon density following Lawrence and Slater (2008):

$$f_{\text{org}} = \min\left(1, \frac{C_{\text{lit}} + C_{\text{fast}} + C_{\text{slow}}}{\rho_{\text{org}}^{\text{max}}}\right). \quad (\text{B1})$$

$\rho_{\text{org}}^{\text{max}} = 50 \text{ kgC m}^{-3}$ is the maximum soil carbon density, equivalent to a typical carbon density of peat.

Soil thermal and hydraulic properties are simply taken to be a linear combination of mineral and organic values based on f_{org} . This linear combination is applied to porosity (θ_{sat}), dry thermal conductivity (λ_{dry}), solid soil thermal conductivity (λ_{s}), saturated hydraulic conductivity (k_{sat}), saturation matric potential (ψ_{sat}) and b parameter.

975 Mineral soil properties are computed from sand and clay fractions following Lawrence and Slater (2008), based on (Cosby et al., 1984; Farouki, 1981; Clapp and Hornberger, 1978). Sand and clay fractions are taken from either FAO/IIASA/ISRIC/ISSCAS/JRC (2012) or from Shangguan et al. (2014), with the former set as default. Sand and clay fractions are considered to be vertically uniform in each grid cell and constant in time.

980 Organic soil properties are also taken from Lawrence and Slater (2008), partly based on Letts et al. (2000) and Farouki (1981).

Appendix C: Photosynthesis

The maximum daily rate of net photosynthesis V_m is given by:

$$V_m = \frac{1}{a_{C3/4}} \frac{c_1}{c_2} [(2\theta_r - 1)s - (2\theta_r s - c_2)\sigma_m] APAR. \quad (C1)$$

985

$$\sigma_m = \sqrt{1 - \frac{c_2 - s}{c_2 - \theta_r \cdot s}}, \quad (C2)$$

where:

$$s = \frac{24}{d_h} a_{C3/4} \quad (C3)$$

and d_h is the daylength in hours computed from orbital parameters.

990 All PALADYN PFTs follow the C3 photosynthetic pathway, except C4 grasses which follow the C4 pathway. For C3 plants c_1 and c_2 are given by:

$$c_1 = \alpha_{C3} f_{\text{temp}} C_{\text{mass}} \frac{p_i - \Gamma_{\star}}{p_i + \Gamma_{\star}}, \quad (C4)$$

$$c_2 = \frac{p_i - \Gamma_{\star}}{p_i + K_c(1 + [O_2]/K_o)}. \quad (C5)$$

$\alpha_{C3}=0.08$ is the intrinsic quantum efficiency of CO_2 uptake in C3 plants and $C_{\text{mass}}=12$ is the atomic mass of carbon. Γ_{\star} is the CO_2 compensation point:

995

$$\Gamma_{\star} = \frac{[O_2]}{2\tau} \quad (C6)$$

with $[O_2]=20.9$ kPa, the atmospheric O_2 partial pressure. K_c , K_o and τ are kinetic parameters whose temperature dependence is modeled using a Q10 relationship (Haxeltine and Prentice, 1996a). f_{temp} is a PFT specific temperature inhibition function (Sitch et al., 2003).

1000 For C4 plants the same equations are used but with c_1 and c_2 given by:

$$c_1 = \alpha_{C4} f_{temp}, \tag{C7}$$

$$c_2 = 1. \tag{C8}$$

$\alpha_{C4}=0.053$ is the intrinsic quantum efficiency of CO_2

Appendix D: Aggregation of potential vegetation

1005 In order to compare the modelled with the potential vegetation distribution of Ramankutty and Foley (1999), the potential vegetation needs to be aggregated to the plant functional types represented in PALADYN. We partly follow Blyth et al. (2011) and map vegetation classes of Ramankutty and Foley (1999) to the PALADYN PFTs as described in Table D1. The grass class in Table D1 is divided into C3 and C4 grasses based on the modelled grass type in each grid cell.

Table D1. Mapping of Ramankutty and Foley (1999) potential vegetation classes to PALADYN PFTs.

	BL	NL	grass	Shrubs	Bare soil
Tropical evergreen	0.9	0.0	0.0	0.0	0.1
Tropical deciduous	0.8	0.0	0.1	0.0	0.1
Temperate broadleaved evergreen	0.9	0.0	0.0	0.0	0.1
Temperate needleleaved evergreen	0.0	0.9	0.0	0.0	0.1
Temperate deciduous	0.9	0.0	0.0	0.0	0.1
Boreal evergreen	0.0	0.9	0.0	0.0	0.1
Boreal deciduous	0.0	0.8	0.1	0.0	0.1
Mixed evergreen/deciduous	0.1	0.7	0.0	0.1	0.1
Savanna	0.3	0.0	0.6	0.0	0.1
Grassland/steppe	0.0	0.0	0.9	0.0	0.1
Dense shrub	0.0	0.0	0.1	0.8	0.1
Open shrub	0.0	0.0	0.2	0.5	0.3
Tundra	0.0	0.0	0.35	0.35	0.3

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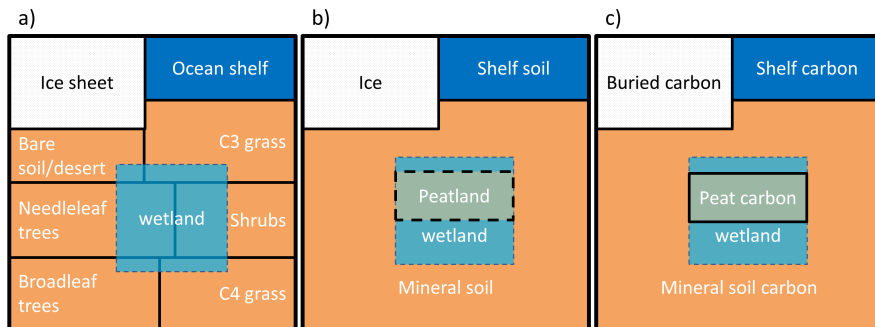


Figure 1. PALADYN surface types ([left](#)), 'soil' columns ([middle](#)) and soil carbon [pools](#) types ([right](#)).

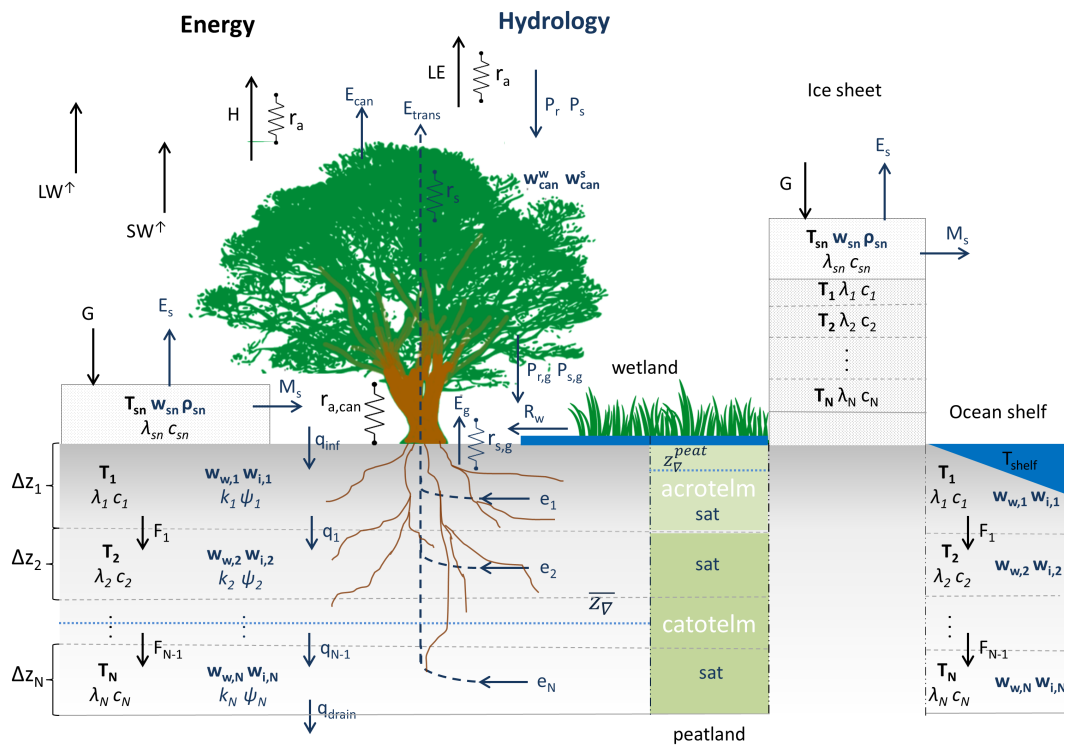


Figure 2. Illustration of the physical processes included in PALADYN. Energy fluxes and variables are indicated in black while water fluxes and hydrological variables are indicated in blue. Prognostic variables are in bold and fluxes are accompanied by arrows.

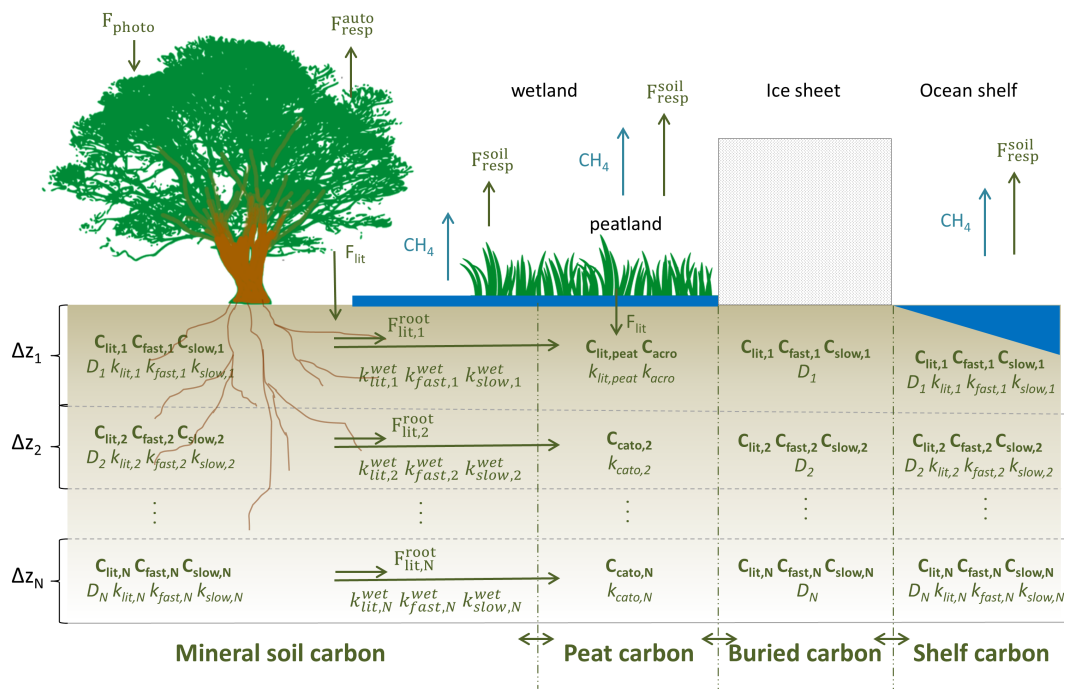


Figure 3. Illustration of the carbon cycle processes represented in PALADYN. Prognostic variables are in bold and fluxes are accompanied by arrows.

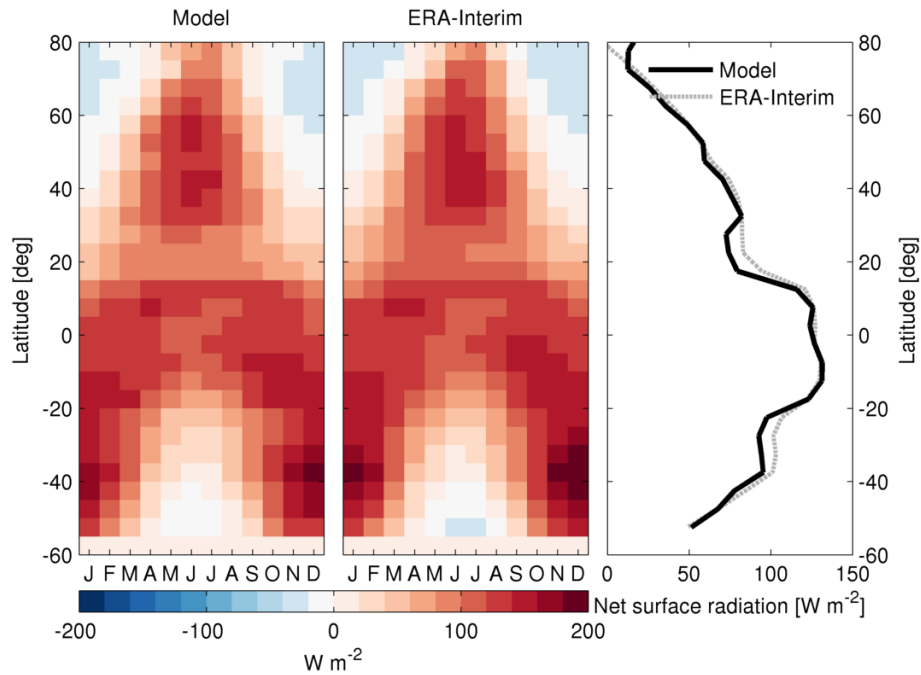


Figure 4. Seasonal variation of zonal mean net radiation at the surface modelled by PALADYN ([a](#)[left](#)) and from ERA-Interim reanalysis (Dee et al., 2011) ([b](#)[middle](#)). ([c](#)[Right](#)): Modelled zonal annual mean net surface radiation compared to ERA-Interim reanalysis (Dee et al., 2011).

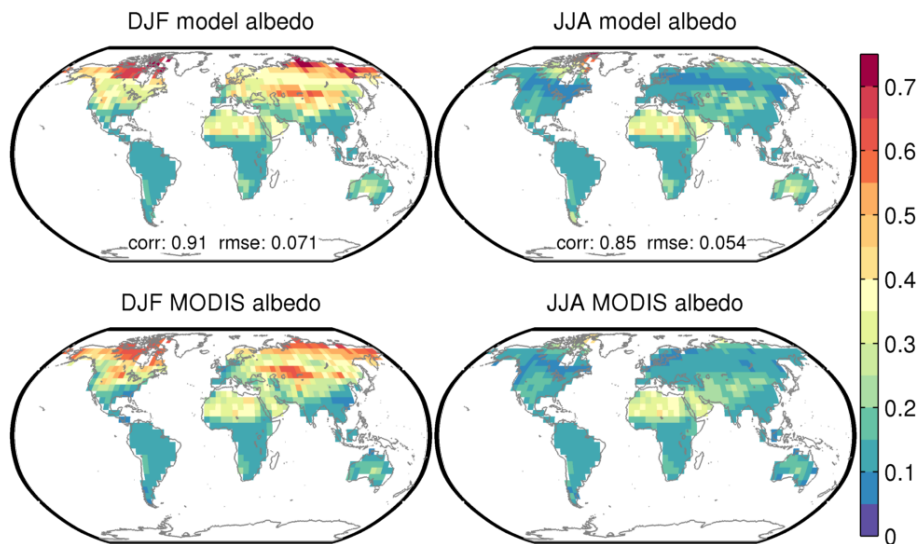


Figure 5. December-January-February (left) and June-July-August (right) surface albedo as modelled by PALADYN (top) and derived from MODIS data (Schaaf and Wang, 2015) (bottom). The displayed surface albedo is a weighted mean of visible and near infrared broadband albedo for diffuse radiation. [Spatial correlation between model and data \(corr\) and root mean square error \(rmse\) are indicated in the top panels.](#)

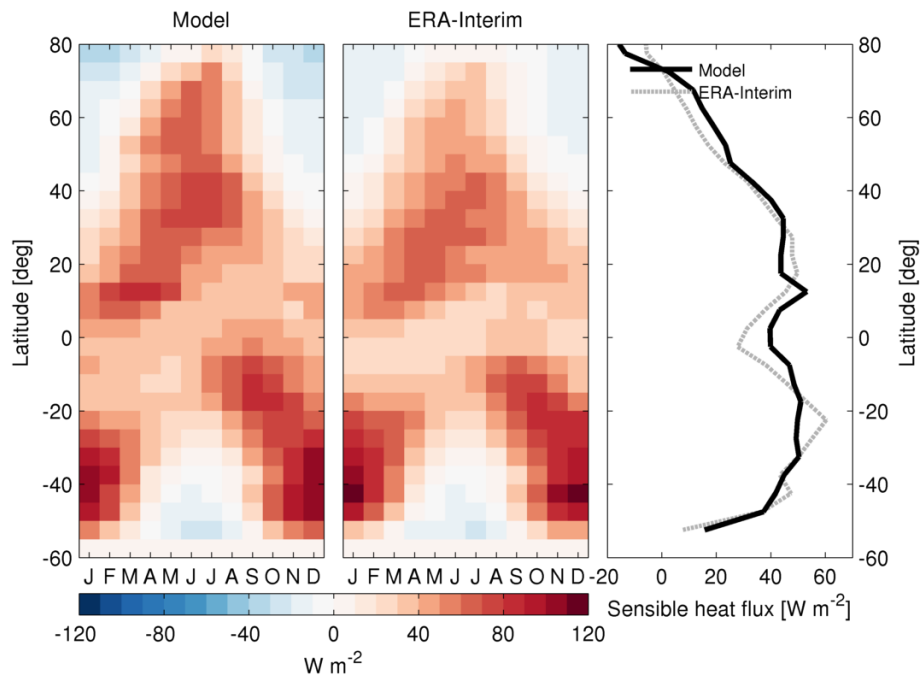


Figure 6. Seasonal variation of zonal mean sensible heat flux modelled by PALADYN (left) and from ERA-Interim reanalysis (Dee et al., 2011) (middle). (right) Modelled zonal annual mean sensible heat flux compared to ERA-Interim reanalysis (Dee et al., 2011).

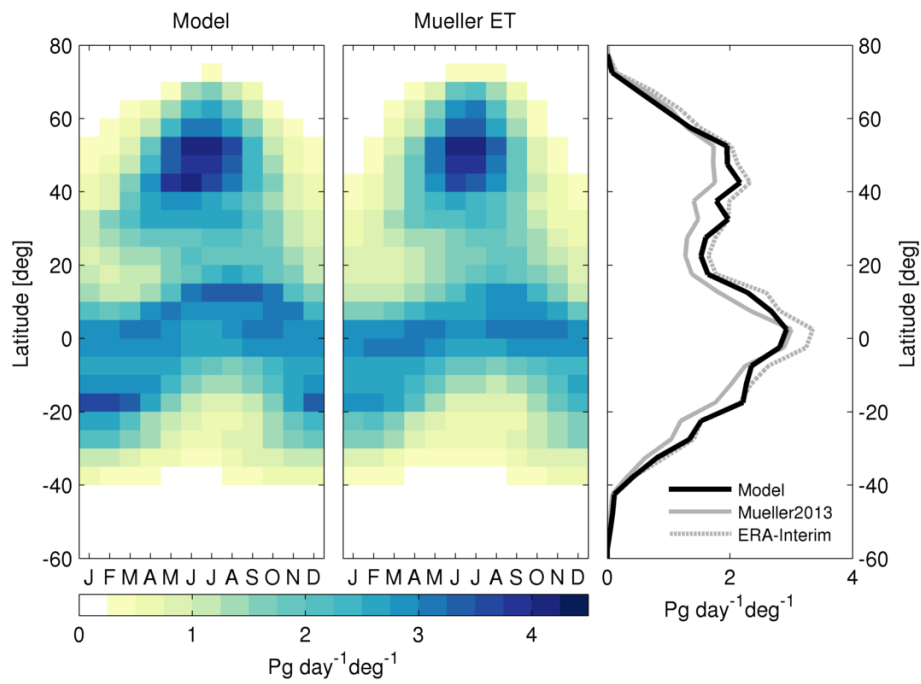


Figure 7. Seasonal variation of zonally integrated evapotranspiration modelled by PALADYN (left) and estimated by Mueller et al. (2013) (middle). ~~(right) Modelled~~ Right: modelled zonal annual mean evapotranspiration compared to observation-based estimates from Mueller et al. (2013) and ERA-Interim reanalysis (Dee et al., 2011).

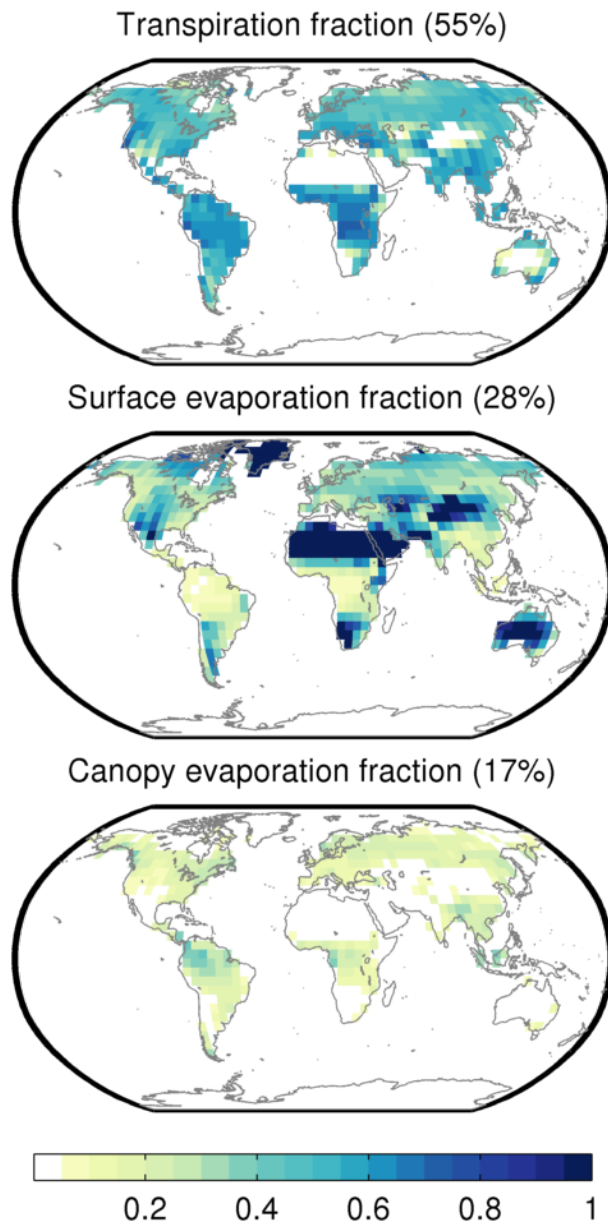


Figure 8. Partitioning of modelled total annual evapotranspiration between transpiration (top), surface evaporation (middle) and canopy evaporation (bottom). The global percentage of each component is shown above the corresponding plot.

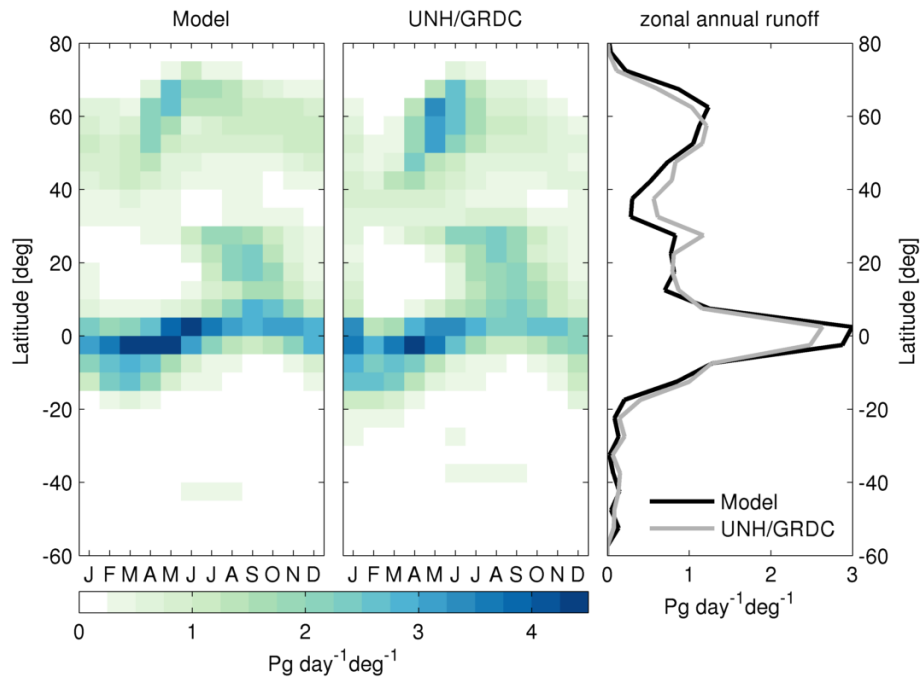


Figure 9. Seasonal variation of zonally integrated water runoff modelled by PALADYN (left) and **observed by observations from** UNH/GRDC (Fekete et al., 2002) (middle). **(right) Modelled Right: modelled** zonal annual mean runoff compared to observation-based estimates from Fekete et al. (2002). Modelled and observed runoff is averaged over the time period 1979-2010.

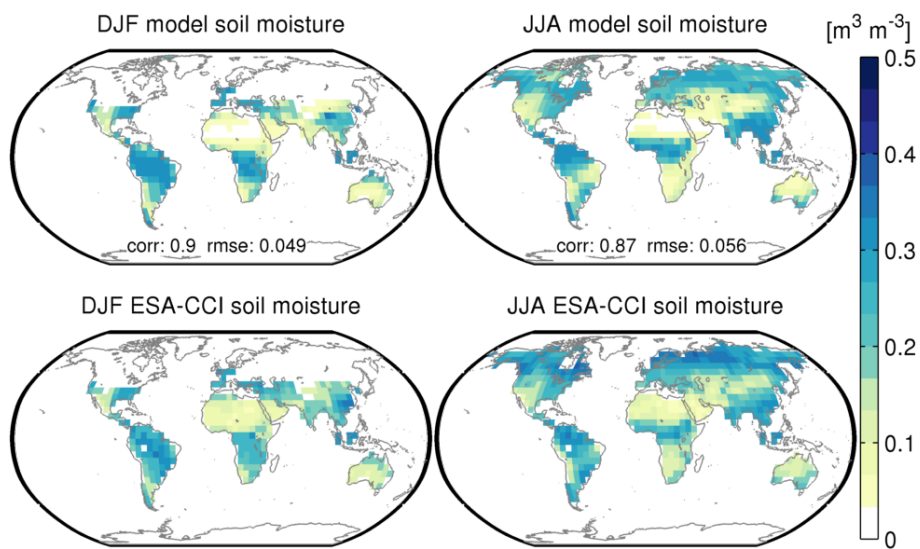


Figure 10. December-January-February (left) and June-July-August (right) soil moisture. The modelled soil moisture (top) is the volumetric soil moisture of the top soil layer (top 20 cm). The observed soil moisture is from ESA-CCI (Liu et al., 2012; Wagner et al., 2012) and represents the moisture content of the top few centimeters of soil. Snow covered regions are masked out. [Spatial correlation between model and data \(corr\) and root mean square error \(rmse\) are indicated between the panels.](#)

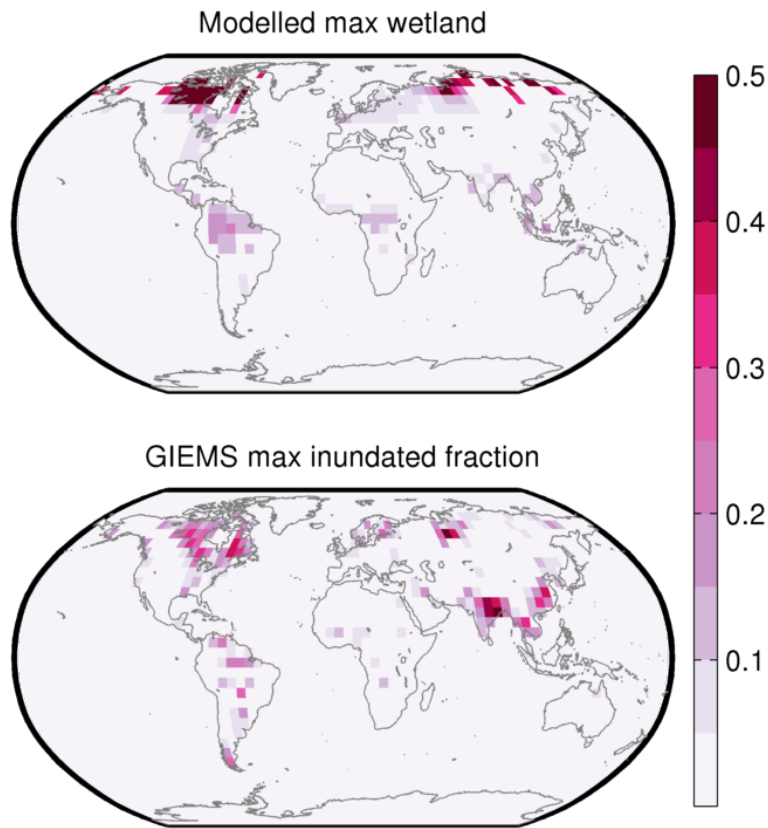


Figure 11. Monthly maximum wetland fraction over the time interval 1993-2007 as modelled by PALADYN (top) and inferred by GIEMS (Prigent et al., 2007; Papa et al., 2010) (bottom).

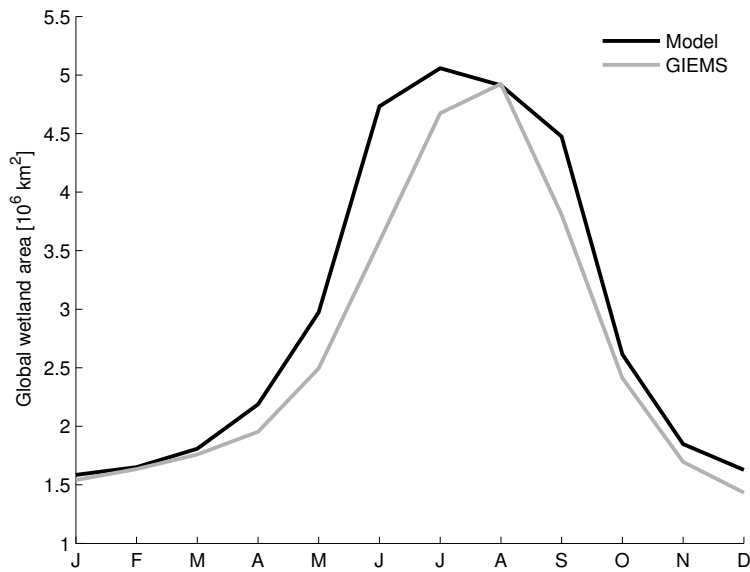


Figure 12. Mean seasonal global wetland extent over the time interval 1993-2007 as modelled by PALADYN and inferred by GIEMS (Prigent et al., 2007; Papa et al., 2010).

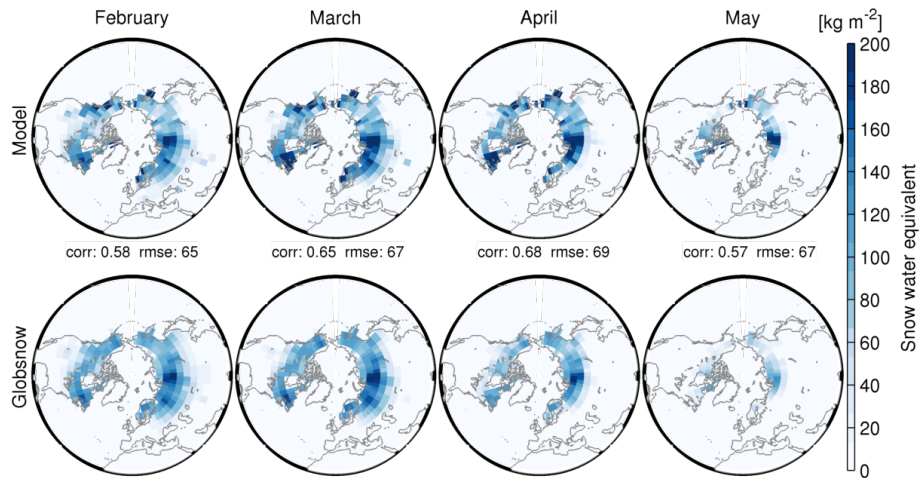


Figure 13. February to May snow water equivalent mean over the period 1980-2010 for PALADYN (top) compared to data from the GlobSnow project (Takala et al., 2011; Luojus et al., 2013) (bottom). [Spatial correlation between model and data \(corr\) and root mean square error \(rmse\) are indicated in the top panels.](#)

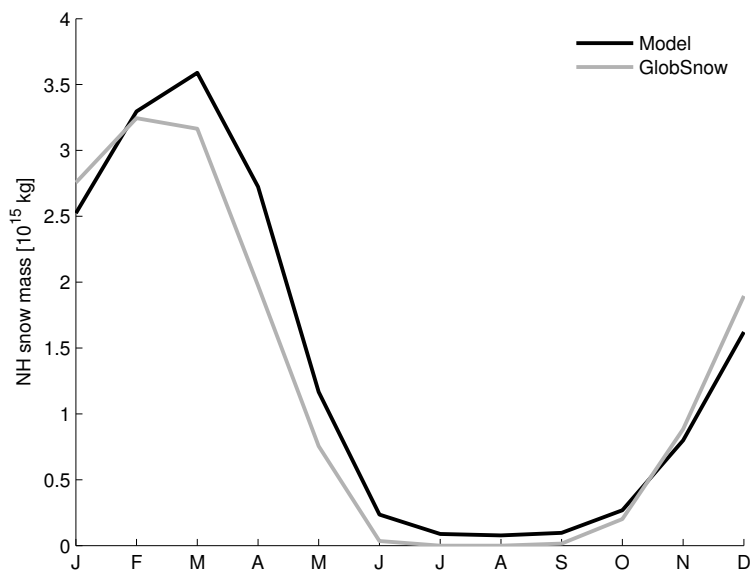


Figure 14. Mean 1980-2010 seasonal evolution of the total Northern Hemisphere snow mass compared to data from the GlobSnow project (Takala et al., 2011; Luojus et al., 2013).

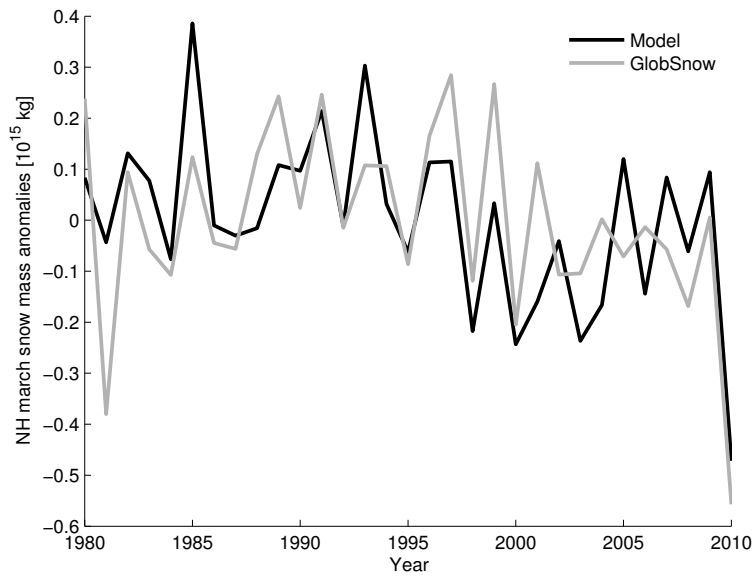


Figure 15. Northern Hemisphere March snow mass anomalies from 1980 to 2010 compared to data from the GlobSnow project (Takala et al., 2011; Luoju et al., 2013).

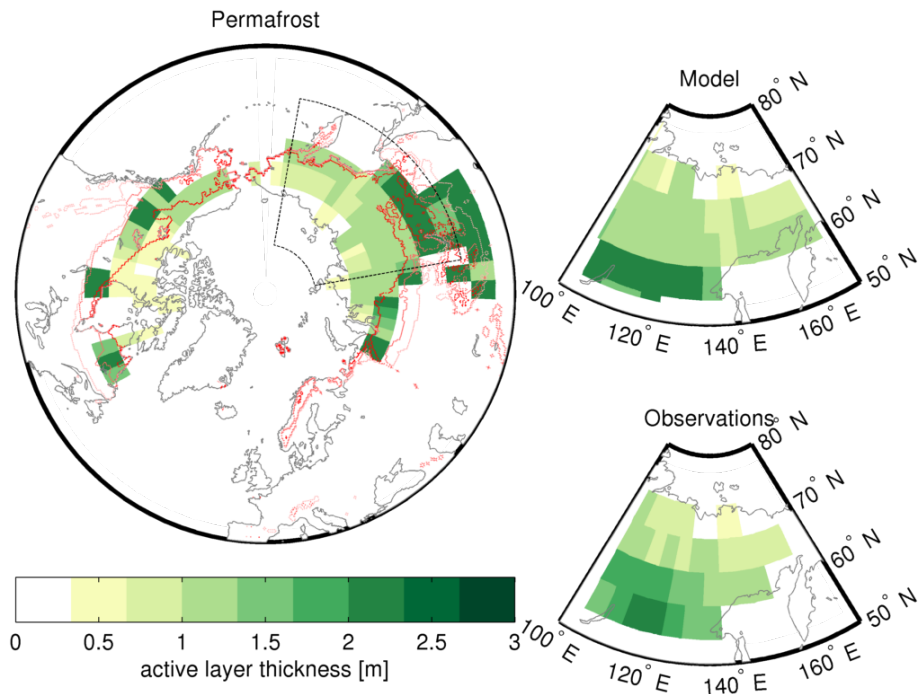


Figure 16. Left: modelled permafrost extent and active layer thickness compared to the observed extent of continuous, discontinuous and isolated permafrost (red lines, from dark red to light red) from (Brown et al., 2014). Right: comparison of modelled (top) and observed (bottom) active layer thickness over Yakutia. Active layer thickness data are from Beer et al. (2013). The modelled active layer thickness is calculated as the mean over the period 1981-2010 in grid cells that are permafrost during the whole time period.

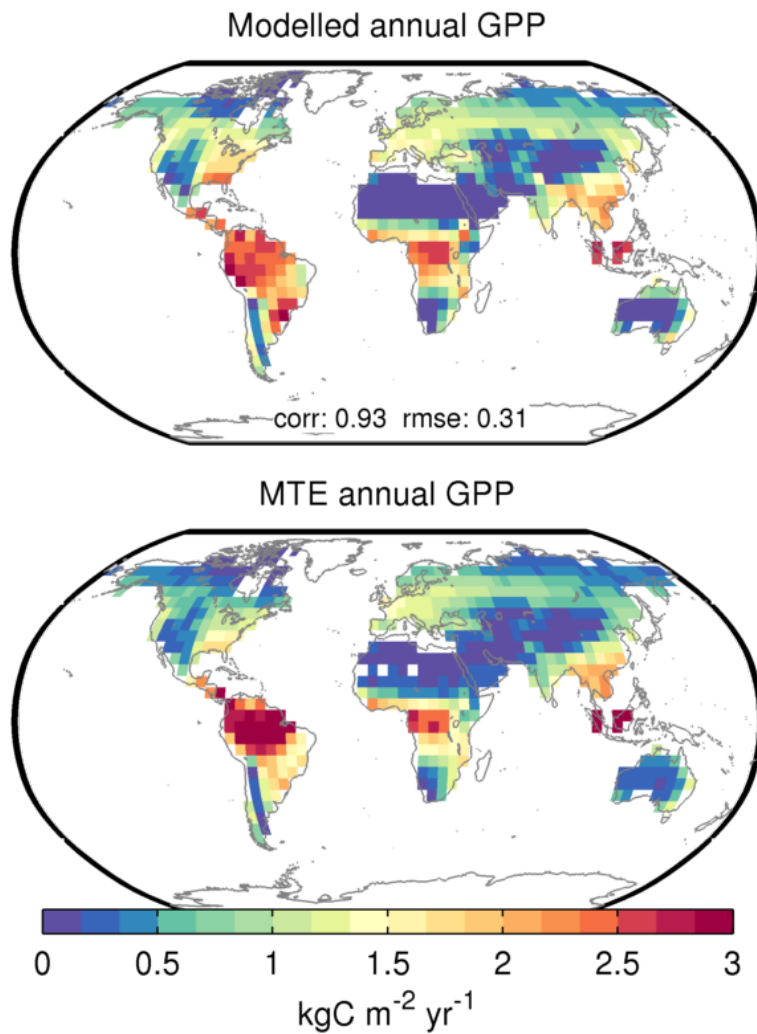


Figure 17. Mean annual gross primary production (GPP) over the time interval 1980-2010 as modelled by PALADYN (top) and estimated by the model tree ensemble approach (MTE) (Jung et al., 2009, 2011) (bottom). [Spatial correlation between model and data \(corr\) and root mean square error \(rmse\) are indicated in the top panel.](#)

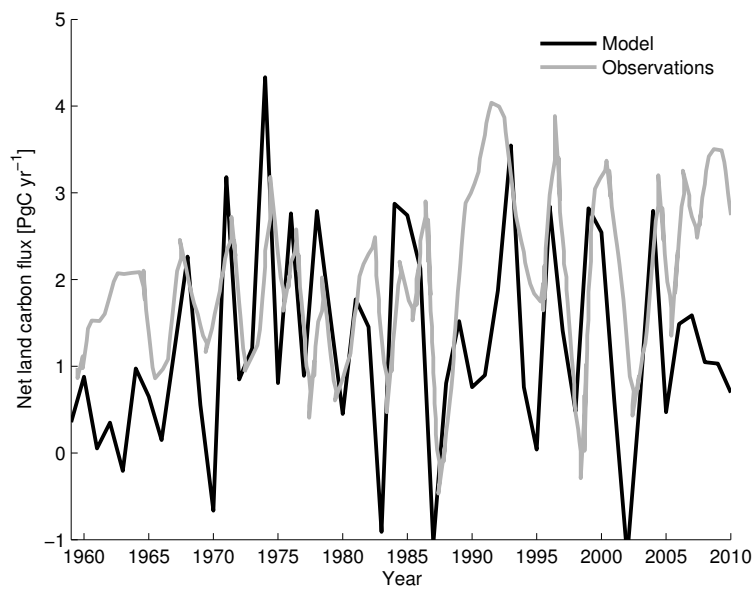


Figure 18. Net land carbon uptake for the historical simulation compared to observations from IPCC.

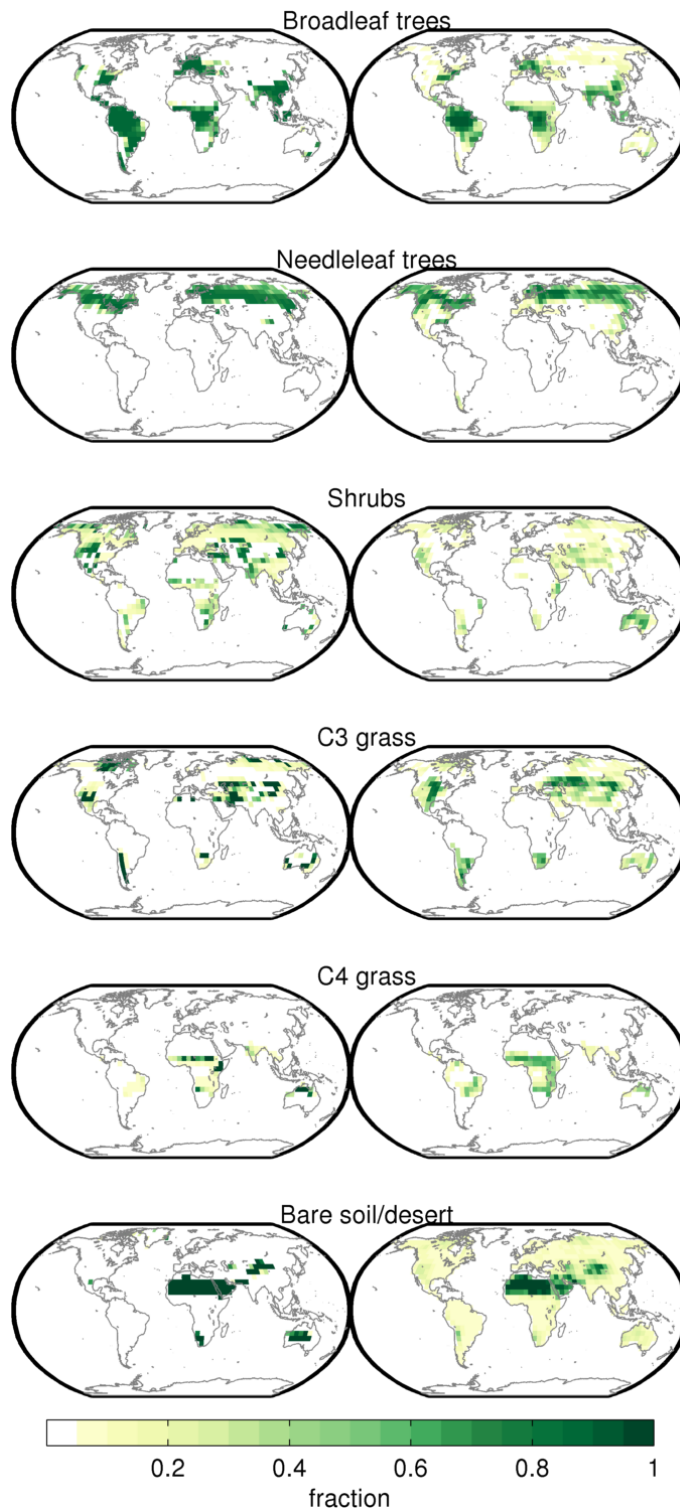


Figure 19. Comparison of modelled plant functional types fraction (left) with potential vegetation distribution adapted from Ramankutty and Foley (1999) as described in Appendix D (right).

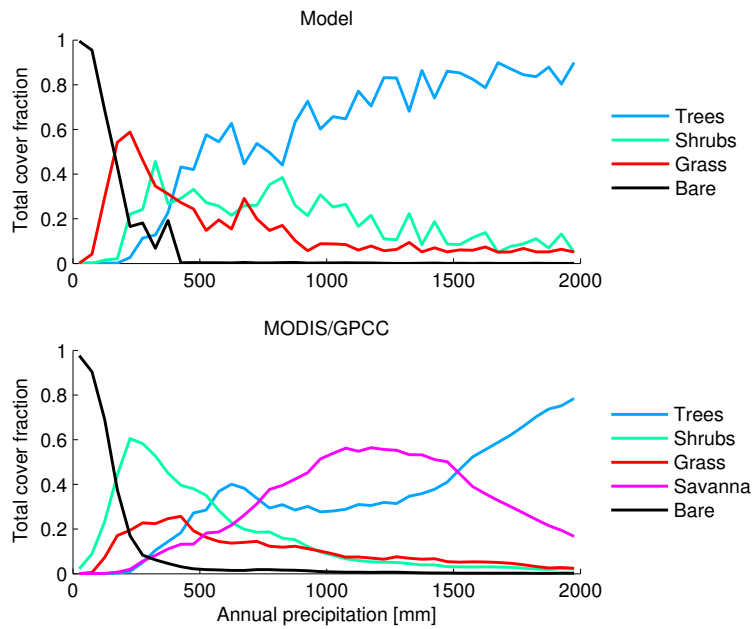


Figure 20. The dependence of the average percent coverages of PFTs on annual precipitation in the model (top) compared to land cover data from MODIS (Friedl et al., 2010; Channan et al., 2014) and precipitation from GPCC (Schneider et al., 2014) (bottom). MODIS data are at 1deg spatial resolution and GPCC data are interpolated to the MODIS data grid from the original 1deg resolution. MODIS data additionally include savanna as a land cover type, which is not included in the model.

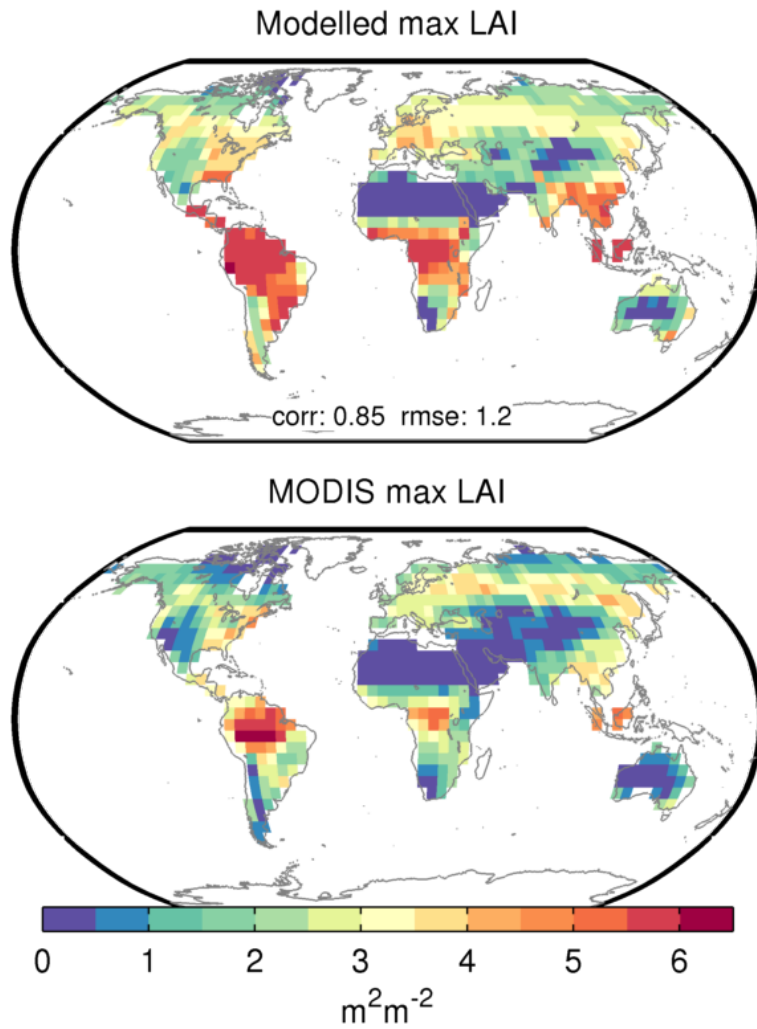


Figure 21. Comparison of modelled maximum annual leaf area index (top) with observational estimates from MODIS (Yuan et al., 2011) (bottom). Spatial correlation between model and data (corr) and root mean square error (rmse) are indicated in the top panel.

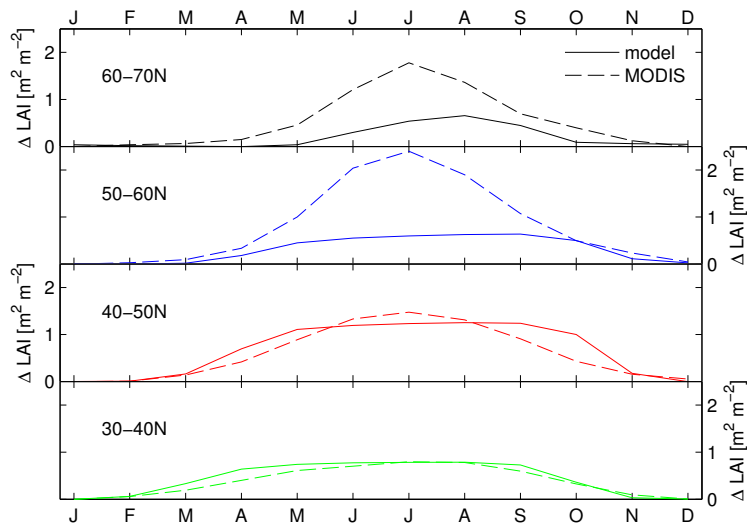


Figure 22. Seasonality of leaf area index for different latitudinal bands in the Northern Hemisphere as indicated in the individual panels. The modelled seasonality (continuous lines) is compared to MODIS data (dashed lines) (Yuan et al., 2011).

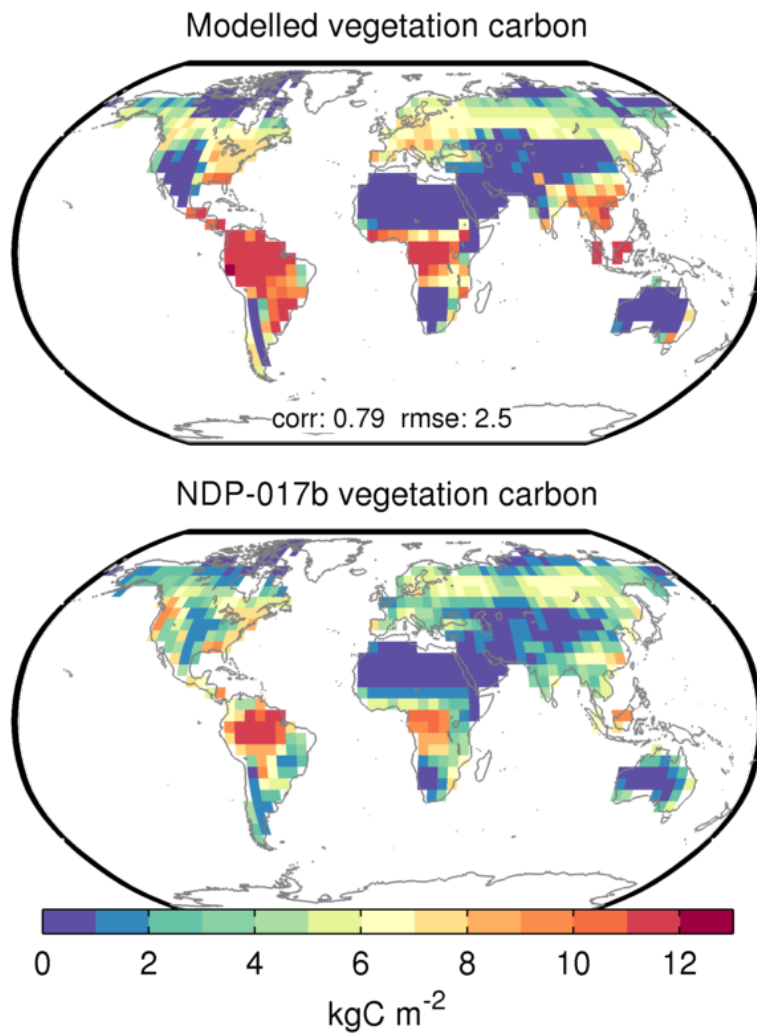


Figure 23. Comparison of modelled vegetation carbon content (top) with the observational estimates from the NDP-017b dataset (Gibbs, 2006) (bottom). Spatial correlation between model and data (corr) and root mean square error (rmse) are indicated in the top panel.

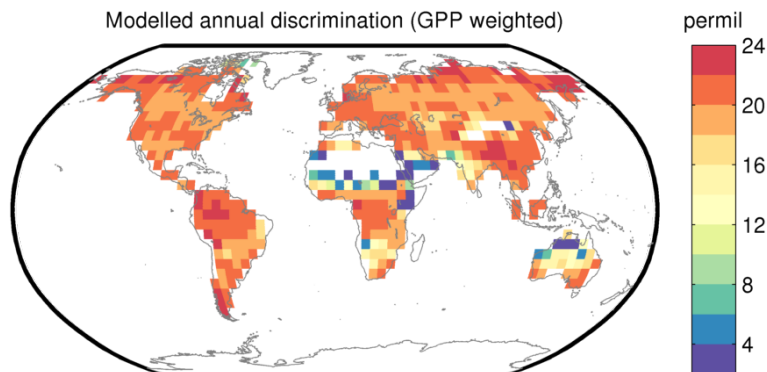


Figure 24. Modelled annual flux weighted discrimination during photosynthesis.

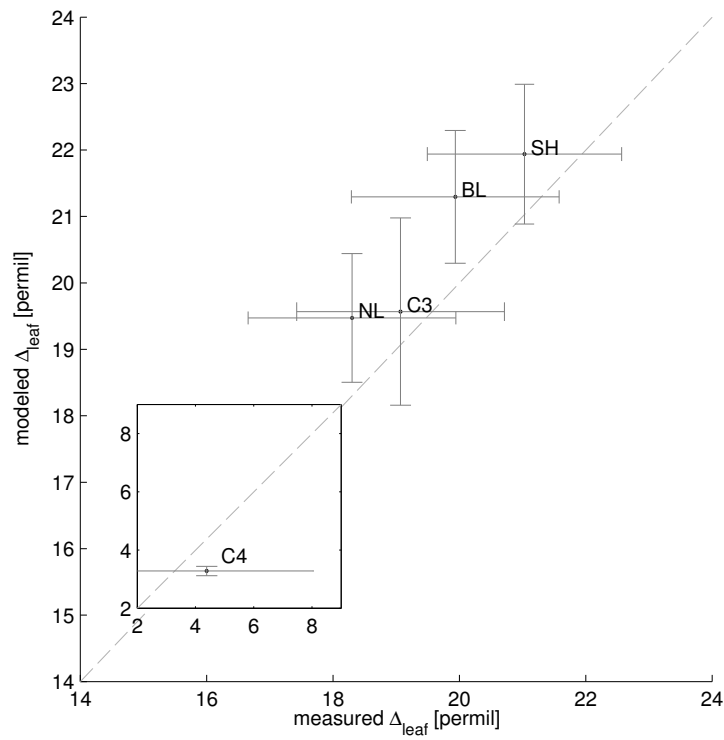


Figure 25. Comparison of modelled and observed discrimination during photosynthesis for different plant functional types. Observational data are from Kaplan et al. (2002).

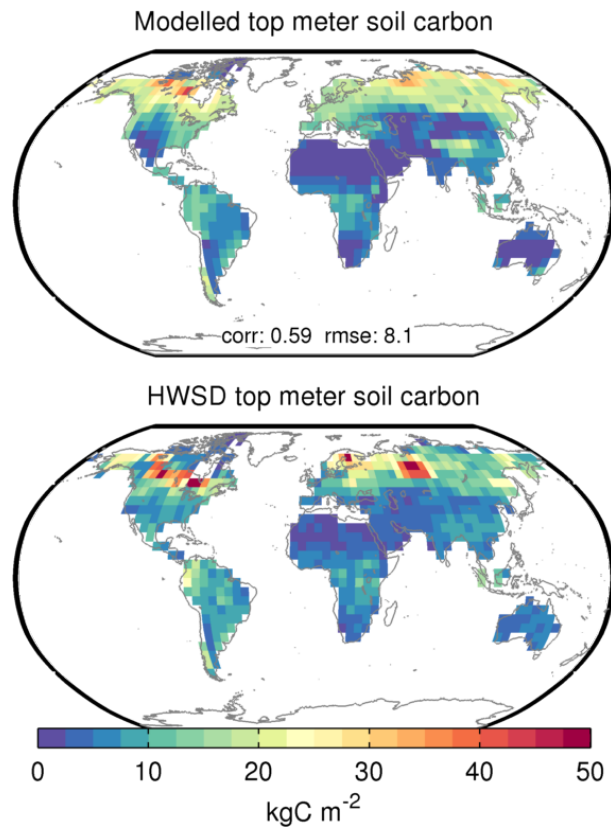


Figure 26. Top 1 m soil carbon as modelled by PALADYN (top) and derived from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) (bottom). [Spatial correlation between model and data \(corr\)](#) and [root mean square error \(rmse\)](#) are indicated in the top panel.

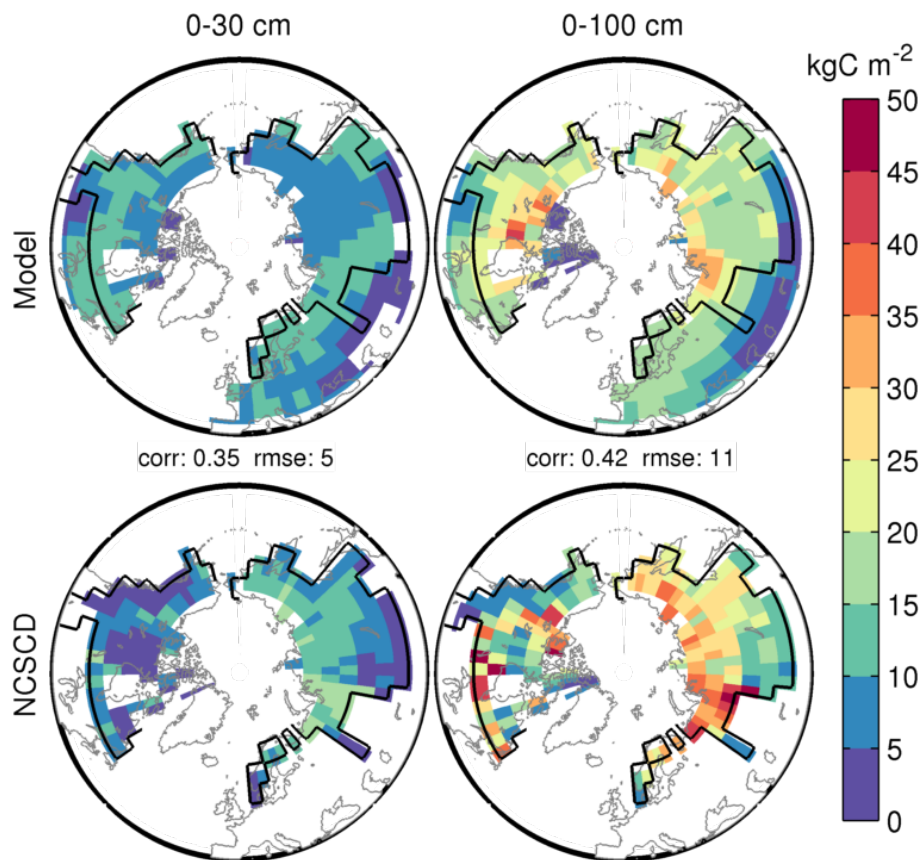


Figure 27. Comparison of modelled (top) soil carbon in Northern permafrost regions with estimates from the Northern Circumpolar Soil Carbon Database (NCSCD) (Hugelius et al., 2013b, a; Tarnocai et al., 2009) (bottom) for two depth ranges: (left) 0-30 cm and (right) 0-100 cm. [Spatial correlation between model and data \(corr\) and root mean square error \(rmse\) are indicated between the panels.](#)

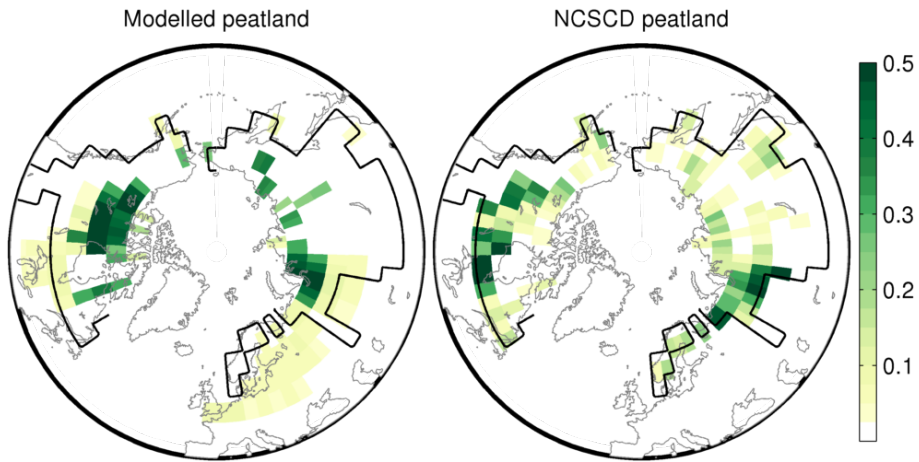


Figure 28. Peat fraction as modelled by PALADYN (left) compared to estimates from the Northern Circumpolar Soil Carbon Database (NCSCD) (Hugelius et al., 2013b, a; Tarnocai et al., 2009) (right). The permafrost area as defined in NCSCD is shown as black line. No data are available from the NCSCD dataset outside this area.

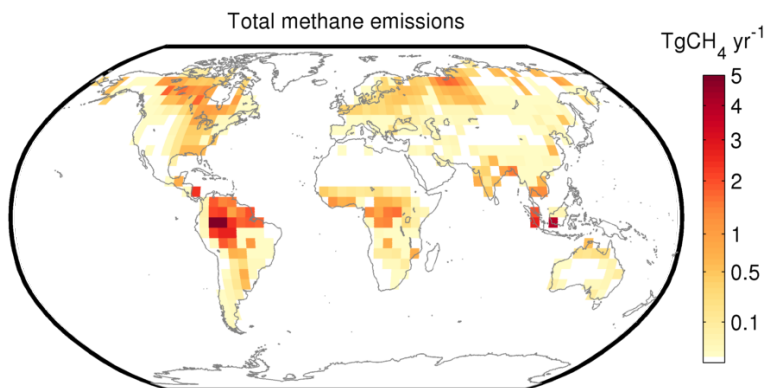


Figure 29. Modelled annual methane emissions.

Table 1: Symbol definitions

Symbol	Units	Definition
Δ	‰	isotopic discrimination
Δz_l	m	thickness of soil layer l
Λ	$\text{kgC m}^{-2} \text{s}^{-1}$	litterfall rate
Λ_{bur}	$\text{kgC m}^{-2} \text{s}^{-1}$	vegetation carbon burial rate under ice sheets
Λ_l	$\text{kgC m}^{-2} \text{s}^{-1}$	leaf litterfall rate
Λ_{loc}	$\text{kgC m}^{-2} \text{s}^{-1}$	local litterfall rate
Λ_{peat}	$\text{kgC m}^{-2} \text{s}^{-1}$	litterfall rate over peatland
Λ_{shelf}	$\text{kgC m}^{-2} \text{s}^{-1}$	litterfall rate over ocean shelf
Λ_{veg}	$\text{kgC m}^{-2} \text{s}^{-1}$	litterfall rate over vegetated grid cell area
α		surface albedo
α_a		factor for <i>APAR</i>
α^{dir}		albedo for direct radiation
α^{dif}		albedo for diffuse radiation
α^{vis}		visible broadband albedo
α^{nir}		near infrared broadband albedo
α_{can}		canopy albedo
α_g		ground albedo
α_{int}^s		snowfall interception factor
α_{int}^w		rainfall interception factor
α_{leaf}		leaf albedo
α_{sn}		snow albedo
$\alpha_{\text{sn}}^{\text{can}}$		albedo of snow covered canopy
$\alpha_{\text{sn,fresh}}$		fresh snow albedo
α_{snfree}		snowfree surface albedo
$\alpha_{\text{snfree}}^{\text{can}}$		albedo of snowfree canopy
α_{soil}		snowfree soil albedo
β_{θ}		soil moisture limitation factor for photosynthesis
β_s		surface evaporation factor
γ_v	s^{-1}	PFT disturbance rate
$\gamma_{v,\text{min}}$	s^{-1}	minimum PFT disturbance rate
γ_l	s^{-1}	leaf turnover rate
γ_r	s^{-1}	root turnover rate
γ_s	s^{-1}	stem turnover rate
ϵ		longwave emissivity

η	Pa s	snow viscosity
η_0	Pa s	reference snow viscosity
θ	$\text{m}^3 \text{m}^{-3}$	volumetric total soil moisture
<u>θ_1</u>	$\text{m}^3 \text{m}^{-3}$	<u>top-layer volumetric soil moisture</u>
θ_{crit}	$\text{m}^3 \text{m}^{-3}$	critical soil moisture for fire
θ_{fc}	$\text{m}^3 \text{m}^{-3}$	volumetric soil moisture at field capacity
θ_i	$\text{m}^3 \text{m}^{-3}$	volumetric frozen soil moisture
θ_r		shape parameter for photosynthesis
θ_{sat}	$\text{m}^3 \text{m}^{-3}$	soil porosity
θ_w	$\text{m}^3 \text{m}^{-3}$	volumetric liquid soil moisture
θ_{wp}	$\text{m}^3 \text{m}^{-3}$	volumetric soil moisture at wilting point
κ		von Karman constant
λ	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity
λ_{NPP}		<i>NPP</i> partitioning factor
λ_a	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity of air
λ_c		ratio of intercellular to atmospheric CO_2
λ_{dry}	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity of dry soil
λ_i	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity of ice
λ_s	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity of soil
$\lambda_{\text{s},1}$	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity of top soil <u>or snow</u> layer
λ_{sat}	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity of saturated soil
λ_{sn}	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity of snow
λ_w	$\text{W m}^{-1} \text{K}^{-1}$	heat conductivity of water
μ	radians	solar zenith angle
ν		PFT fractional area coverage
ν_{seed}		PFT seed fraction
ρ_a	kg m^{-3}	air density
<u>ρ_{acro}</u>	kgC m^{-3}	<u>acrotelm carbon density</u>
<u>ρ_{cato}</u>	kgC m^{-3}	<u>catotelm carbon density</u>
ρ_i	kg m^{-3}	density of ice
ρ_{sn}	kg m^{-3}	density of snow
$\rho_{\text{sn},\text{fresh}}$	kg m^{-3}	density of fresh snow
$\rho_{\text{sn},\text{min}}$	kg m^{-3}	minimum density of snow
ρ_w	kg m^{-3}	density of liquid water
σ	$\text{W m}^{-2} \text{K}^{-4}$	Stefan-Boltzmann constant
τ_{fire}	s	fire return time scale
τ_s	s	canopy snow removal time scale

τ_w	s	canopy water removal time scale
ϕ		phenology factor
ψ	m	soil matric potential
ψ_{sat}	m	saturated soil matric potential
<u>A</u>	m s^{-1}	<u>vertical advection velocity for soil carbon</u>
$APAR$	$\text{mol m}^{-2} \text{ day}^{-1}$	absorbed photosynthetically active radiation
A_g	$\text{gC m}^{-2} \text{ day}^{-1}$	daily gross assimilation
A_n	$\text{gC m}^{-2} \text{ day}^{-1}$	daily net assimilation
A_{nd}	$\text{gC m}^{-2} \text{ day}^{-1}$	daytime net assimilation
C_{DN}^m		neutral drag coefficient for momentum
C_{DN}^h		neutral drag coefficient for heat and water
C_{D}^m		drag coefficient for momentum
C_{D}^h		drag coefficient for heat and water
C_{acro}	kgC m^{-2}	acrotelm carbon
$C_{\text{acro,crit}}$	kgC m^{-2}	critical acrotelm carbon for catotelm formation
C_{bare} bare soil drag coefficient C_{can}		below canopy drag coefficient
C_{cato}	kgC m^{-3}	catotelm carbon density
C_{dense} dense canopy drag coefficient C_p <u>C_{fast}</u>	kgC m^{-3}	specific heat capacity of air at constant pressure <u>fast soil carbon density</u>
C_i	$\text{J kg}^{-1} \text{ K}^{-1}$	specific heat capacity of ice
C_{lit}	kgC m^{-3}	litter carbon density
$C_{\text{lit,peat}}$	kgC m^{-2}	peat litter carbon
C_{fast} <u>C_R</u>	$\text{J kg}^{-1} \text{ K}^{-1}$	fast soil carbon density <u>specific heat capacity of air at constant pressure</u>
C_{peat}	kgC m^{-2}	peat carbon
<u>$C_{\text{peat}}^{\text{crit}}$</u>	kgC m^{-2}	<u>minimum peat carbon content for peat survival</u>
C_{slow}	kgC m^{-3}	slow soil carbon density
C_v	kgC m^{-2}	vegetation carbon
$C_{v,\text{ag}}$	kgC m^{-2}	aboveground vegetation carbon
$C_{v,\text{high}}$	kgC m^{-2}	aboveground vegetation carbon parameter for fire
$C_{v,\text{l}}$	kgC m^{-2}	leaf carbon
$C_{v,\text{low}}$	kgC m^{-2}	aboveground vegetation carbon parameter for fire
$C_{v,\text{r}}$	kgC m^{-2}	root carbon
$C_{v,\text{s}}$	kgC m^{-2}	stem carbon
C_w	$\text{J kg}^{-1} \text{ K}^{-1}$	specific heat capacity of water
D	$\text{m}^2 \text{ s}^{-1}$	vertical soil carbon diffusivity
D_{bio}	$\text{m}^2 \text{ s}^{-1}$	bioturbation carbon diffusivity
D_{cryo}	$\text{m}^2 \text{ s}^{-1}$	cryoturbation carbon diffusivity
E	$\text{kg m}^{-2} \text{ s}^{-1}$	evapotranspiration

E_{can}	$\text{kg m}^{-2} \text{s}^{-1}$	canopy evaporation and sublimation
$E_{\text{can}}^{\text{S}}$	$\text{kg m}^{-2} \text{s}^{-1}$	canopy sublimation
$E_{\text{can}}^{\text{W}}$	$\text{kg m}^{-2} \text{s}^{-1}$	canopy evaporation
E_{s}	$\text{kg m}^{-2} \text{s}^{-1}$	snow sublimation
G	W m^{-2}	ground heat flux
H	W m^{-2}	sensible heat flux
$I_{\text{can}}^{\text{S}}$	$\text{kg m}^{-2} \text{s}^{-1}$	canopy snow interception
$I_{\text{can}}^{\text{W}}$	$\text{kg m}^{-2} \text{s}^{-1}$	canopy rain interception
J_{C}	$\text{gC m}^{-2} \text{day}^{-1}$	Rubisco limited photosynthesis rate
J_{E}	$\text{gC m}^{-2} \text{day}^{-1}$	light limited photosynthesis rate
K		Kersten number
L	J kg^{-1}	latent heat of vaporisation
L_{ai}	$\text{m}^2 \text{m}^{-2}$	leaf area index
$L_{\text{ai,b}}$	$\text{m}^2 \text{m}^{-2}$	balanced leaf area index
L_{f}	J kg^{-1}	latent heat of fusion of water
LW^{\downarrow}	W m^{-2}	downward longwave radiation at the surface
LW^{\uparrow}	W m^{-2}	upward longwave radiation at the surface
M_{s}	$\text{kg m}^{-2} \text{s}^{-1}$	snowmelt
NPP	$\text{kgC m}^{-2} \text{s}^{-1}$	net primary production
P_{s}	$\text{kg m}^{-2} \text{s}^{-1}$	snowfall rate
$P_{\text{s,g}}$	$\text{kg m}^{-2} \text{s}^{-1}$	snowfall rate reaching the ground
P_{r}	$\text{kg m}^{-2} \text{s}^{-1}$	rainfall rate
$P_{\text{r,g}}$	$\text{kg m}^{-2} \text{s}^{-1}$	rainfall rate reaching the ground
R_{d}	$\text{gC m}^{-2} \text{day}^{-1}$	leaf respiration
R_{i}		bulk Richardson number
R_{w}	$\text{kg m}^{-2} \text{s}^{-1}$	surface water runoff
SLA	$\text{m}^2 \text{kgC}^{-1}$	specific leaf area
S_{ai}	$\text{m}^2 \text{m}^{-2}$	stem area index
SW^{\downarrow}	W m^{-2}	downward shortwave radiation at the surface
T_0	K	freezing temperature of water
T_{\star}	K	skin temperature
T_{a}	K	air temperature at height z_{ref}
$T_{\text{cmon}}^{\text{max}}$	K	maximum coldest month temperature for establishment
$T_{\text{cmon}}^{\text{min}}$	K	minimum coldest month temperature for establishment
$T_{\text{cmon}}^{\text{phen}}$	K	coldest month temperature for phenology
$T_{\text{gdd}}^{\text{base}}$	K	base temperature for phenology
$T_{\text{s,1}}$	K	top soil layer or snow temperature

T_s	K	soil/snow temperature
T_{su}	K	snow temperature
VPD	kPa	vapor pressure deficit
V_a	$m\ s^{-1}$	wind speed at height z_{ref}
V_m	$gC\ m^{-2}\ day^{-1}$	maximum daily rate of net photosynthesis
a_C		factor for leaf respiration
a_{wt}	m	allometric coefficient for plant height
a_{ws}	$kgC\ m^{-2}$	ratio of total to respiring stem carbon allometric coefficient
b		Clapp and Hornberger parameter
b_{wl}		allometric coefficient
c	$J\ m^{-3}\ K^{-1}$	volumetric heat capacity
c_1	$g\ mol^{-1}$	factor for light limited assimilation
c_2		factor for Rubisco limited assimilation
c_a	$mol\ mol^{-1}$	atmospheric CO_2 mole fraction
c_i	$mol\ mol^{-1}$	intercellular CO_2 mole fraction
c_{ij}		PFT competition coefficients
c_q	$mol\ J^{-1}$	conversion factor for solar radiation
c_s	$J\ m^{-3}\ K^{-1}$	volumetric heat capacity of dry soil
c_{sn}	$J\ m^{-3}\ K^{-1}$	volumetric heat capacity of snow
d	m	zero plane displacement
d_h	hours	daylength
$d_{r,1}$	m	root distribution paramter
$d_{r,2}$	m	root distribution parameter
e	$kg\ m^{-2}\ s^{-1}$	soil moisture removal by evapotranspiration
f_{∇}		parameter for computation of water table depth
f_{θ}		soil moisture factor for soil carbon decomposition rate
$f_{\theta,peat}$		soil moisture factor for peat carbon decomposition rate
$f_{\theta,sat}$		soil moisture factor for soil carbon decomposition rate at saturation
f_T		temperature factor for soil carbon decomposition rate
f_{μ}		solar zenith angle factor for snow albedo
f_{age}		snow age factor
f_{can}^s		snow covered canopy fraction
f_{can}^w		water covered canopy fraction
$f_{frz,crit}$		critical fraction of frozen soil water for permafrost carbon
f_{ice}		fraction of grid cell covered by ice sheets
f_{inert}		frozen soil factor for soil carbon decomposition
f_{inun}		inundated grid cell fraction

f_{lit}^{resp}		fraction of decomposed litter carbon going to atmosphere
$f_{lit \rightarrow fast}$		fraction of decomposed litter transferred to fast carbon pool
$f_{lit \rightarrow slow}$		fraction of decomposed litter transferred to slow carbon pool
f_{org} organic soil fraction	f_{oxic}	fraction of litter and acrotelm respiring in oxic conditions
f_{peat}		peatland fraction
f_{peat}^{min}		minimum peatland fraction
$f_{peat,pot}$		potential peatland fraction
f_{sat}		saturated grid cell fraction
f_{sat}^{max}		maximum saturated grid cell fraction
f_{shelf}		fraction of grid cell below sea level
f_{sn}		snow fraction
f_{sn}^{can} canopy snow fraction	f_{sv}	sky view factor
f_{sv}^{dir}		direct beam sky view factor
f_{sv}^{dif}		diffuse radiation sky view factor
$f_{veg \rightarrow bur}$		fraction of vegetation carbon buried below ice sheets
f_{wet}		wetland fraction
g	$m\ s^{-2}$	gravitational acceleration
gdd	K	growing degree days above T_{gdd}^{base}
gdd_{crit}	K	critical growing degree days for phenology
gdd_{min}	K	minimum growing degree days for establishment
g_0	$m\ s^{-1}$	cuticular canopy conductance
g_1		parameter in optimal stomatal conductance model
g_{can}	$m\ s^{-1}$	canopy conductance
g_{min}	$m\ s^{-1}$	minimum canopy conductance
h_{sn}	m	snow thickness
h_{soil}	m	depth of the soil column
h_v	m	vegetation height
k	$kg\ m^{-2}\ s^{-1}$	hydraulic soil conductivity
k_{acro}	s^{-1}	acrotelm carbon turnover rate
$k_{acro \rightarrow cato}$	s^{-1}	catotelm formation rate
k_{cato}	s^{-1}	catotelm carbon turnover rate
k_{ext}		extinction coefficient for radiation
k_{fast}	s^{-1}	fast carbon turnover rate
$k_{fast,10}$	s^{-1}	fast soil carbon turnover rate at 10 °C
k_{inert}	s^{-1}	inert soil carbon turnover rate
k_{lit}	s^{-1}	litter carbon turnover rate
$k_{lit,10}$	s^{-1}	litter carbon turnover rate at 10 °C

$k_{lit,peat}$	s^{-1}	peat litter carbon turnover rate
k_{sat}	$kg\ m^{-2}\ s^{-1}$	hydraulic soil conductivity at saturation
k_{slow}	s^{-1}	slow soil carbon turnover rate
$k_{slow,10}$	s^{-1}	slow soil carbon turnover rate at 10 °C
k_{ρ}	$m^3\ kg^{-1}$	factor for density dependence of snow viscosity
k_T	K^{-1}	factor for temperature dependence of snow viscosity
n_{al}		multiple of active layer thickness for cryoturbation
p_a	Pa	partial pressure of atmospheric CO ₂
p_i	Pa	partial pressure of intercellular CO ₂
q	$kg\ m^{-2}\ s^{-1}$	soil water flux
q_a	$kg\ kg^{-1}$	air specific humidity at height z_{ref}
q_{drain}	$kg\ m^{-2}\ s^{-1}$	soil water drainage
q_{inf}	$kg\ m^{-2}\ s^{-1}$	soil water infiltration
q_{inf}^{max}	$kg\ m^{-2}\ s^{-1}$	maximum soil water infiltration
q_{sat}	$kg\ kg^{-1}$	specific humidity at saturation
r		cumulative root fraction
r_a	$s\ m^{-1}$	aerodynamic resistance
$r_{a,can}$	$s\ m^{-1}$	below-canopy aerodynamic resistance
r_l		<u>root fraction in layer l</u>
r_s	$s\ m^{-1}$	<u>surface-canopy</u> resistance to water vapor flux
u_* friction-velocity w_{can}^w	$kg\ m^{-2}$	canopy liquid water
w_{can}^s	$kg\ m^{-2}$	canopy snow water equivalent
w_i	$kg\ m^{-2}$	soil frozen water content
w_{sn}	$kg\ m^{-2}$	snow water equivalent
w_w	$kg\ m^{-2}$	soil liquid water content
w_w^{max}	$kg\ m^{-2}$	maximum soil liquid water content
z_0^b	m	bare soil roughness length
z_0^i	m	ice roughness length
z_0^{sn}	m	snow roughness length
z_0^{snfree}	m	snow-free roughness length
z_0^v	m	vegetation roughness length
z_0^w water-roughness-length z_{∇}	m	grid cell mean water table depth
z_{∇}^{min}	m	minimum water table depth
z_{∇}^{peat}	m	peatland water table depth
z_{at} z_{acro}	m	<u>active-layer-acrotelm</u> thickness
z_{acro} z_{al}	m	<u>acrotelm-active layer</u> thickness
z_m z_b	m	roughness length for <u>momentum scalars</u>

Table 2. Surface model parameters.

$k_{\text{ext}} = 0.5$	extinction coefficient for radiation
$\alpha_{\text{sn,fresh}}^{\text{vis,dif}} = 0.95$	diffuse visible fresh snow albedo
$\alpha_{\text{sn,fresh}}^{\text{nir,dif}} = 0.65$	diffuse near infrared fresh snow albedo
$z_0^{\text{b}} = 0.005 \text{ m}$	bare soil roughness length
$z_0^{\text{i}} = 0.01 \text{ m}$	ice roughness length
$z_0^{\text{w}} = 0.001 \text{ m}$ water roughness length $z_0^{\text{sn}} = 0.0024 \text{ m}$	snow roughness length
$C_{\text{bare}} = 0.05$ bare soil drag coefficient $C_{\text{dense}} = 0.005$ $C_{\text{can}} = 0.006$ dense canopy drag coefficient drag coefficient for fluxes below the canopy	
$\alpha_{\text{int}}^{\text{w}} = 0.2$	canopy water interception parameter
$\alpha_{\text{int}}^{\text{s}} = 0.5$	canopy snow interception parameter
$\tau_{\text{w}} = 1 \text{ day}$	canopy water removal time scale
$\tau_{\text{s}} = 10 \text{ days}$	canopy snow removal time scale
$\rho_{\text{sn,min}} = 50 \text{ kg m}^{-3}$	minimum snow density
$\eta_0 = 9 \times 10^6 \text{ Pa s}$	reference snow viscosity
$k_{\text{T}} = 0.06 \text{ K}^{-1}$	temperature parameter for snow viscosity
$k_{\rho} = 0.02 \text{ m}^3 \text{ kg}^{-1}$	density parameter for snow viscosity
$f_{\text{v}} = 1.6$ $f_{\text{v}} = 1.7$	parameter for saturated grid cell fraction

Table 3. Soil model parameters.

$c_{\text{s}} = 2.3 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$	volumetric heat capacity of soil
$\lambda_{\text{s}} = 5.0 \text{ W m}^{-1} \text{ K}^{-1}$	soil heat conductivity at saturation
$\lambda_{\text{dry}} = 0.2 \text{ W m}^{-1} \text{ K}^{-1}$	dry soil heat conductivity
$\theta_{\text{sat}} = 0.43 \text{ m}^3 \text{ m}^{-3}$	soil porosity
$\theta_{\text{fc}} = 0.25 \text{ m}^3 \text{ m}^{-3}$	volumetric soil moisture at field capacity
$\theta_{\text{wp}} = 0.14 \text{ m}^3 \text{ m}^{-3}$	volumetric soil moisture at wilting point
$\psi_{\text{sat}} = -0.2 \text{ m}$	soil matric potential at saturation
$k_{\text{sat}} = 520 \text{ kg m}^{-2} \text{ day}^{-1}$	soil hydraulic conductivity at saturation
$b = 6$	Clapp-Hornberger parameter

z_{h} z_{w}	m	roughness length for scalars momentum
z_{ref}	m	reference height

Table 4. Photosynthesis model parameters (Sitch et al., 2003).

θ_r

α_{leaf}

~~α~~ α_a

c_q

a_{C3}

a_{C4}

~~α_{C3} 0.08 intrinsic quantum efficiency of uptake in C3 plants α_{C4} 0.053 intrinsic quantum efficiency of uptake in C4 plants $[O_2]$ 20.9 partial pressure~~

Table 5. Plant functional type specific model parameters.

		Broadleaf tree	Needleleaf tree	C3 grass
$d_{r,1}$	root distribution parameter (Oleson et al., 2013)	6.5	7.0	11.0
$d_{r,2}$	root distribution parameter (Oleson et al., 2013)	1.5	2.0	2.0
$\alpha_{\text{snfree}}^{\text{can,vis,dir}}$	snowfree visible canopy albedo for direct radiation (Houldcroft et al., 2009)	0.011 <u>0.02</u>	0.004 <u>0.01</u>	0.038 <u>0.04</u>
$\alpha_{\text{snfree}}^{\text{can,vis,dif}}$	snowfree visible canopy albedo for diffuse radiation (Houldcroft et al., 2009)	0.013 <u>0.03</u>	0.005 <u>0.01</u>	0.043 <u>0.05</u>
$\alpha_{\text{snfree}}^{\text{can,nir,dir}}$	snowfree near infrared canopy albedo for direct radiation (Houldcroft et al., 2009)	0.22	0.141 <u>0.18</u>	0.269 <u>0.27</u>
$\alpha_{\text{snfree}}^{\text{can,nir,dif}}$	snowfree near infrared canopy albedo for diffuse radiation (Houldcroft et al., 2009)	0.256 <u>0.26</u>	0.154 <u>0.19</u>	0.306 <u>0.31</u>
$\alpha_{\text{sn}}^{\text{can,vis,dir/dif}}$	snowfree visible canopy albedo (Moody et al., 2007)	0.44	0.31	0.70
$\alpha_{\text{sn}}^{\text{can,nir,dir/dif}}$	snowfree near infrared canopy albedo (Moody et al., 2007)	0.33	0.24	0.48
$T_{\text{cmon}}^{\text{min}} [^{\circ}\text{C}]$	minimum coldest month temperature for establishment (Sitch et al., 2003)	-17.0	-	-
$T_{\text{cmon}}^{\text{max}} [^{\circ}\text{C}]$	maximum coldest month temperature for establishment (Sitch et al., 2003)	-	-2.0 <u>-5.0</u>	15.5
$gdd_{\text{min}} [^{\circ}\text{C}]$	minimum gdd for establishment (Sitch et al., 2003)	1200	350	0
$T_{\text{cmon}}^{\text{phen}} [^{\circ}\text{C}]$	coldest month temperature for phenology	5.0	-999 <u></u>	0.0
$T_{\text{base}}^{\text{gdd}} [^{\circ}\text{C}]$	base temperature for gdd (Sitch et al., 2003)	5.0	2.0	2.0
$gdd_{\text{crit}} [^{\circ}\text{C}]$	gdd for full phenology (Sitch et al., 2003)	300	-	100
$g_{\text{min}} [\text{mm s}^{-1}]$	minimum canopy conductance (Sitch et al., 2003)	0.5	0.3	0.5
g_1	parameter in optimal stomatal conductance formulation (Lin et al., 2015)	4.0	2.3	3
$L_{\text{ai}}^{\text{min}} [\text{m}^2 \text{m}^{-2}]$	minimum leaf area index modified from Clark et al. (2011)	1.0 <u>1</u>	1.0 <u>1</u>	0.1 <u>1</u>
$L_{\text{ai}}^{\text{max}} [\text{m}^2 \text{m}^{-2}]$	maximum leaf area index modified from Clark et al. (2011)	9.0 <u>8</u>	7.0 <u>6</u>	4.0 <u>3</u>
$SLA [\text{m}^{-2} \text{kgC}^{-1}]$	specific leaf area (Kattge et al., 2011)	12.5 <u>20</u>	6 <u>10</u>	20 <u>40</u>
$\gamma_l [\text{yr}^{-1}]$	leaf turnover rate (Kattge et al., 2011)	0.5	0.3	1.0
$\gamma_r [\text{yr}^{-1}]$	root turnover rate	0.5	0.3	0.5
$\gamma_s [\text{yr}^{-1}]$	stem turnover rate modified from Clark et al. (2011)	0.005	0.005	0.2
$a_{\text{wl}} [\text{kgC m}^{-2}]$	allometric coefficient	0.65 <u>2.0</u>	0.75 <u>2.0</u>	0.005 <u>0.01</u>
$\alpha_{\text{ws}} = \alpha_{\text{wh}}$	ratio of total to respiring stem carbon allometric coefficient for plant height	10 <u>3.5</u>	10 <u>6</u>	1 <u>0.15</u>

Table 6. Dynamic vegetation model parameters.

$\nu_{\text{seed}} = 0.001$	vegetation seed fraction
$\gamma_{v,\text{min}} = 0.002 \text{ yr}^{-1}$	minimum vegetation disturbance rate
$\tau_{\text{fire}} = 10 \text{ yr}$	fire return time scale
$\theta_{\text{crit}} = 0.15 \text{ m}^3 \text{ m}^{-3}$	critical soil moisture for fire disturbance
$C_{v,\text{low}} = 0.2 \text{ kgC m}^{-2}$	minimum aboveground vegetation carbon for fire disturbance
$C_{v,\text{high}} = 1.0 \text{ kgC m}^{-2}$	maximum aboveground vegetation carbon for fire disturbance

Table 7. Soil carbon model parameters.

$f_{\text{lit}}^{\text{resp}} = 0.7$	fraction of decomposed litter carbon going to atmosphere
$f_{\text{lit} \rightarrow \text{fast}} = 0.985$	fraction of decomposed litter transferred to fast carbon pool
$f_{\text{lit} \rightarrow \text{slow}} = 0.015$	fraction of decomposed litter transferred to slow carbon pool
$D_{\text{bio}} = 1 \times 10^{-4} \text{ m}^2 \text{ year}^{-1}$	bioturbation rate (Braakhekke et al., 2011)
$D_{\text{cryo}} = 5 \times 10^{-4} \text{ m}^2 \text{ year}^{-1}$	cryoturbation rate (Koven et al., 2009, 2013)
$k_{\text{lit},10} = 2.86 \text{ yr}^{-1}$	litter carbon turnover rate at 10 °C (Sitch et al., 2003)
$k_{\text{fast},10} = 33.3 \text{ yr}^{-1}$	fast soil carbon turnover rate at 10 °C (Sitch et al., 2003)
$k_{\text{slow},10} = 1000 \text{ yr}^{-1}$	slow soil carbon turnover rate at 10 °C (Sitch et al., 2003)
$k_{\text{acro},10} = 30 \text{ yr}^{-1}$	acrotelm carbon turnover rate at 10 °C
$k_{\text{cato},10} = 1000 \text{ yr}^{-1}$	catotelm carbon turnover rate at 10 °C (Spahni et al., 2002)
$k_{\text{acro} \rightarrow \text{cato}} = 15 \times 10^{-3} \text{ yr}^{-1}$	catotelm formation rate (Wania et al., 2009; Kleinen et al., 2009)
$f_{\theta,\text{peat}} = 0.3$	soil moisture factor for peat carbon decomposition rate
$\rho_{\text{acro}} = 20 \text{ kgC m}^{-3}$	acrotelm carbon density (Clymo, 1984; R. S. Clymo et al., 1996)
$\rho_{\text{cato}} = 50 \text{ kgC m}^{-3}$	catotelm carbon density (Turunen et al., 2002; Malmgren et al., 2002)
$\rho_{\text{soc,max}} = \rho_{\text{cato}}$ maximum carbon density of soil organic carbon $C_{\text{acro,crit}} = 5 \text{ kgC m}^{-2}$	minimum acrotelm carbon content for catotelm formation
$C_{\text{peat}}^{\text{crit}} = 50 \text{ kgC m}^{-2}$	minimum peat carbon content for peat survival (Stocker et al., 2002)
$f_{\text{peat}}^{\text{min}} = 0.001$	minimum peatland fraction
$\left. \frac{dC_{\text{peat}}}{dt} \right _{\text{crit}} = 10^{-3} \text{ kgC m}^{-2} \text{ yr}^{-1}$	minimum peat carbon uptake for peat survival (Stocker et al., 2002)
$f_{\text{CH}_4:\text{C}}^{\text{wet}} = 0.07$	fraction of carbon respired as methane from wetland
$f_{\text{CH}_4:\text{C}}^{\text{peat}} = 0.2$	fraction of carbon respired as methane from peatland

Table 8. Global values of relevant model quantities over the time period 1981–2010 compared to observation based estimates.

	Model	Observation based estimates
evapotranspiration [$\times 10^{15}$ kg yr ⁻¹]	73 - <u>71</u>	64–73 (Mueller et al., 2013; Trenberth et al., 2007)
runoff [$\times 10^{15}$ kg yr ⁻¹]	35 - <u>37</u>	38–40 (Fekete et al., 2002; Baumgartner and Reichel, 1975)
permafrost area [mln km ²]	16.5 - <u>16</u>	13–18 (Gruber, 2012)
GPP [PgC yr ⁻¹]	126 - <u>132</u>	115–131 (Beer et al., 2010)
NPP [PgC yr ⁻¹]	65 - <u>70</u>	42–70 (Ito, 2011)
vegetation carbon [PgC]	500 - <u>580</u>	470–650 (Prentice et al., 2001)
top meter soil carbon [PgC]	1030 - <u>1170</u>	890–1660 (Todd-Brown et al., 2013)
soil carbon in permafrost area [PgC]	590 - <u>555</u>	1100–1500 (Hugelius et al., 2014)
northern peat carbon [PgC]	520 - <u>510</u>	470–620 - <u>530–694</u> (Yu et al., 2010)
maximum monthly wetland area [mln km ²]	5.7 - <u>5.1</u>	5 (Prigent et al., 2007; Papa et al., 2010)
northern peatland area [mln km ²]	2.9 - <u>3.8</u>	3.6–4 - <u>4.4</u> (Yu et al., 2010)
total CH ₄ emissions [TgCH ₄ yr ⁻¹]	175 - <u>160</u>	115–215 (Bloom et al., 2010; Bousquet et al., 2006)
tropical CH ₄ emissions [TgCH ₄ yr ⁻¹]	105 - <u>96</u>	63–119 (Bloom et al., 2010; Bousquet et al., 2006)
extratropical CH ₄ emissions [TgCH ₄ yr ⁻¹]	70 - <u>72</u>	39–89 (Bloom et al., 2010; Bousquet et al., 2006)

Table 9. Climate forcing fields needed to run PALADYN in offline mode.

Surface air temperature
Surface air specific humidity
Downwelling shortwave radiation at the surface
Downwelling longwave radiation at the surface
Rainfall
Snowfall
Wind speed
Surface pressure