SURFEX Users Workshop

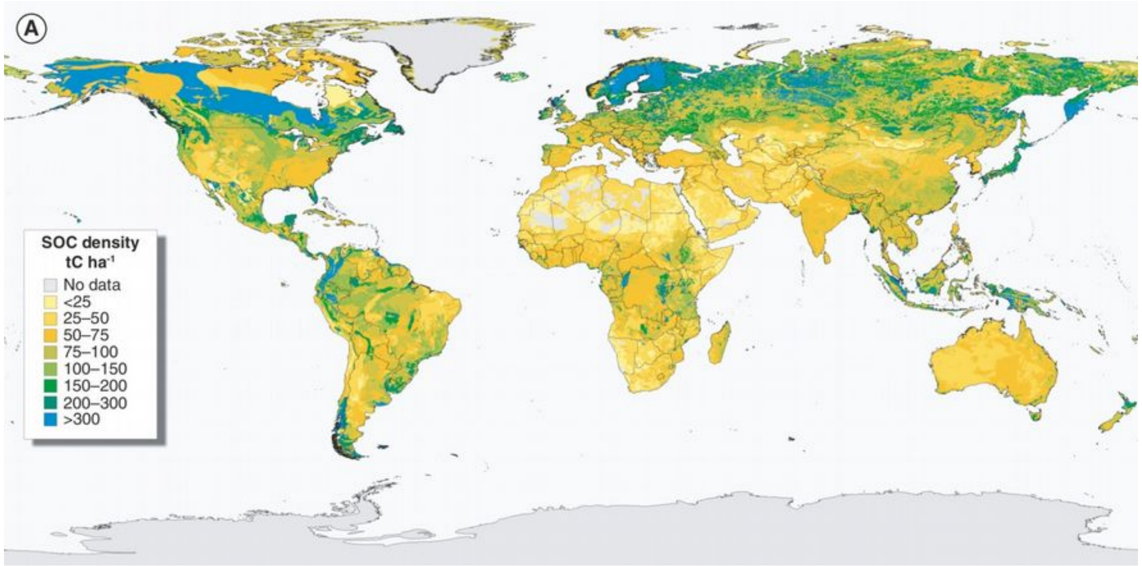
Simulating the carbon, water, energy budgets and greenhouse gas emissions of arctic soils with the ISBA land surface model

X. Morel – B. Decharme – C. Delire

Toulouse – February 27th – 1st March 2017

Soil organic carbon and permafrost

Latitudunal localisation of permafrost soils *[Schuur et al., 2008]*



Soil organic carbon density – mean over the first meter *[Scharlemann et al., 2014]*

Permafrost : subsurface soil layer, frozen for at least two consecutive years

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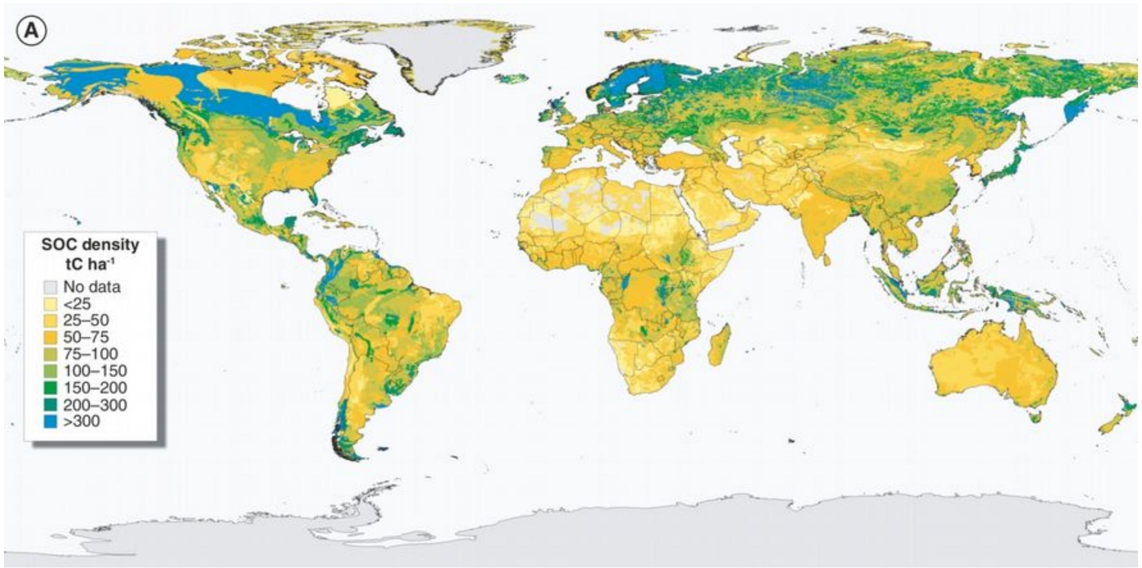

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<u>Permafrost :</u> subsurface soil layer, frozen for at least two consecutive years

- 1672 Gt of organic carbon [Tarnocai et al., 2009], i.e. 50 % of total subterranean stock
- located on 18,782 × 10^3 km^2, i.e. 16 % of earth soil surface

➡ Big pool of old organic matter, subject to microbial decomposition ...

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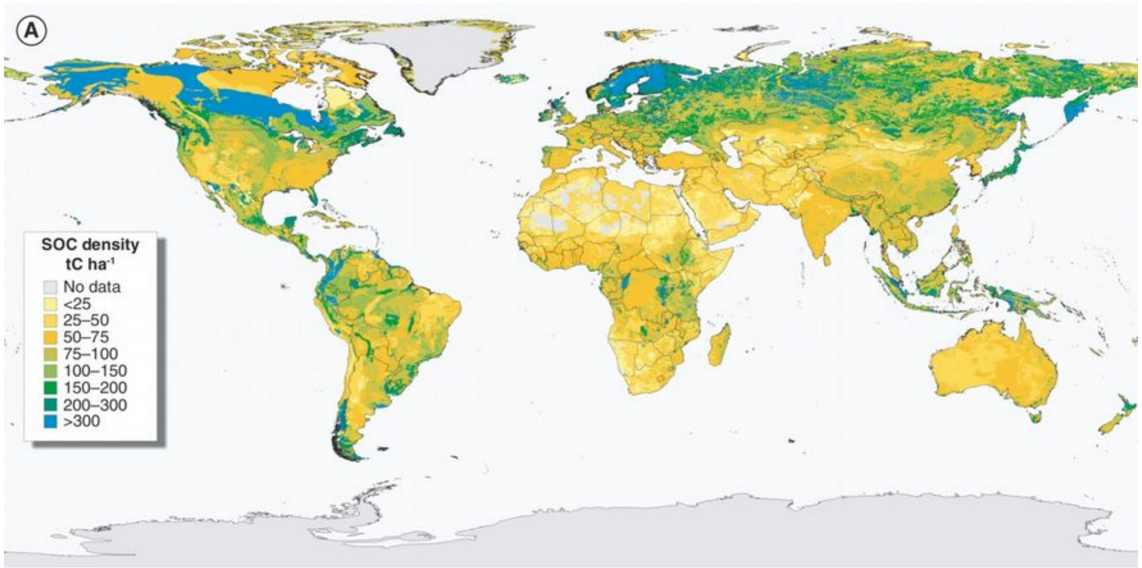

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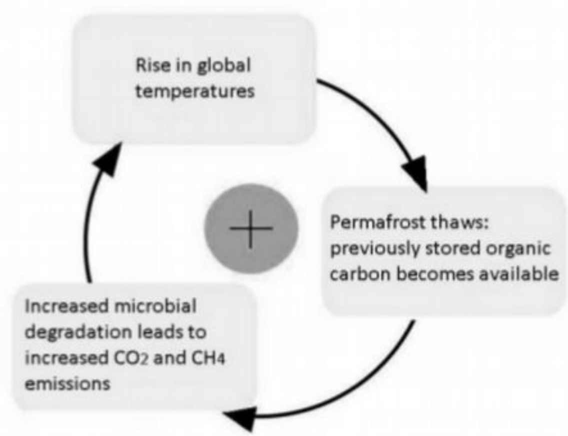
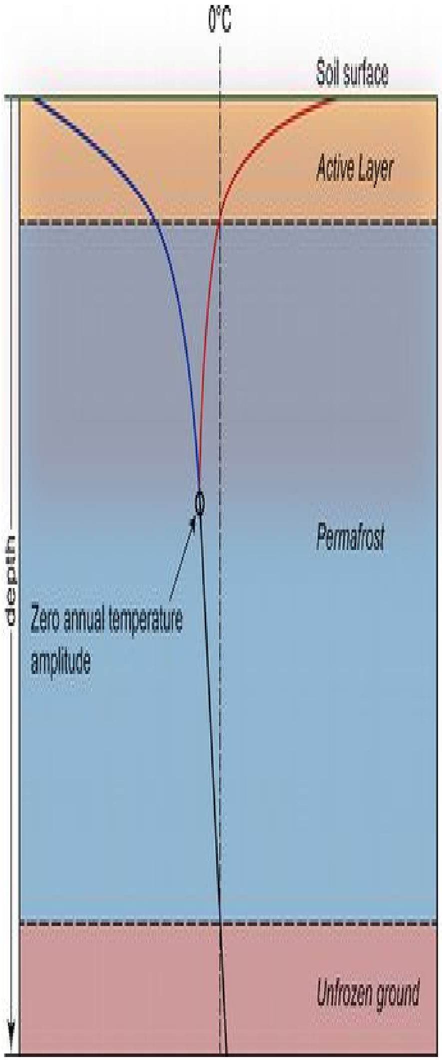


➡ Big pool of old organic matter, subject to microbial decomposition ...

… and critical in a climate change context.

Biogeochemical processes and greenhouse gas emissions in permafrost soils



Cross-section of a typical permafrost profile

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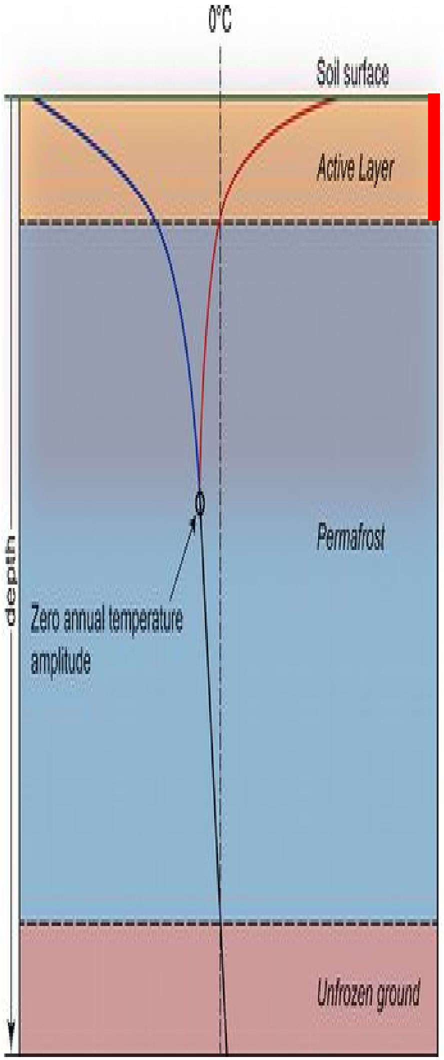

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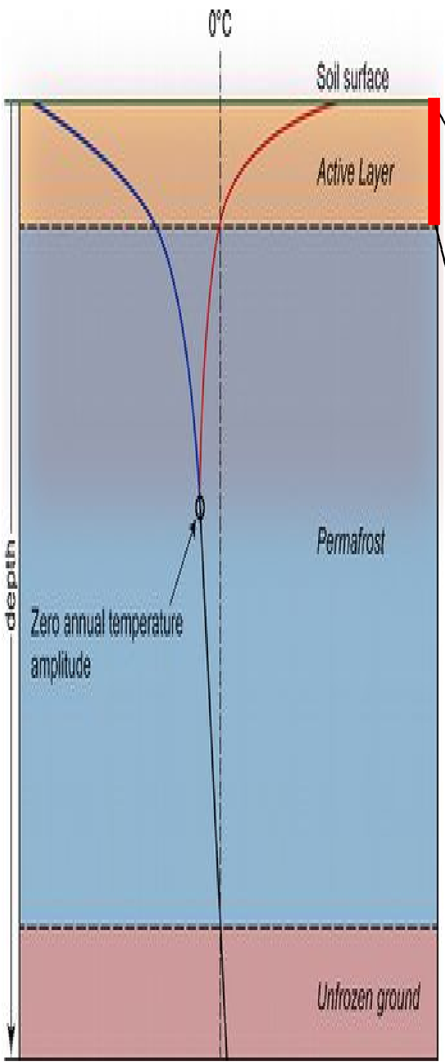

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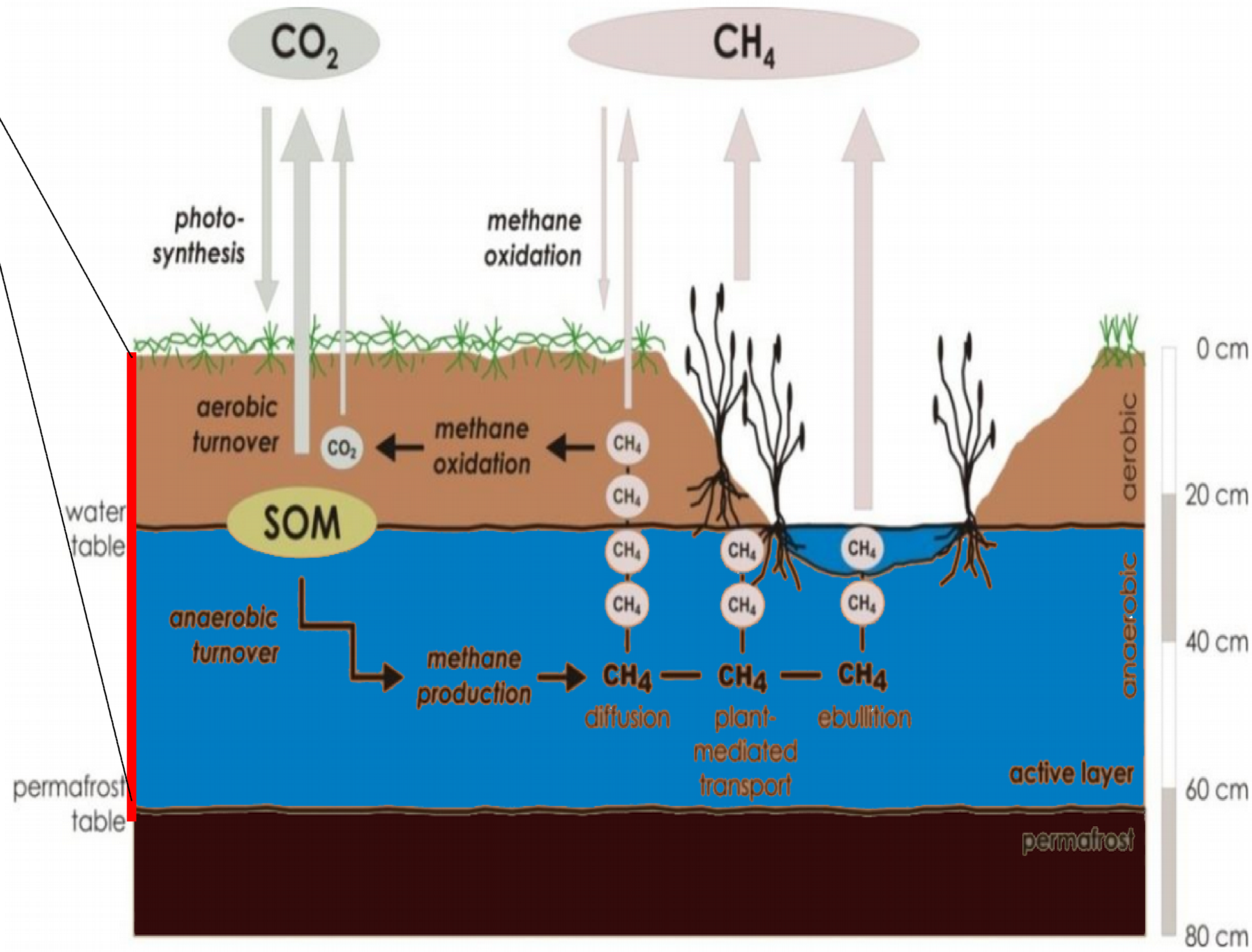
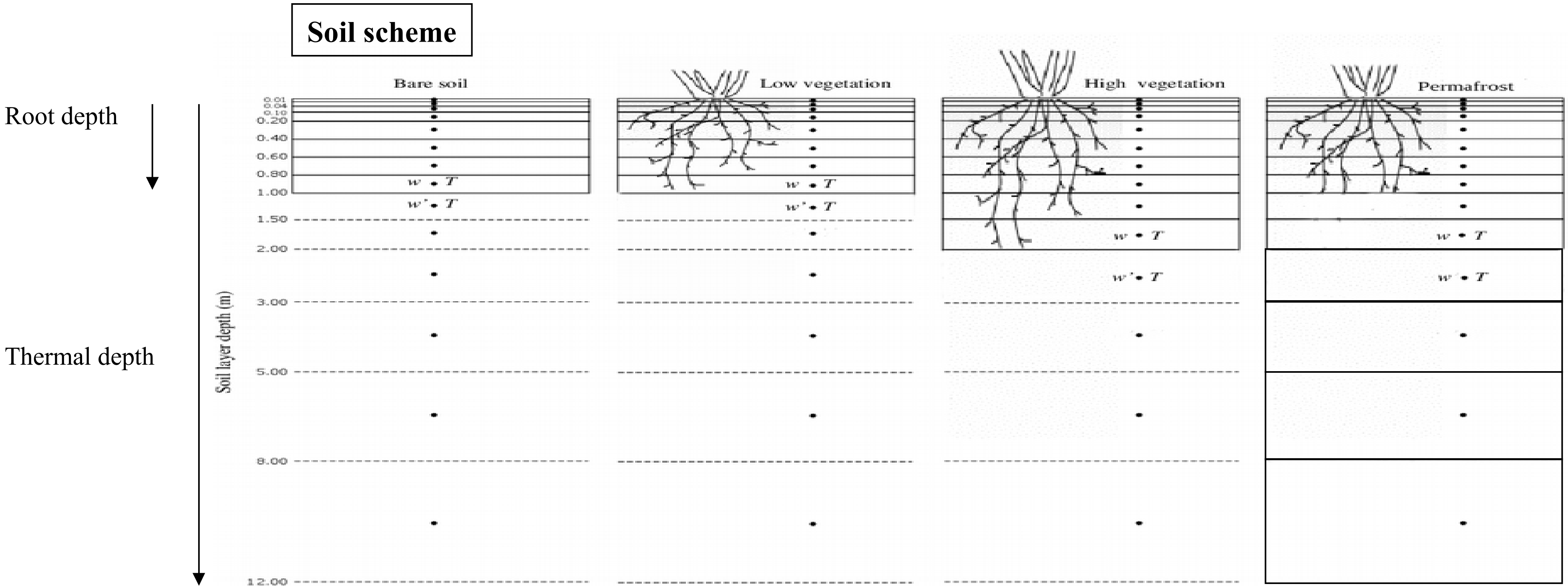


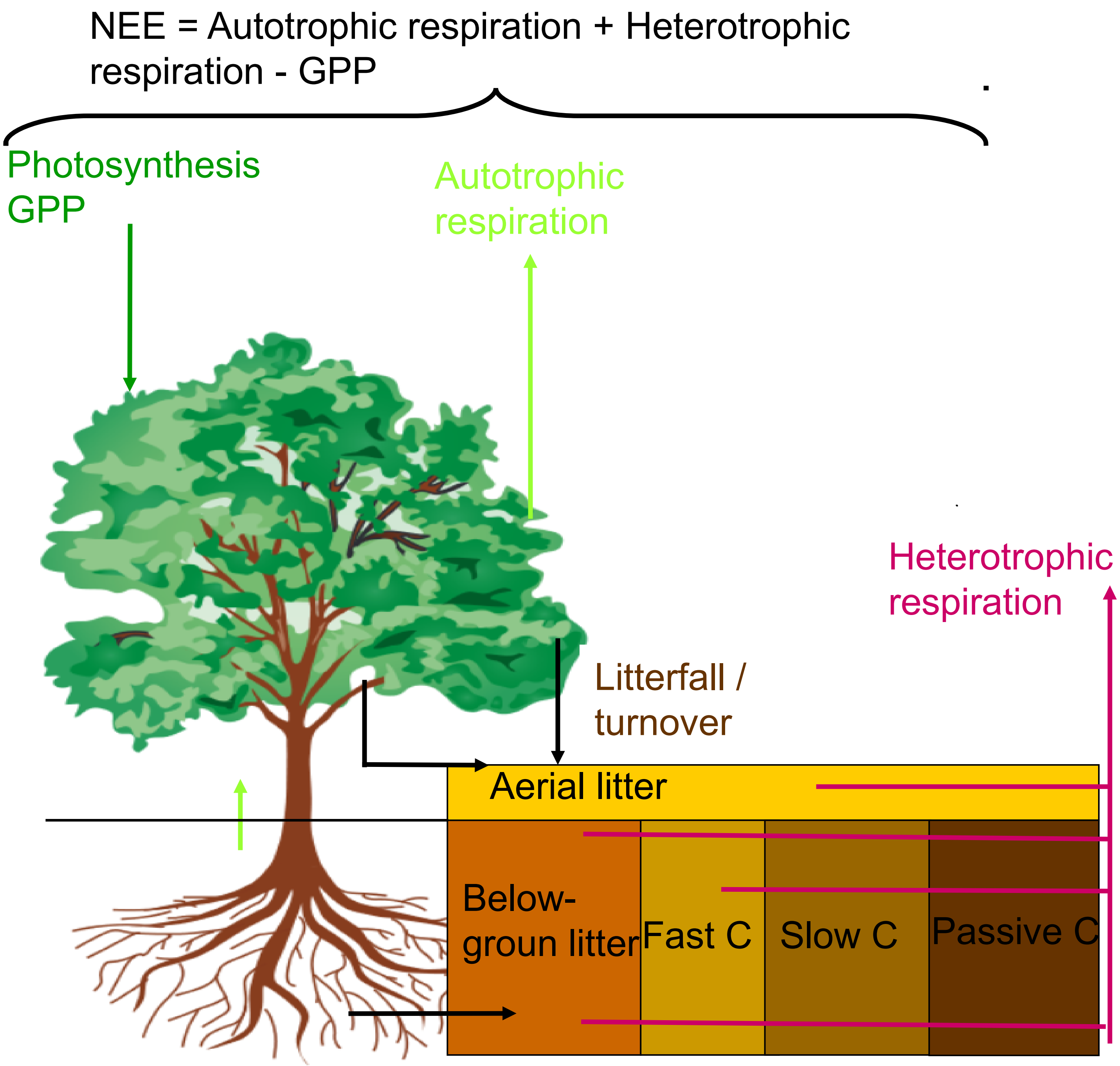
SURFEX (ISBA) Explicit Soil Configuration

- 14 soil layers, with a 12m “thermical” depth (Fourier Law)
- “Hydrological” depth (soil+roots), depending on the Plant-Functional Type. (1.5m for grassland, 12m for permafrost)
- 12 snow layers, explicit scheme



(Decharme et al. 2013, JGR)

CENTURY Soil organic matter model (Parton et al., 1987)



- Simulate soil carbon dynamic

- CENTURY : single-layer carbon model

- Non consistent with
  - ISBA resolution
  - process complexity

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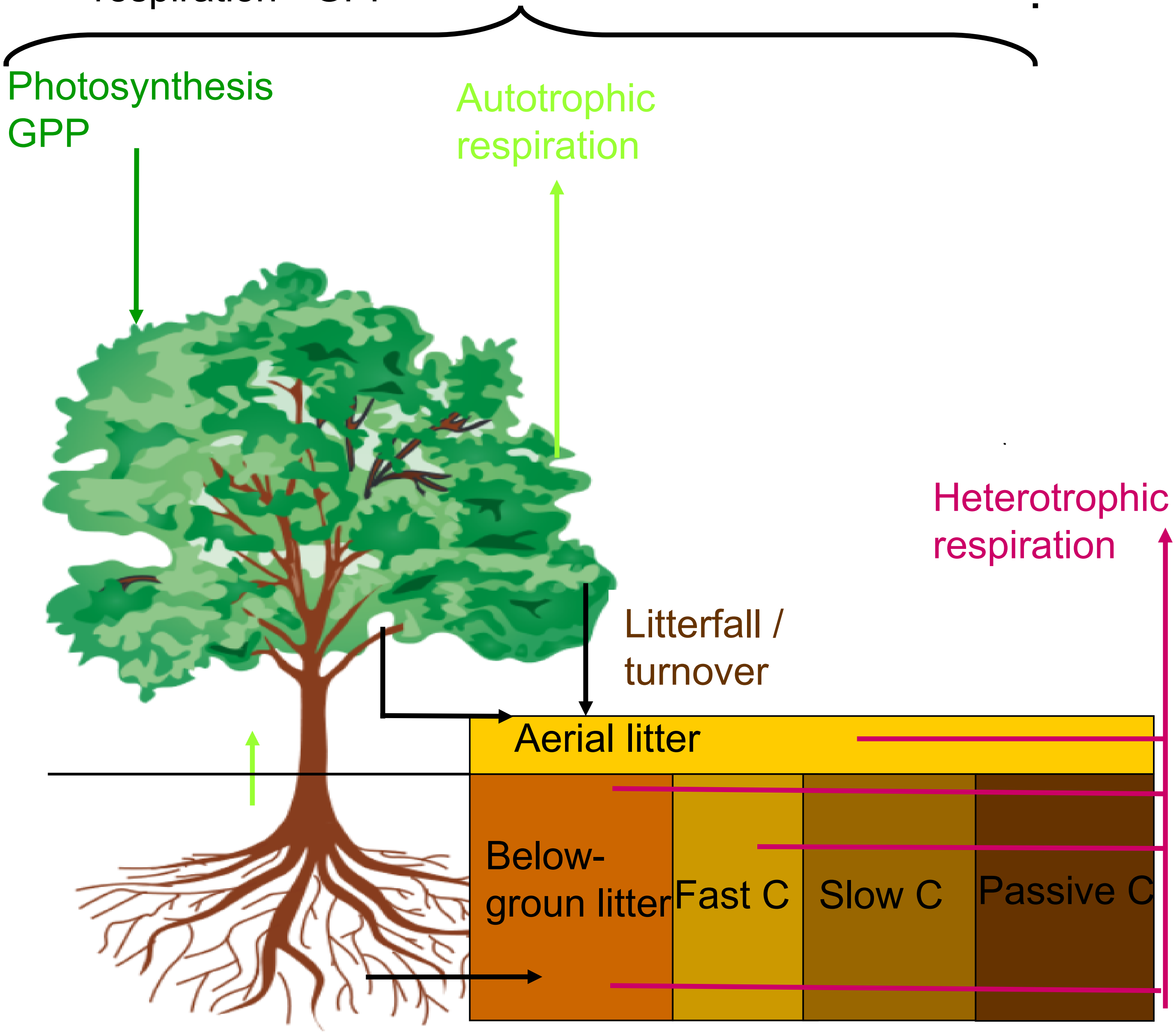
NEE = Autotrophic respiration + Heterotrophic respiration - GPP



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<u>Intermediate step :</u>
Unify hydrology, thermic and soil carbon
=> Discretize soil carbon at ISBA nodes

Soil carbon discretisation

For a carbon pool C_i

$$\frac{\partial C_i}{\partial t} = S_i + \sum_{j \neq i} (1 - r_j) f_{ji} \kappa_j C_j - \kappa_i C_i$$

Input from vegetation — Input from other pools — Oxic decomposition

r_j : respired fraction
f_{ij} fraction of j^{th} pool going to i^{th} pool
k_i : time constant + environment rate modifier (moisture, temperature)

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Discrétisation

$$\frac{\partial C_i(z)}{\partial t} = S_i(z) + \sum_{j \neq i} (1 - r_j) f_{ji} \kappa_j(z) C_j(z) - \kappa_i(z) C_i(z) + \frac{\partial}{\partial z}\left[D(z) \frac{\partial C_i(z)}{\partial z} \right]$$

cryoturbation

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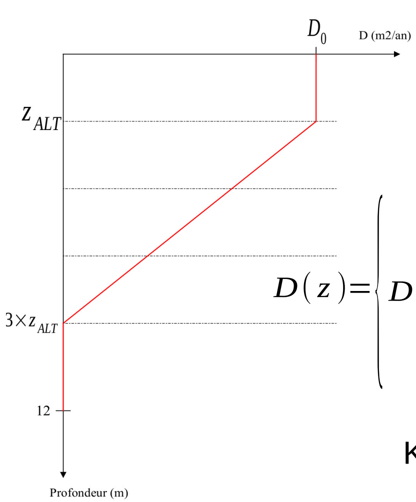
- $\frac{\partial}{\partial z}\left[D(z) \frac{\partial C_i(z)}{\partial z} \right]$: cryoturbation



$$D(z) = \begin{cases} D_0 & z \leq z_{ALT} \\ D_0 \left(1 - \frac{z - z_{ALT}}{2 \times z_{ALT}} \right) & z_{ALT} \leq z \leq 3 \times z_{ALT} \\ 0 & z \geq 3 z_{ALT} \end{cases}$$

Koven et al, 2009

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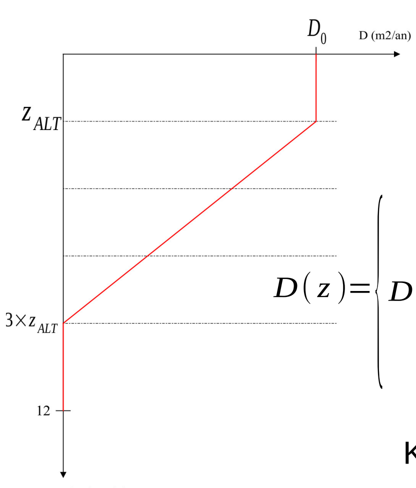

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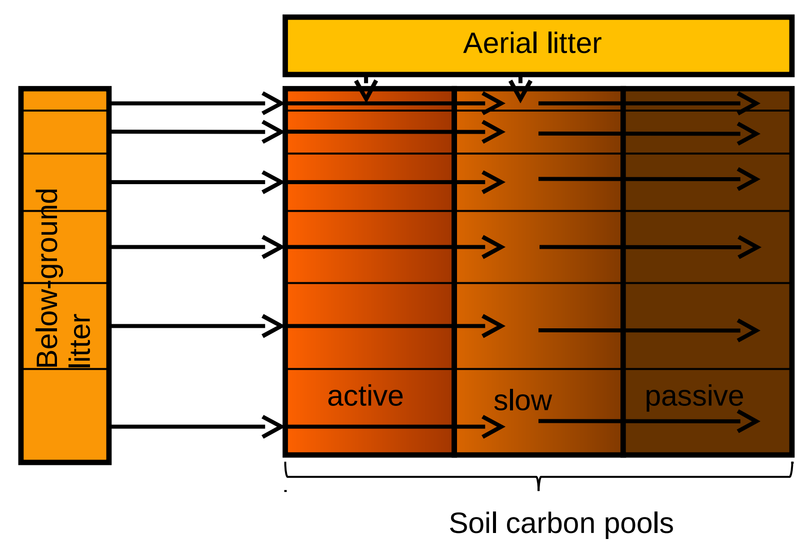

Soil gas governing equations

Soil CO2 equations

$$\frac{\partial \epsilon_{CO_2}(z,t) CO_2(z,t)}{\partial t} = \frac{\partial}{\partial z}\left[\widetilde{D_{CO_2}}(z,t)\frac{\partial CH_4(z,t)}{\partial z}\right] + F_{oxic}(z,t) + F_{MT}(z,t)\frac{M_{CO_2}}{M_{CH_4}}\frac{\epsilon_{CO_2}}{\epsilon_{CH_4}}$$

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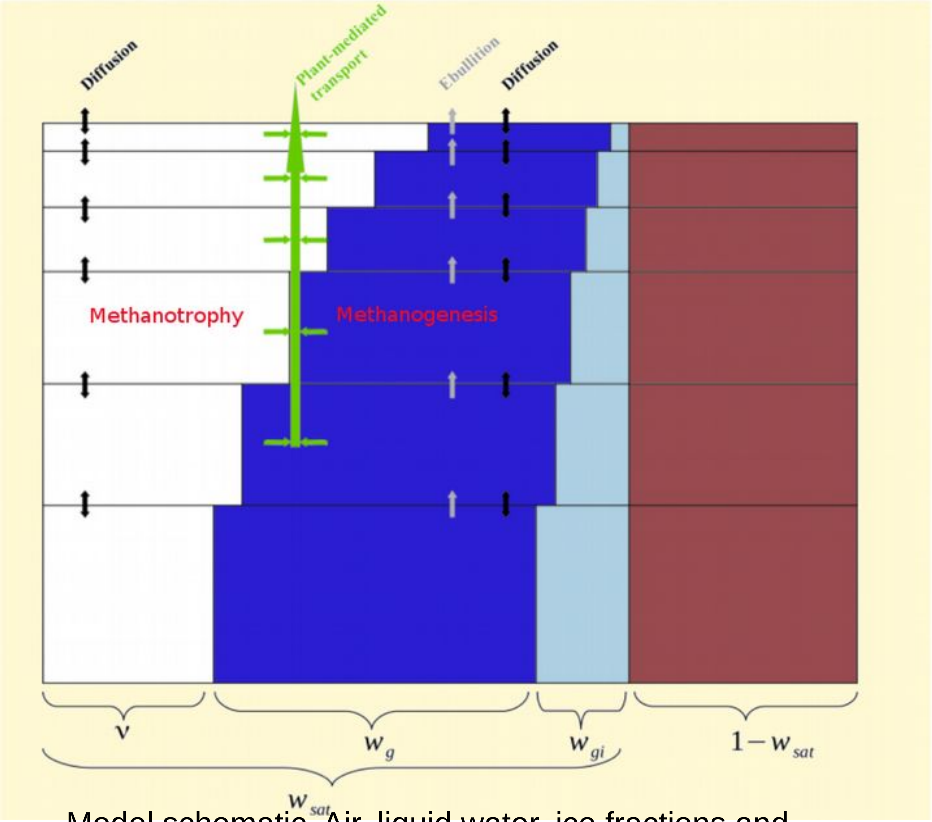

Model schematic. Air, liquid water, ice fractions and soil porosity are respectively v, w_g, w_{gi} and w_{sat}

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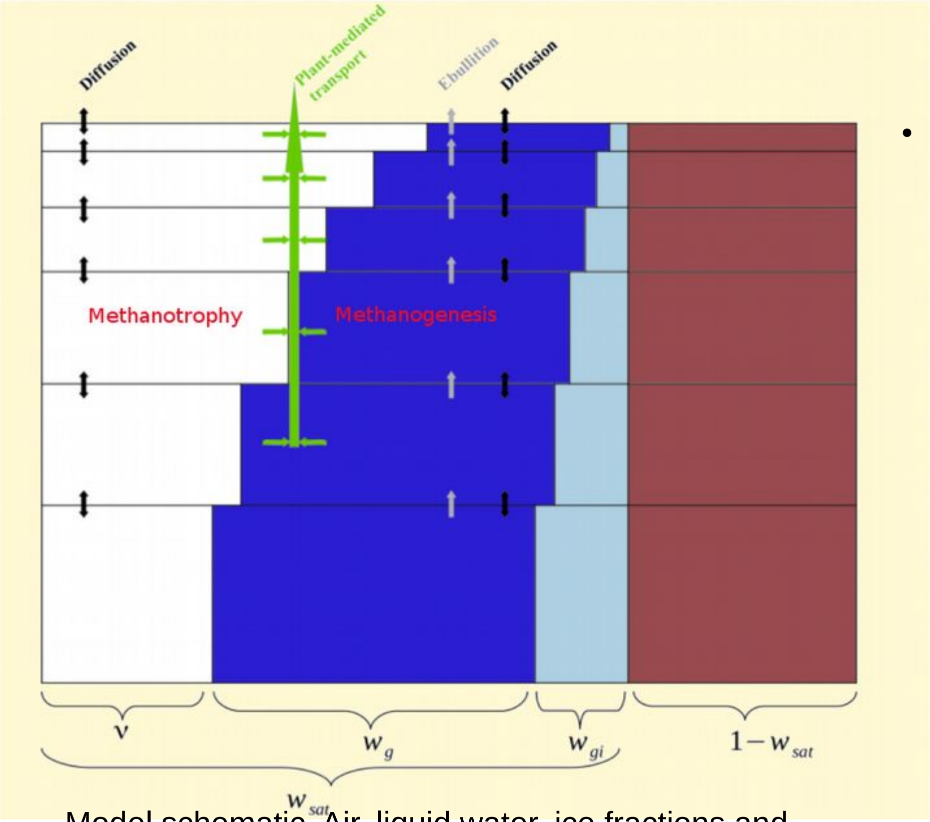

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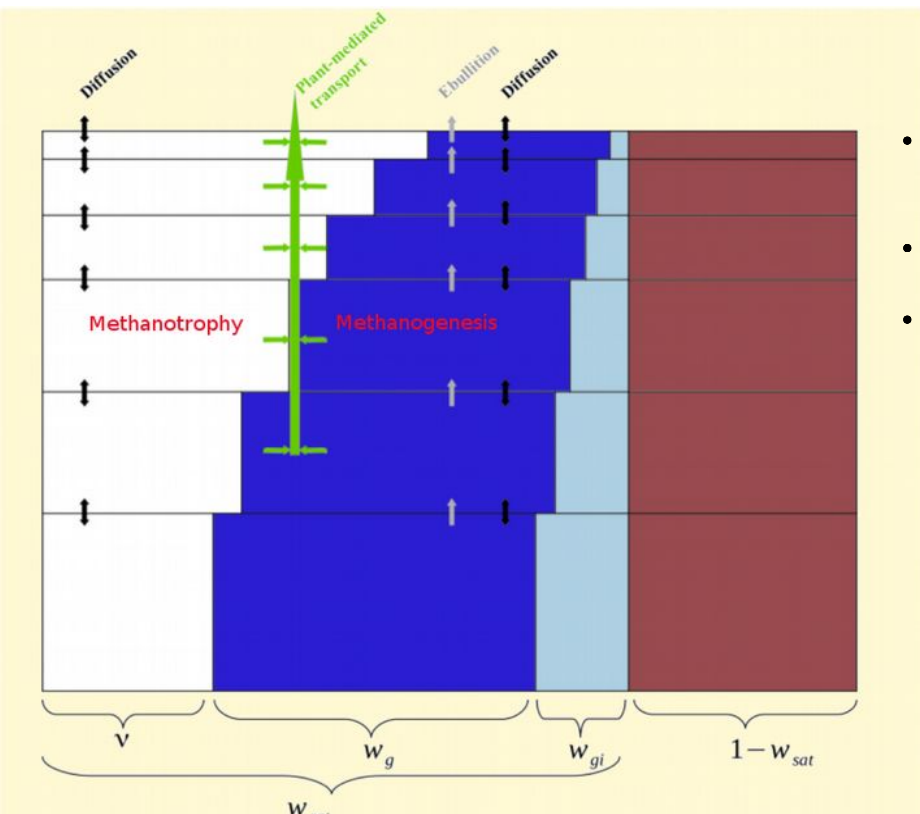

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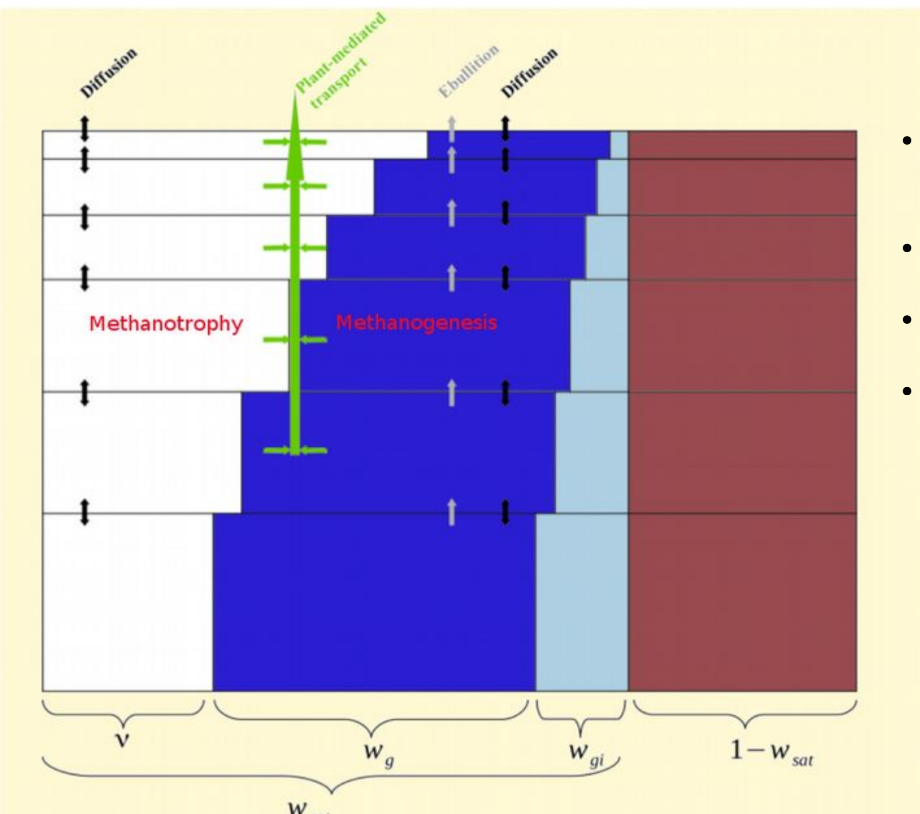

Model schematic. Air, liquid water, ice fractions and soil porosity are respectively v, w_g, w_{gi} and w_{sat}

- Each layer is fractioned between saturated and unsaturated pores
- Methanogenesis in liquid fraction
- Methanotrophy in air-filled pores
- Three pathways for methane :
  - Diffusion (water and air)
  - Ebullition (water)
  - Plant-mediated transport (water and air)

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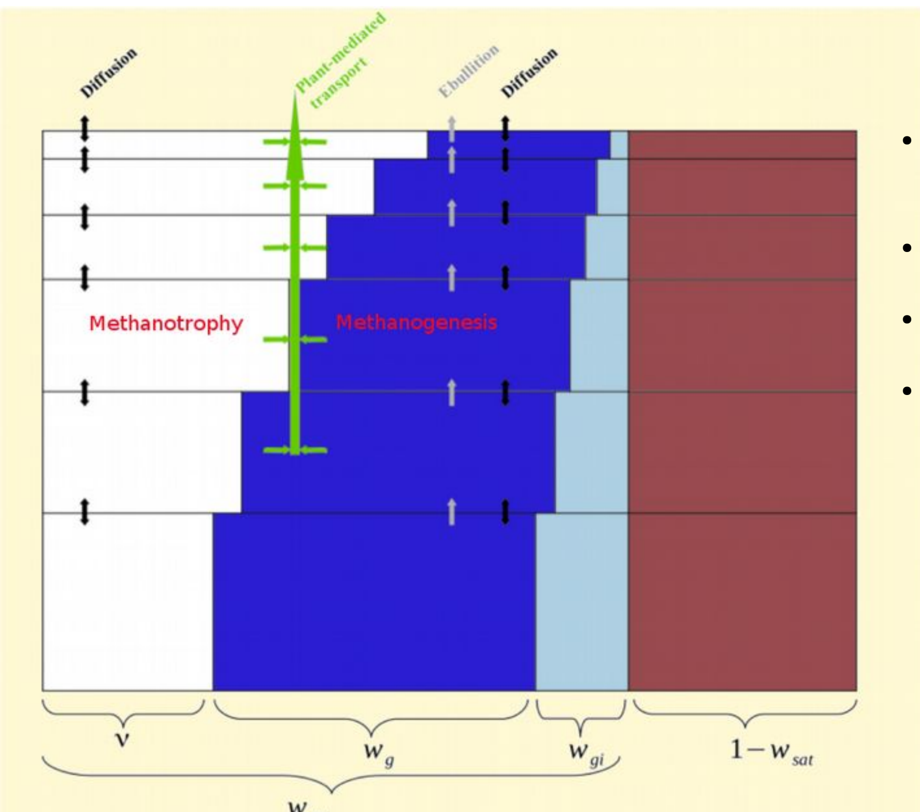

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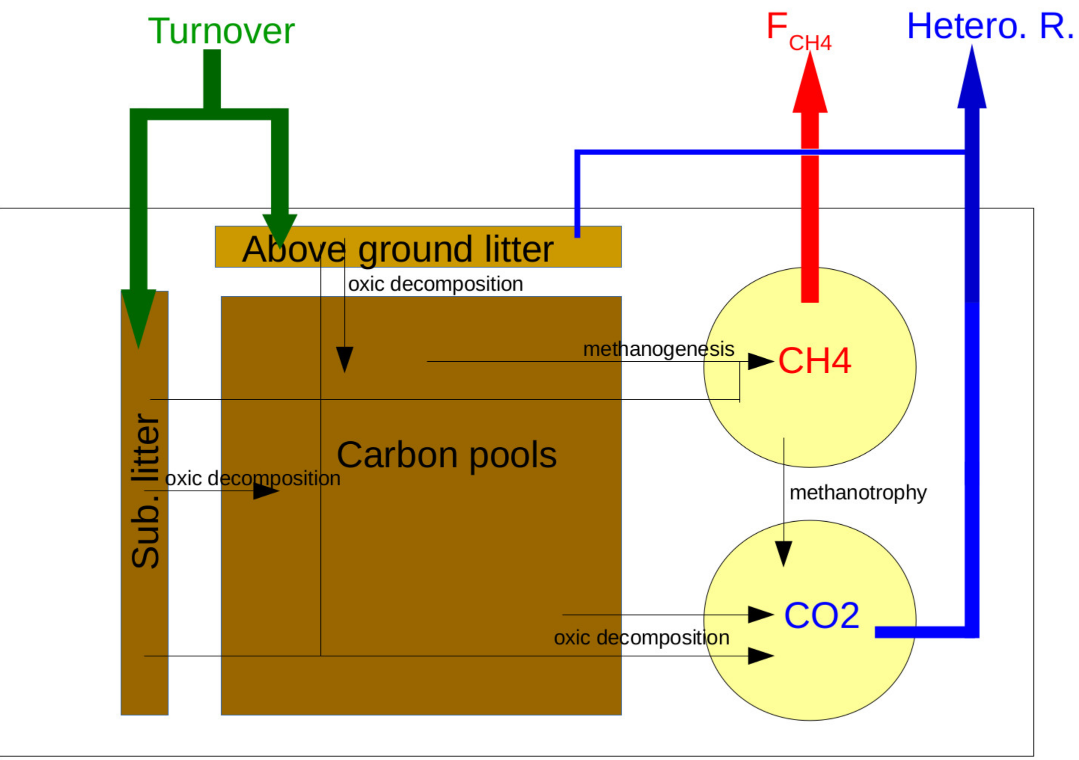
- All processes are treated in parallel, and not in a sequential way.

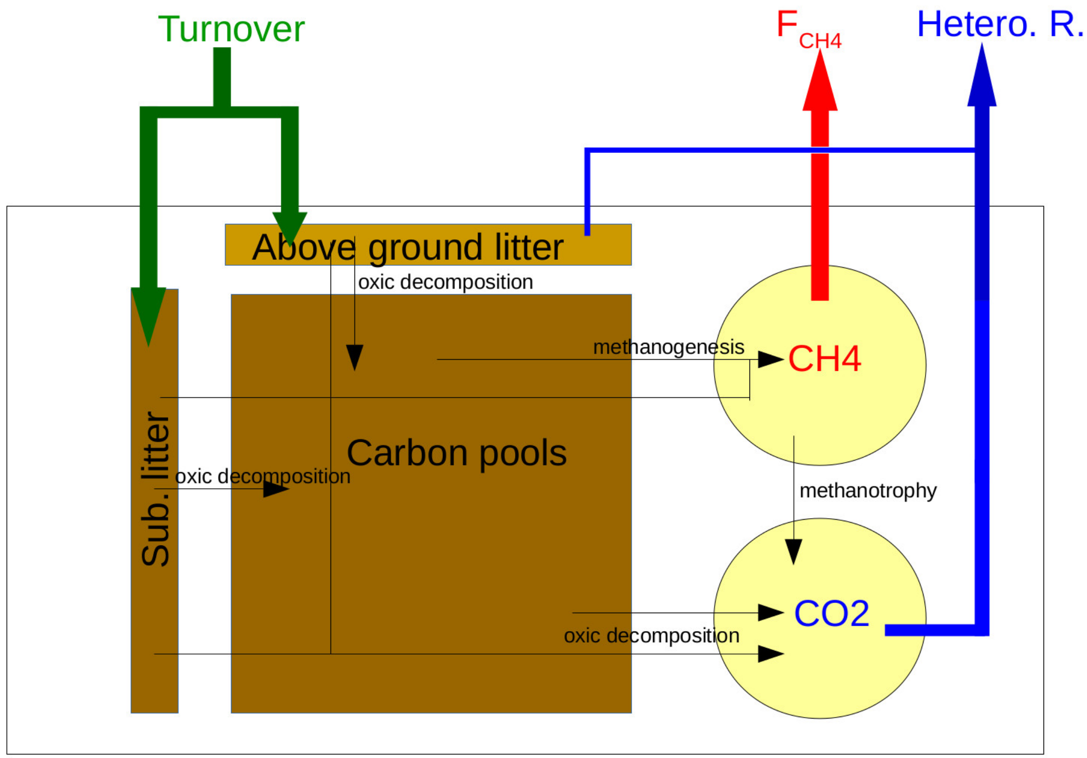
Carbon budget closure



Schematic of model soil carbon pools and fluxes between them.
All pools are vertically discretized (not shown here, for simplicity)

Carbon budget closure

$$BUDGET = \Delta CH_4 + \Delta CO_2 + \Delta Litter + \Delta Carbon - Turnover + R_{hetero} + F_{CH4}$$



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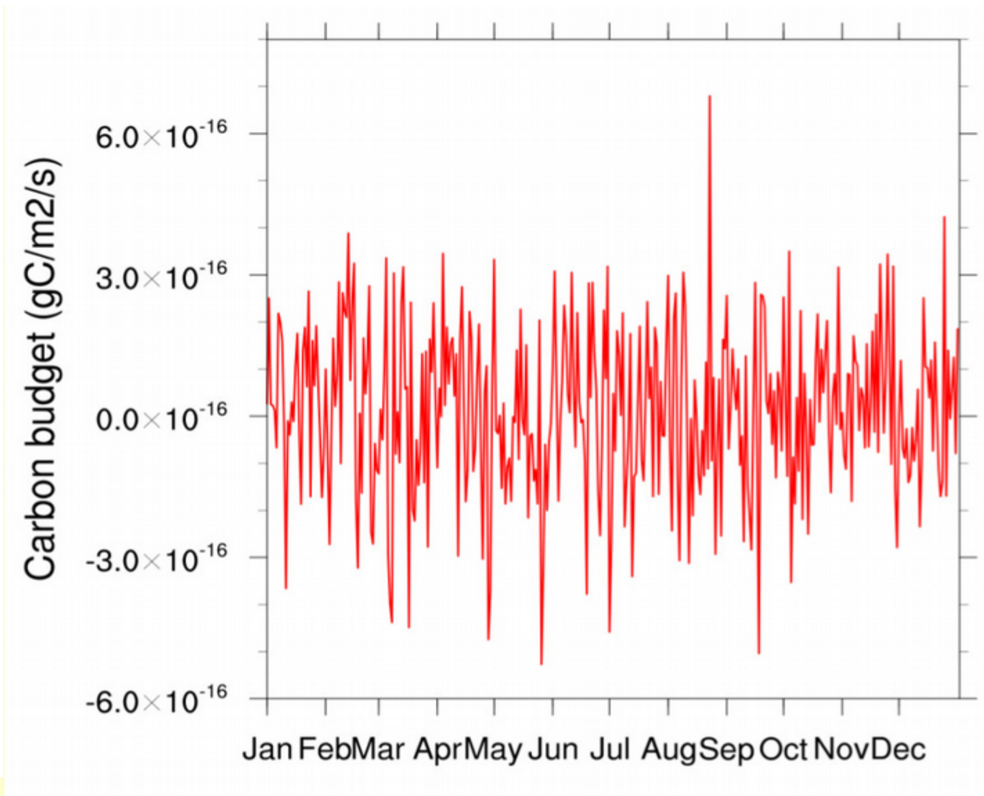
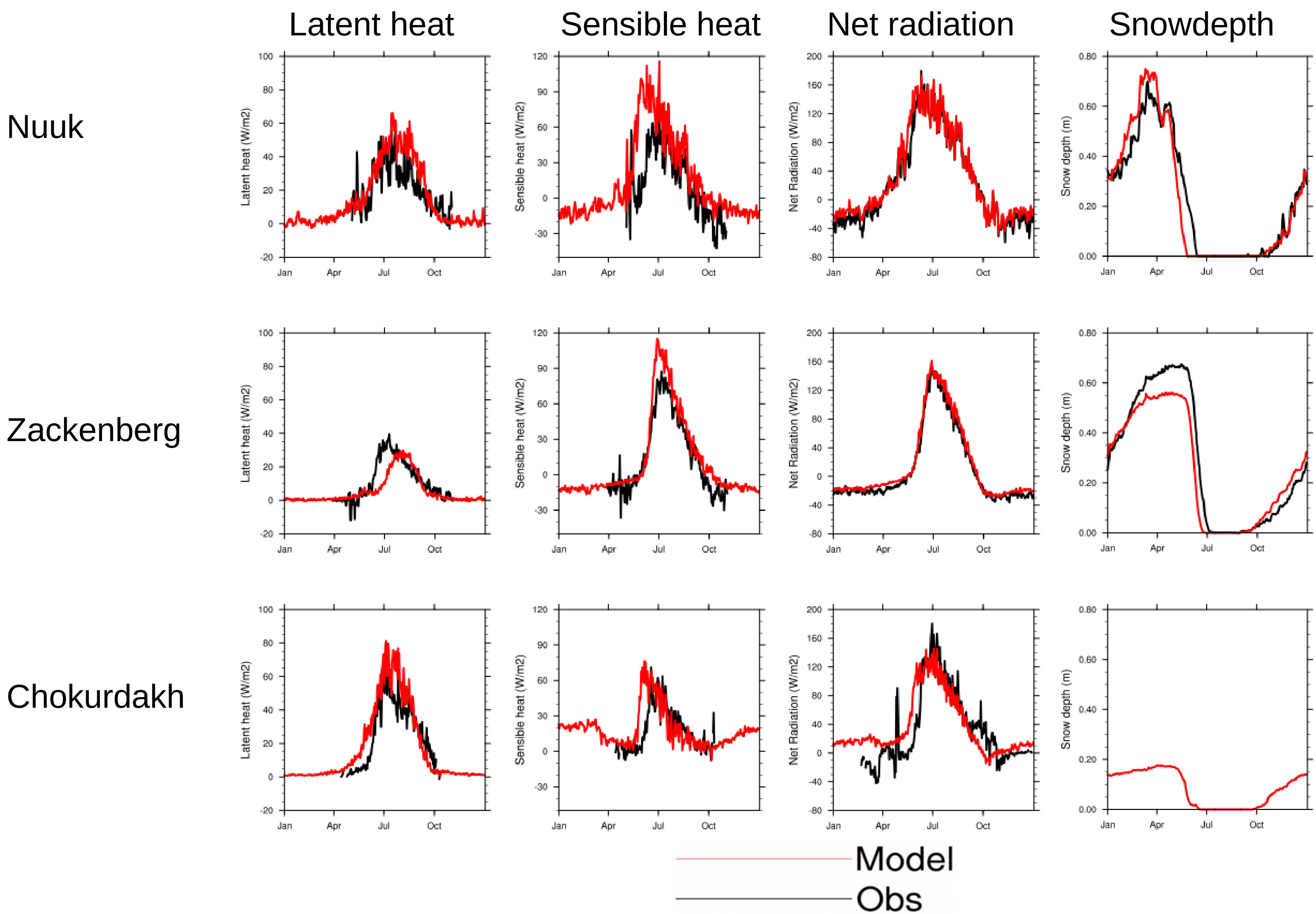


Simulations SURFEX and site validation

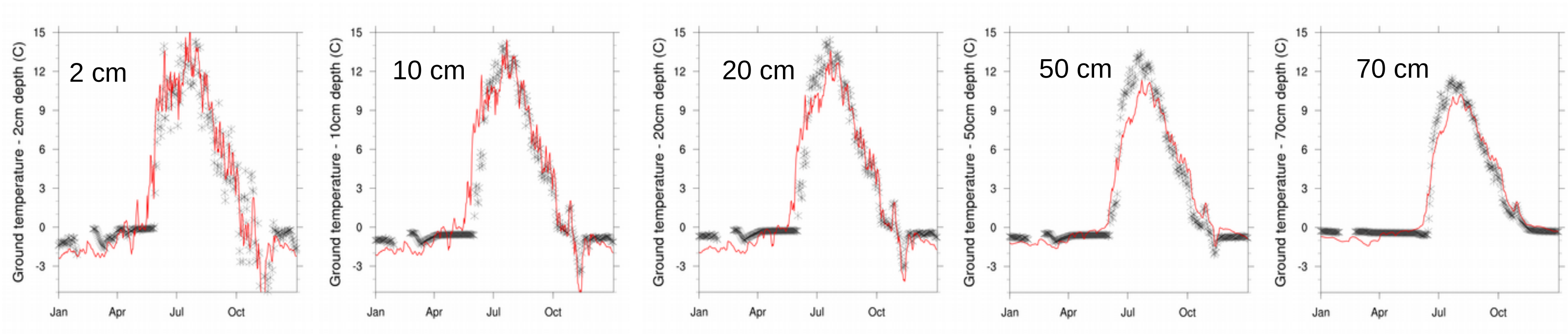
	Nuuk	Zackenberg	Chokurdakh
Lon - Lat	51.3°W, 66.1°N	21°00' W, 74°30'N	147.49°W, 70.82°N
Permafrost	No (Wetland)	Yes	Yes
Spin-up	1500 years	1500 years	1500 years
Soil parameters (clay, sand, organic matter content, ...)	Litterature (annual reports)	Personal communication (J. Palmtag)	Litterature
Data Range	2009-2014	1996-2014	2003-2014
Veg. Type	Boreal grasslands	Boreal grasslands	Boreal grasslands
	Water table forced to 1m		

Mean annual cycles : Radiative + Snowdepth

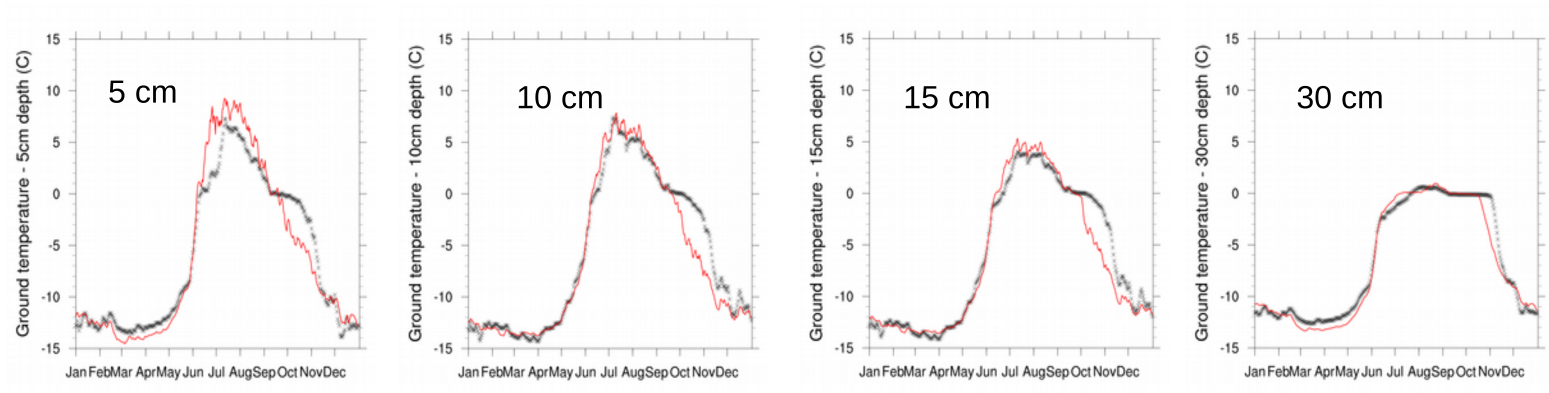


Mean annual cycle : Soil Temperature

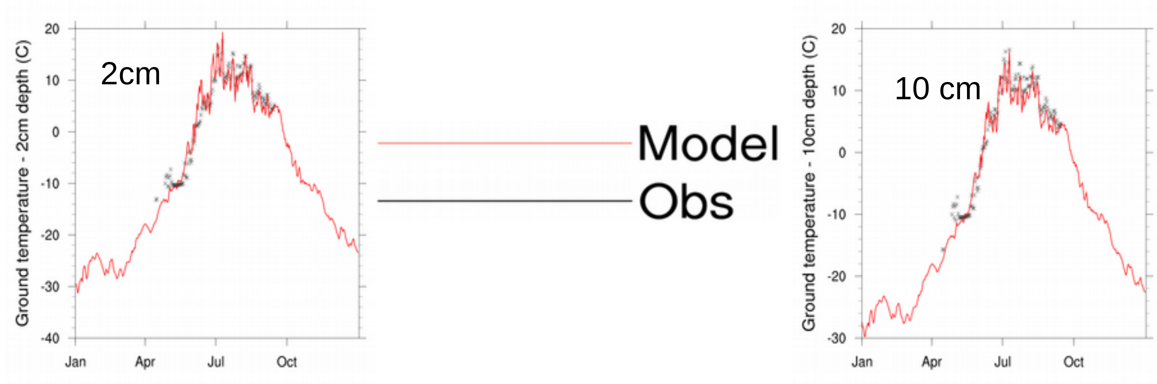
Nuuk



Zackenberg



Chokurdakh



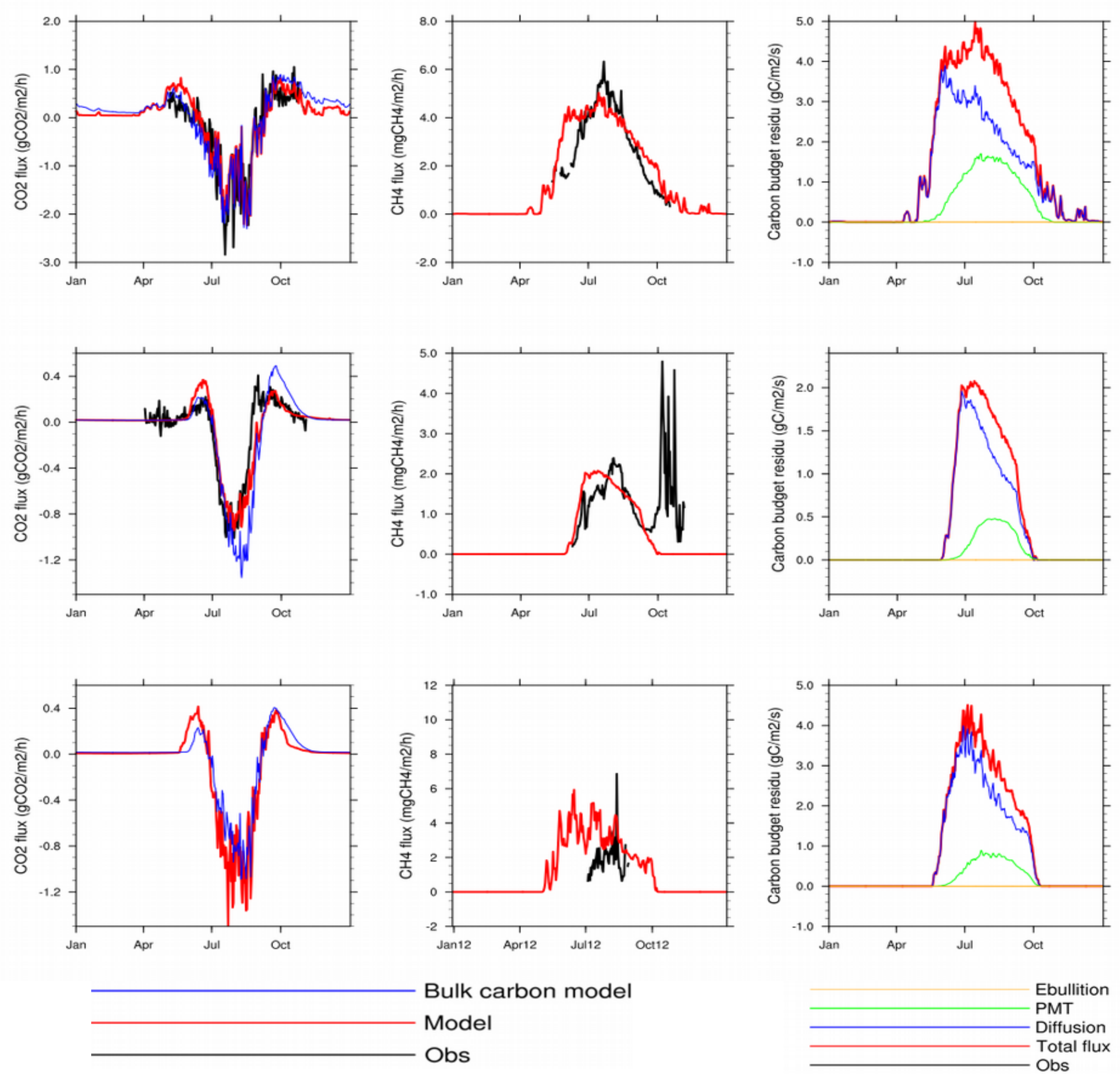
Mean annual cycles : CO2 and methane fluxes

CO2 flux | Methane flux | Splitted methane flux

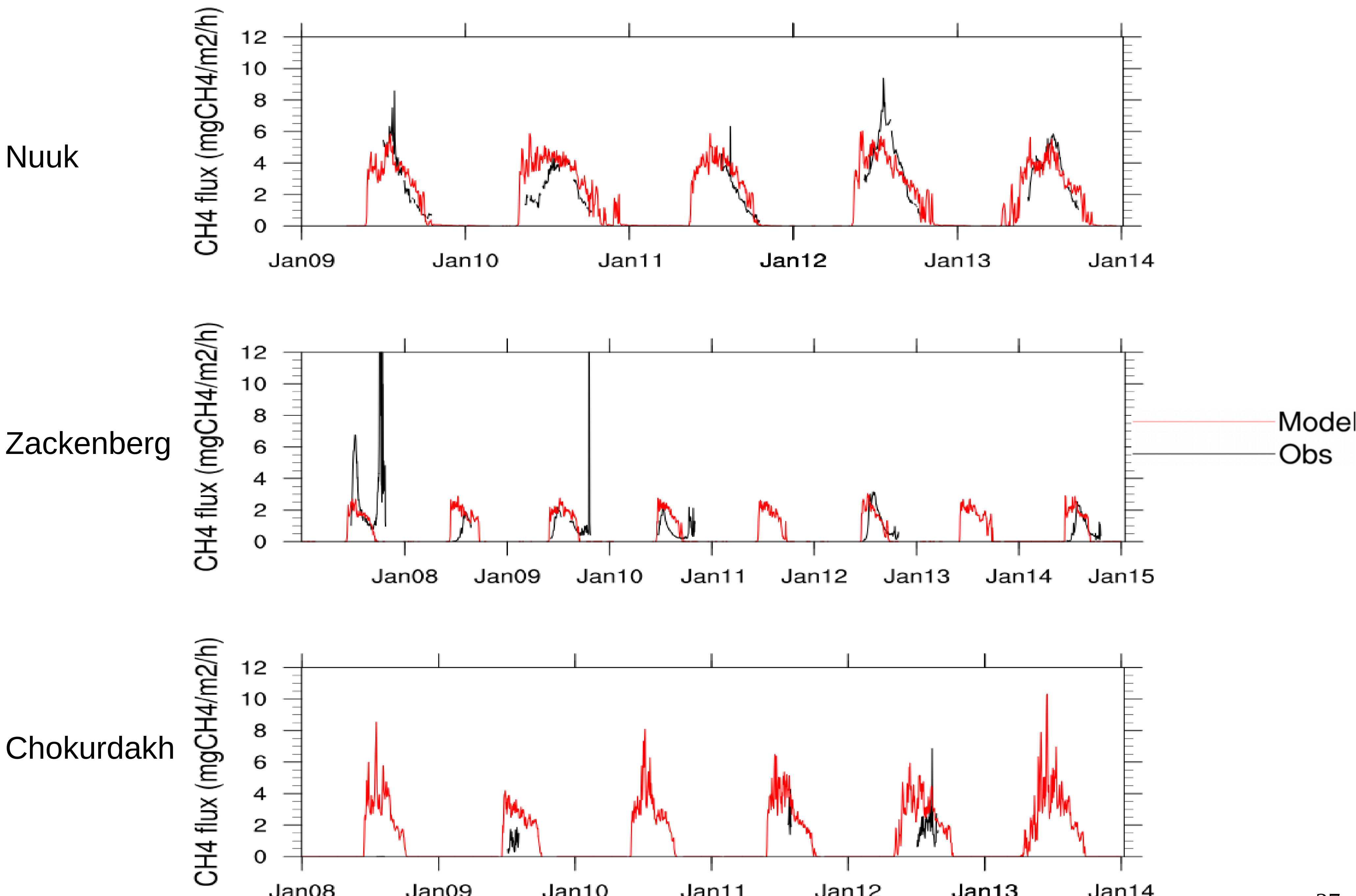
Nuuk

Zackenberg

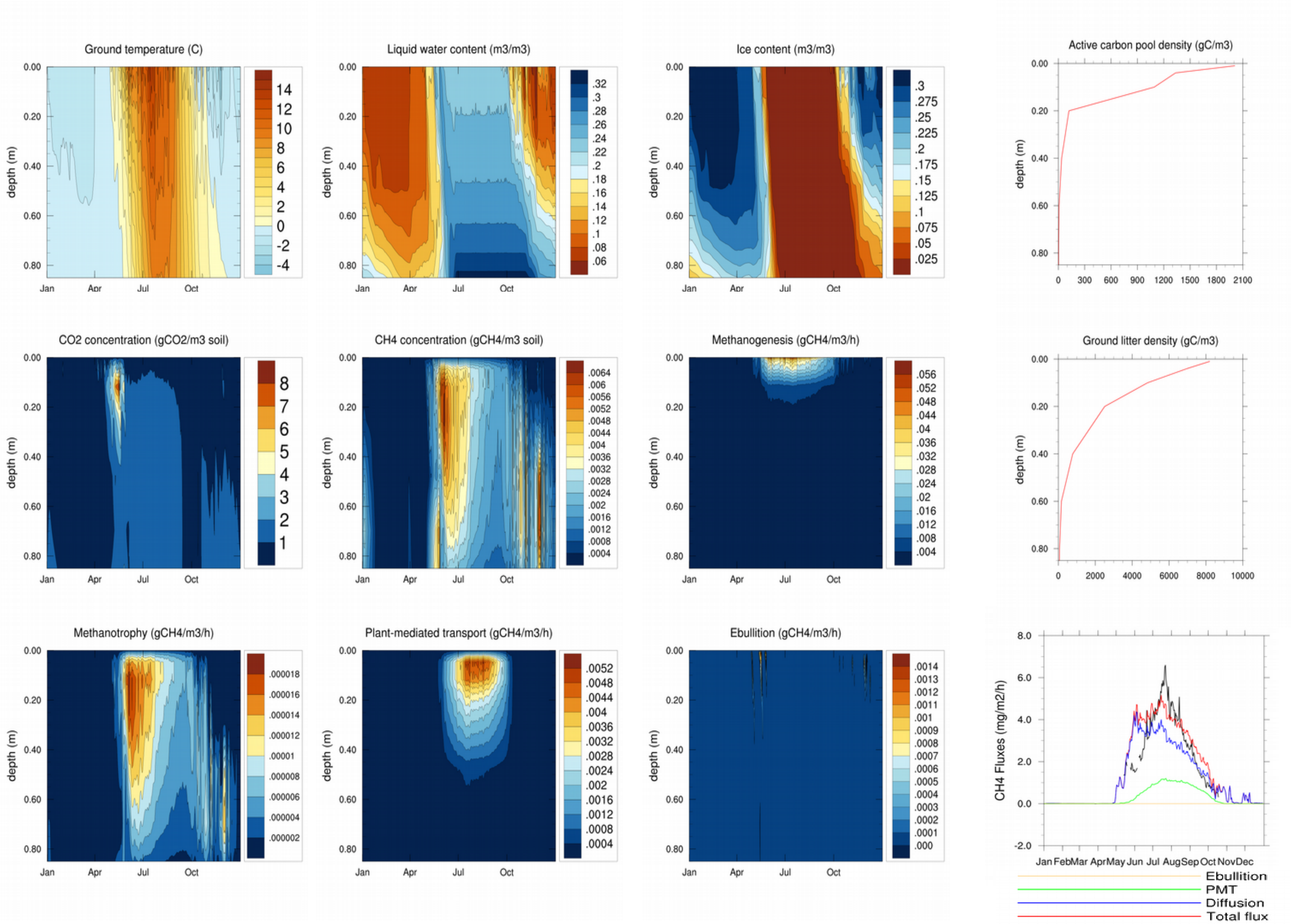
Chokurdakh



Methane fluxes : annual intervariability



Model behaviour : Nuuk



Sensitivity test : impact of surface hydrology

Ebullition occurs, but never in the first layer.
=> Does the model simulate ebullition in saturated/flooded soil condition ? (as observed in the field ?...)

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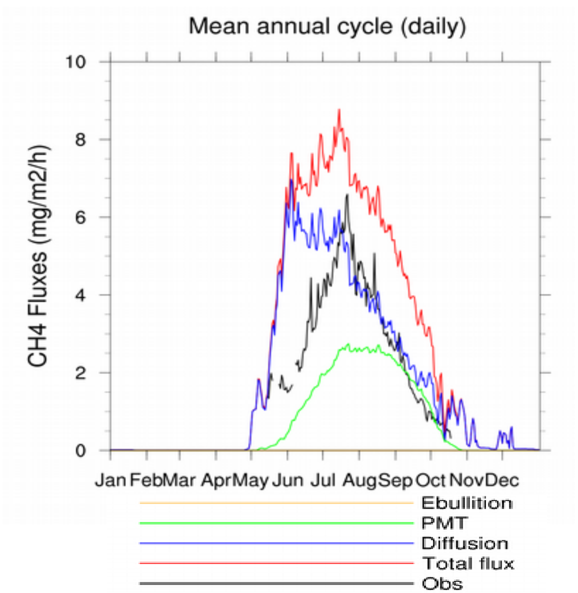

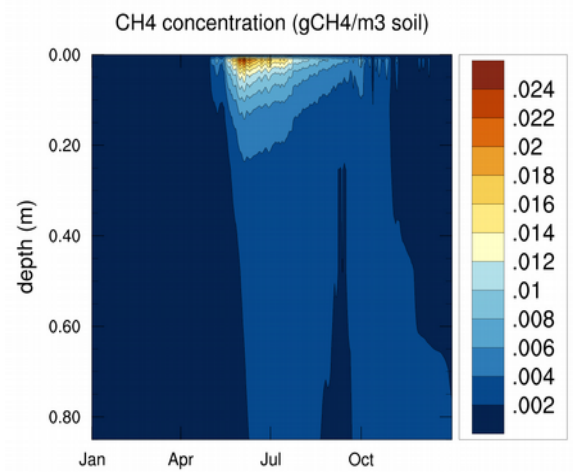

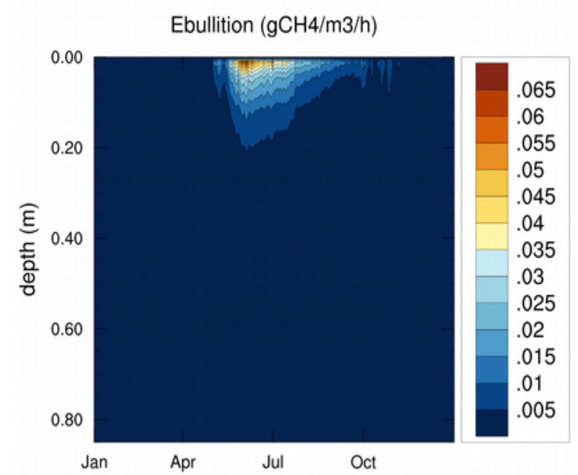

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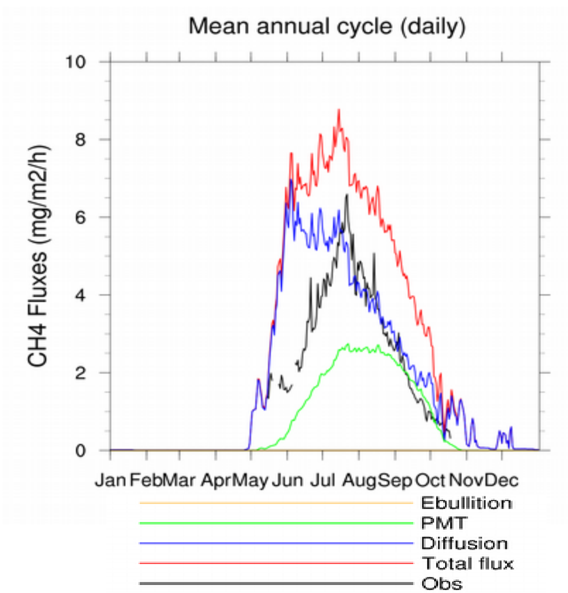
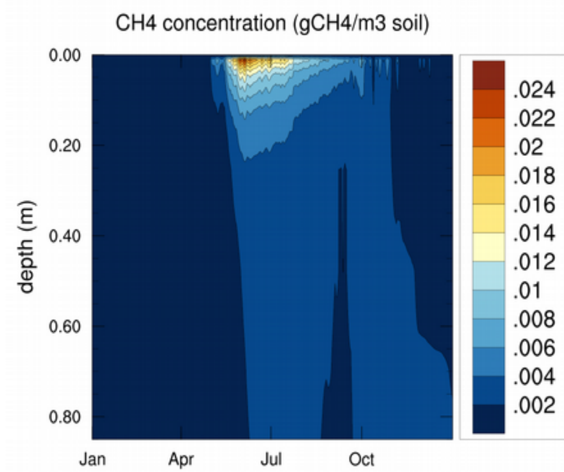
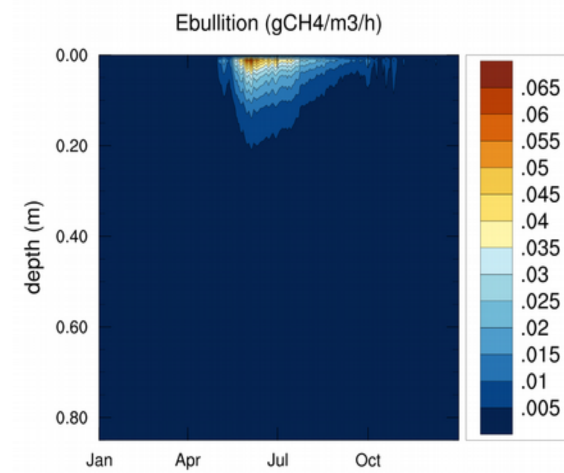
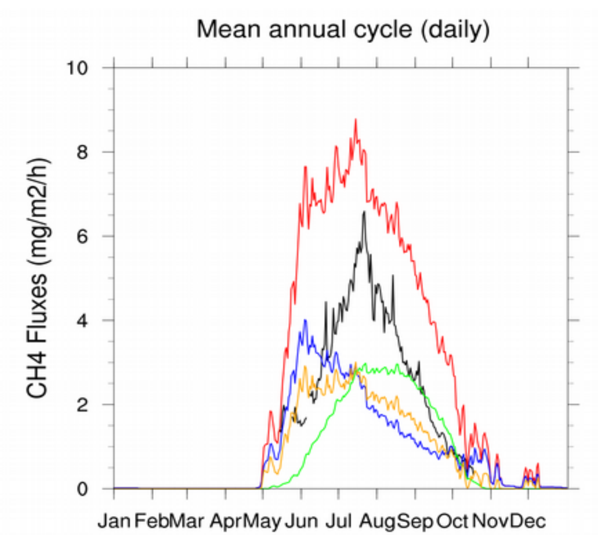


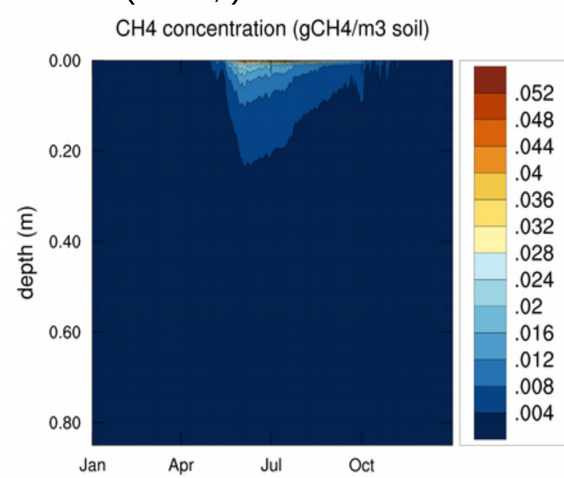


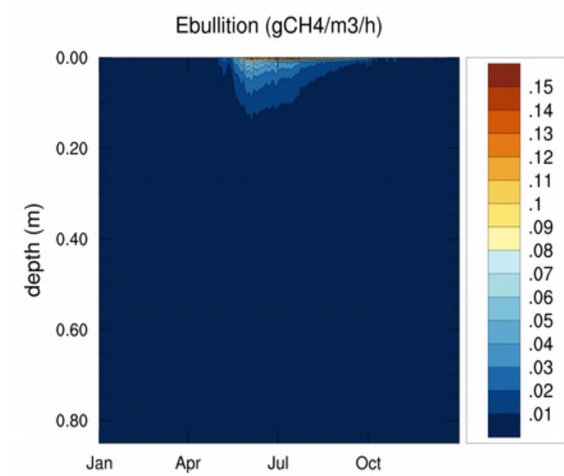


Same parameters than previous simulation, but :
- Wg = Wsat – Wgi (saturated soil column)
- Diffusion coefficient at the interface soil/atmosphere = D(water)
- CH4 (z=0+,t) = 9.4 10E-4 * Bunsen

} flooded

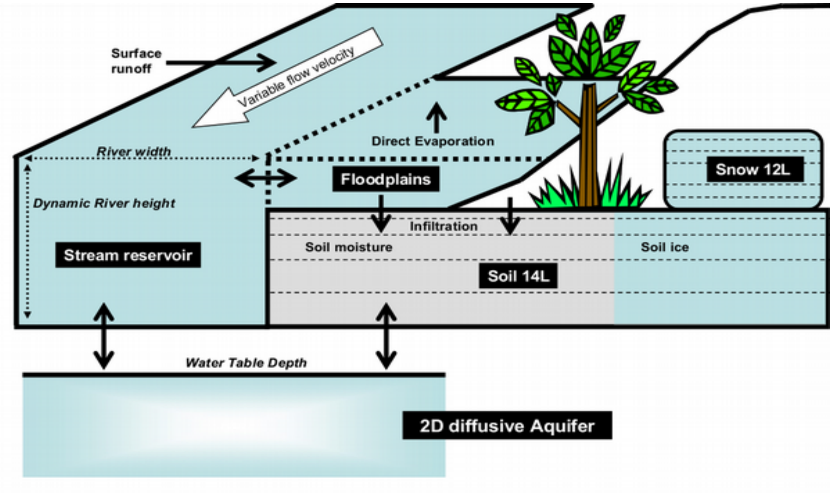






Conclusion and perspectives

- Model development : √
- Site validation : √
- Application to regional/global scale : to do ...
- Hydrology impact :
  - 1D : √
  - 2D : to do ...



Simulating the carbon, water, energy budgets and greenhouse gas emissions of arctic soils with the ISBA land surface model

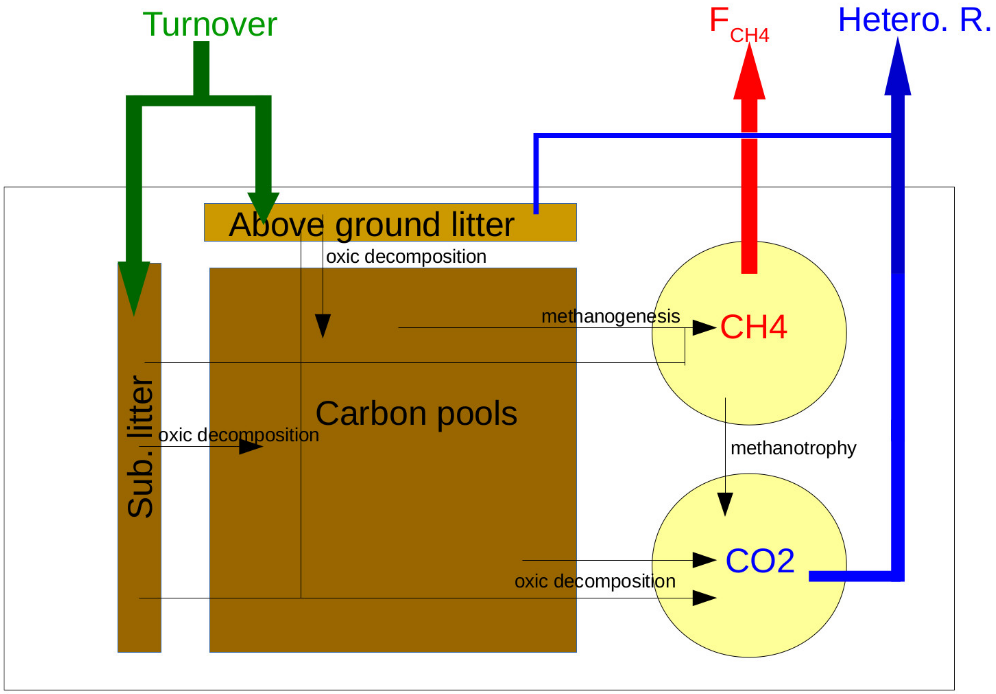
X. Morel – B. Decharme – C. Delire

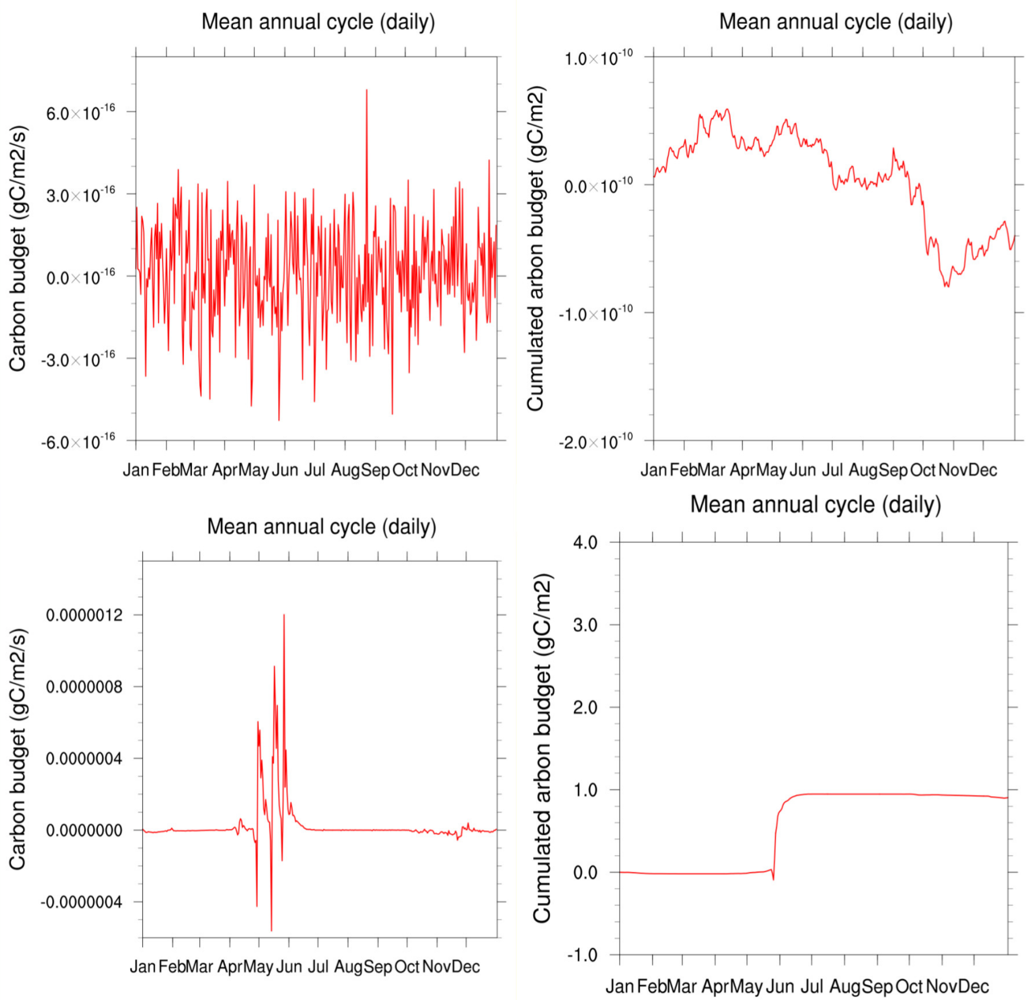
Thank you for your attention !

And now, it is question time !

Carbon budget closure

$$BUDGET = \Delta CH_4 + \Delta CO_2 + \Delta Litter + \Delta Carbon - Turnover + R_{hetero} + F_{CH4}$$





$$\frac{\partial CH_4}{\partial t} = \frac{1}{\epsilon_{CH_4}} \left(\frac{\partial}{\partial z} \left[\widetilde{D_{CH_4}} \frac{\partial CH_4}{\partial z} \right] + F_{MG} - F_{MT} - f_{PMT} + \frac{\partial f_{EBUL}}{\partial z} \right) - \frac{CH_4}{\epsilon_{CH_4}} \frac{\partial \epsilon_{CH_4}}{\partial t}$$

Mean annual cycle (daily) of carbon budget :

- instantaneous (left) and cumulated (right)
- with the term (top) and without (bottom)

ANNEX 1 : Framework for gas calculations within the soil column

For a gas within the soil column X (in our model, X can represent CH_4 or CO_2), let :

$$
\begin{aligned}
X^s(z,t) &= \text{concentration per soil volume } (gX.m_{\text{sol}}^{-3}) \\
X^a(z,t) &= \text{concentration per air volume } (gX.m_{\text{air}}^{-3}) \\
X^e(z,t) &= \text{concentration per liquid water volume } (gX.m_{\text{water}}^{-3}) \\
\nu(z,t) &= \text{volumetric air fraction}(m_{air}^{3}.m_{soil}^{-3}) \\
w_g(z,t) &= \text{volumetric liquid water fraction}(m_{water}^{3}.m_{soil}^{-3}) \\
w_{gi}(z,t) &= \text{volumetric ice fraction}(m_{ice}^{3}.m_{soil}^{-3})
\end{aligned}
$$

We have the following relationship :

$$X^s(z,t) = \nu(z,t)X^a(z,t) + w_g(z,t)X^e(z,t)$$

We suppose that concentrations in air and liquid water are constantly at equilibrium, i.e. :

$$X_e(z,t) = BX_a(z,t)$$

with B the Bunsen coefficient (or Henry's constant) of X. In a first approximation, we consider that the Bunsen is constant.

Introducing the total porosity of element X , defined as $\varepsilon_X(z,t) = \nu(z,t) + Bw_g(z,t)$, we can write :

$$
\begin{aligned}
& X^s(z,t) = \nu(z,t)X^a(z,t) + w_g(z,t)X^e(z,t) \\
\Rightarrow\ & X^s(z,t) = \varepsilon_X(z,t)X^a(z,t) \qquad (1)
\end{aligned}
$$

In a first approach, we look at the simple gas diffusion in the soil, written in terms of X^s and without external source or sink :

$$\frac{\partial X^s}{\partial t}(z,t) = \frac{\partial}{\partial z}\left[D^s(z,t)\frac{\partial X^s}{\partial z}(z,t)\right] \qquad (2)$$

with D^s a diffusion coefficient to determine.

Let us write first the left-hand side of this equation in terms of $X^a(z,t)$, which is the prognostic variable in the model :

$$
\begin{aligned}
\frac{\partial X^s}{\partial t} &= \frac{\partial \varepsilon_X X^a}{\partial t} \\
&= \varepsilon_X \frac{\partial X^a}{\partial t} + X^a \frac{\partial \varepsilon_X}{\partial t}
\end{aligned}
$$

The term $X^a \frac{\partial \varepsilon_X}{\partial t}$ takes into account the temporal changes in air, water and ice fraction, thus the total available volume for soil gas. It has a crucial importance on the carbon soil budget closure (see Annex 4). It does not appear in Khvorostyanov et al, and is mentioned in Kaiser et al.

For the right-hand side, we consider that diffusion takes place in one hand in the saturated part, and in the unsaturated one on the other hand. The diffusion coefficient or gas within the air and within the water are ponderated respectively by ν and w_g. The soil tortuosity η is taken too into account. Hence, we have :

$$\begin{aligned}\frac{\partial X^s}{\partial t} &= \left(\frac{\partial}{\partial z}\nu D^a \eta \frac{\partial X^a}{\partial z}\right) + \left(\frac{\partial}{\partial z} w_g D^e \eta \frac{\partial X^e}{\partial z}\right) \\ &= \left(\frac{\partial}{\partial z}\nu D^a \eta \frac{\partial X^a}{\partial z}\right) + \left(\frac{\partial}{\partial z} w_g D^e B \eta \frac{\partial X^a}{\partial z}\right)\end{aligned}$$

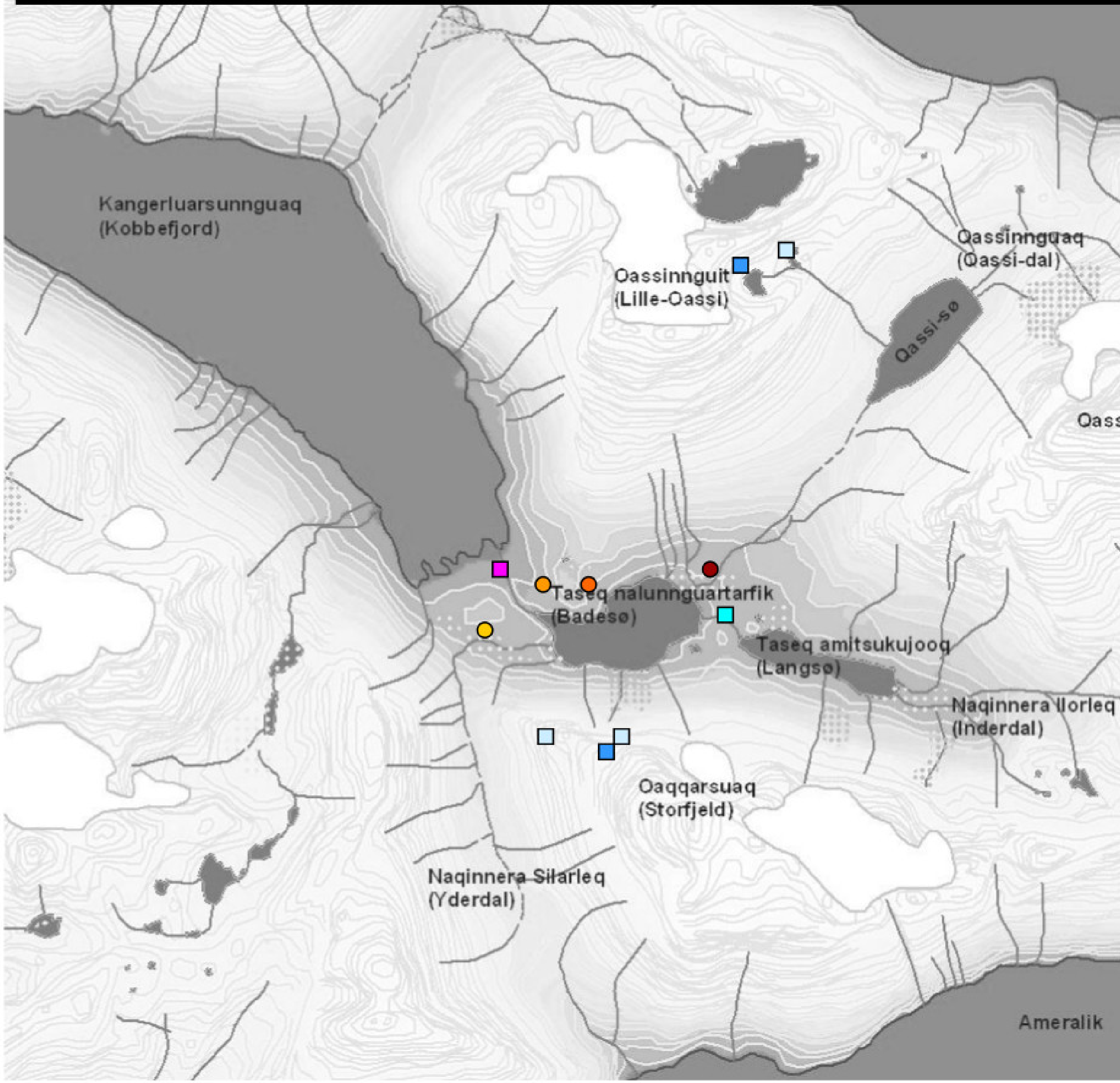
Introducing the diffusion coefficient $\widetilde{D}(z,t) = (\nu D^a + w_g B D^e)\,\eta$ we can write :

$$\frac{\partial X^s}{\partial t} = \frac{\partial}{\partial z}\left[\widetilde{D}(z,t)\frac{\partial X^a}{\partial z}(z,t)\right]$$

Finally, we have the diffusion equation of a gas within the soil column written in terms of the prognostic variable $X^a(z,t)$:

$$\begin{aligned}&\varepsilon_X \frac{\partial X^a}{\partial t} + X^a\left[(B-1)\frac{\partial w_g}{\partial t} - \frac{\partial w_{gi}}{\partial t}\right] = \frac{\partial}{\partial z}\left[\widetilde{D}(z,t)\frac{\partial X^a}{\partial z}(z,t)\right] \\ \Leftrightarrow\ &\frac{\partial X^a}{\partial t}(z,t) = \frac{1}{\varepsilon_X(z,t)}\frac{\partial}{\partial z}\left[\widetilde{D}(z,t)\frac{\partial X^a}{\partial z}(z,t)\right] - \frac{X^a}{\varepsilon_X}\frac{\partial \varepsilon_X}{\partial t}\end{aligned}$$

Localisation of measurements sites



6km x 6km

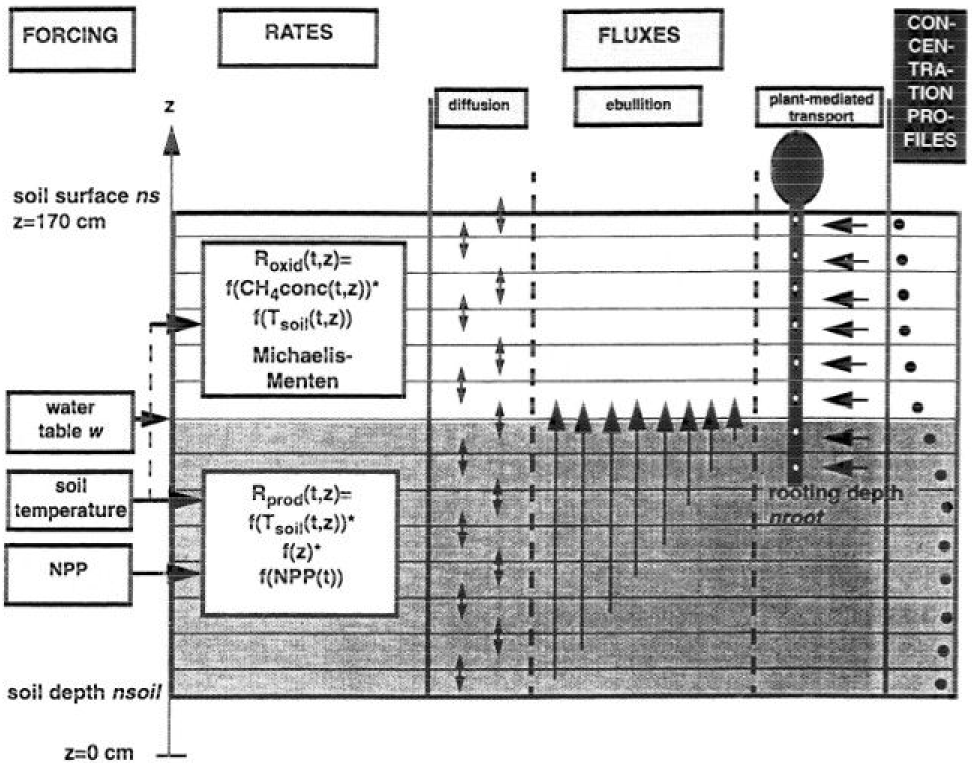
- Research station
- Climat 1 & 2 with snow depth
- M500 & 1000
- Snow cameras: K2_300m, K3&4_500m, K5&6_1000m
- Heath (SPA+EB+CO2)
- SoilEmpSa + Texture : Mart 3 and/or 4 + Temperature
- SoilFen (EB+gaz flux station + eddy covariance) + Texture : Mart 2
- Soil Emp (WG) (WG : good simulation)

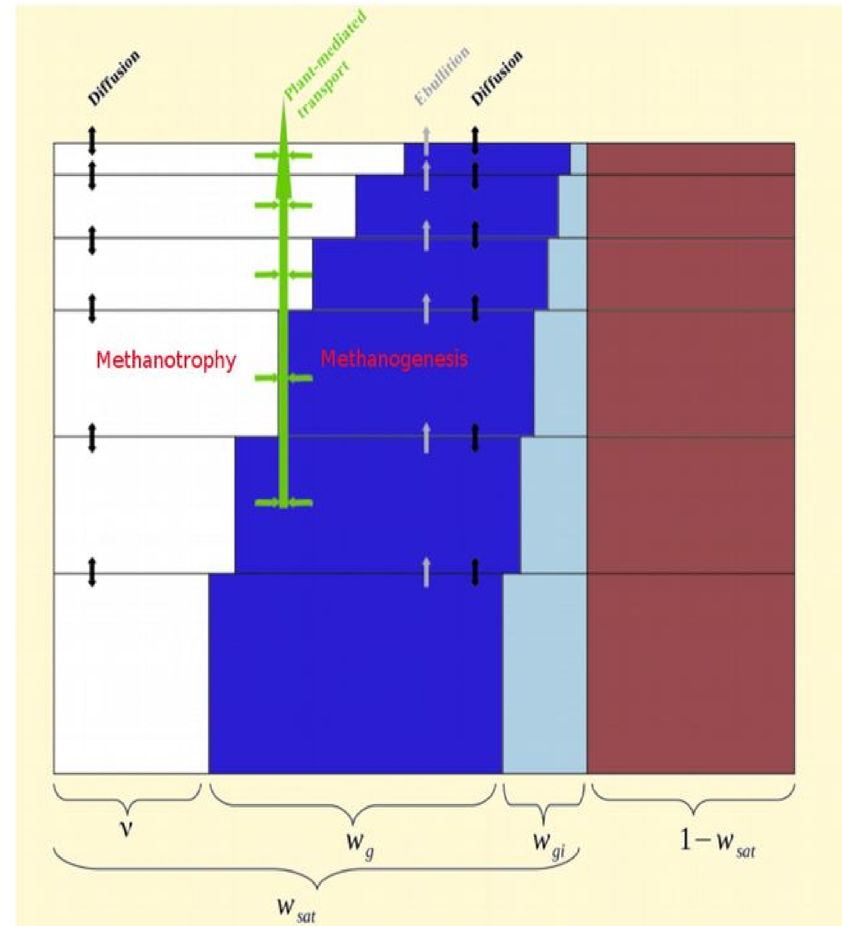
⇒Forte hétérogénéité spatiale :

Textures du sol, végétation … différentes selon les sites de mesure

- Nappe phréatique forcée à 1m.

Differences with Walter's model (2000)





- « Generalisation » of Walter's, layer by layer.
- Adapted to wetland and permafrost
- Non-prescribed carbon soil stock
- No water table parametrisation

Diffusion process (CH4 and CO2)

For a gas X^a (gX/m³ air) :

$$\frac{\partial \epsilon_X X^a}{\partial t}(z,t)=\frac{\partial}{\partial z}\left[\widetilde{D_X}(z,t)\frac{\partial X^a}{\partial z}\right]$$
$$\frac{\partial \epsilon_X X^a}{\partial z}(z=z_{max},t)=0$$
$$X^a(z=0^+,t)=X^o(t)$$

- Diffusivity in a layer :

$$D_X(z,t)=(\nu(z,t)D_X^a+w_g(z,t)B_X D_X^e)\eta$$

η the soil tortuosity (0.66)
With D^a_x the diffusivity in air (m²/s)
D^e_x the diffusivity in water (m²/s)

- $\widetilde{D_X}(z,t)$ interpolated at layers interface, with harmonic mean

- Homogeneous von Neumann condition at the last layer : no flux

- Non-homogeneous Difichlet condition at the interface soil/atmosphere :
  - Atmospheric methane concentration fixed at 9.4 10E-4 g/m³
  - Atmospheric CO2 concentration in the forcing files

- Diffusivity at the interface soil/atmosphere :

$$D_X^0=D_X^a\times(f_{snow}(1-\frac{\rho_{snow}}{\rho_{ice}})+(1-f_{snow}))$$

With f_{snow} the snow fraction, and ρ the densities

Methanogenesis, Methanotrophy and plant-mediated transport

Methanogenesis :

For every layer

$$F_{MG}(t,z)=\left(\frac{C_a(z,t)}{\tau_{MG_1}}+\frac{L(z,t)}{\tau_{MG_2}}\right)\frac{M_{CH_4}}{M_C}f(T)\frac{w_g(t,z)}{w_{sat}}$$

$gCH_4/m^3 sol/s$

- in the anoxic fraction of the soil
- Amount of organic matter (active pool and ground litter) calculated by the model
- Environmental factors : temperature and moisture

Methanotrophy :

For every layer

$$F_{MT}(z,t)=\frac{\epsilon_{CH_4}(z,t)CH_4(z,t)}{\tau_{MT}}(1-\frac{w_g(z,t)+w_{gi}(z,t)}{w_{sat}})1_{T\geq 0}$$

$gCH_4/m^3 sol/s$

- In the oxic fraction of the soil

Plant-mediated transport :

For every layer

$$f_{PMT}(z,t)=\frac{\epsilon_{CH_4}CH_4(z,t)}{\tau_{PMT}}T_{veg}f_{root}(z)h(LAI(t))(1-P_{ox})$$

$$h(LAI)=max(0;4\times min(\frac{LAI-LAI_{min}}{4-LAI_{min}};1))$$

Total PMT flux diagnosed as :

$$F_{PMT}(t)=\int_0^{z_{root}}f_{PMT}(z,t)(z,t)dz$$

Ebullition process

$$\frac{\partial f_{EBUL}(z,t)}{\partial z}$$

$$f_{ebul}(z,t)=E(z,t)max(CH4(z,t)-X_{ebul},0)\epsilon_{CH_4}(z,t)$$
$$=V(z,t)\eta\frac{w_g}{w_{sat}}max(CH4(z,t)-X_{ebul},0)\epsilon_{CH_4}(z,t)$$

Ebullition treshold : $X_{ebul}=(2-f_{veg})\frac{\overline{CH_4}}{B_{CH_4}}$ with $\overline{CH_4}\in[8;16]gCH_4/m^3{}_{eau}$ (Walter et al, 2000)

We restrained numerically bubbles celerity by layer :

$$V_i=min(\frac{\Delta z_i}{\Delta t};0.01)$$

$$V_1=min(\frac{\Delta z_1}{\Delta t};0.01)\times g_{snow}=min(\frac{\Delta z_1}{\Delta t};0.01)\times(f_{snow}(max(1-\rho_{snow},0))+(1-f_{snow}))$$

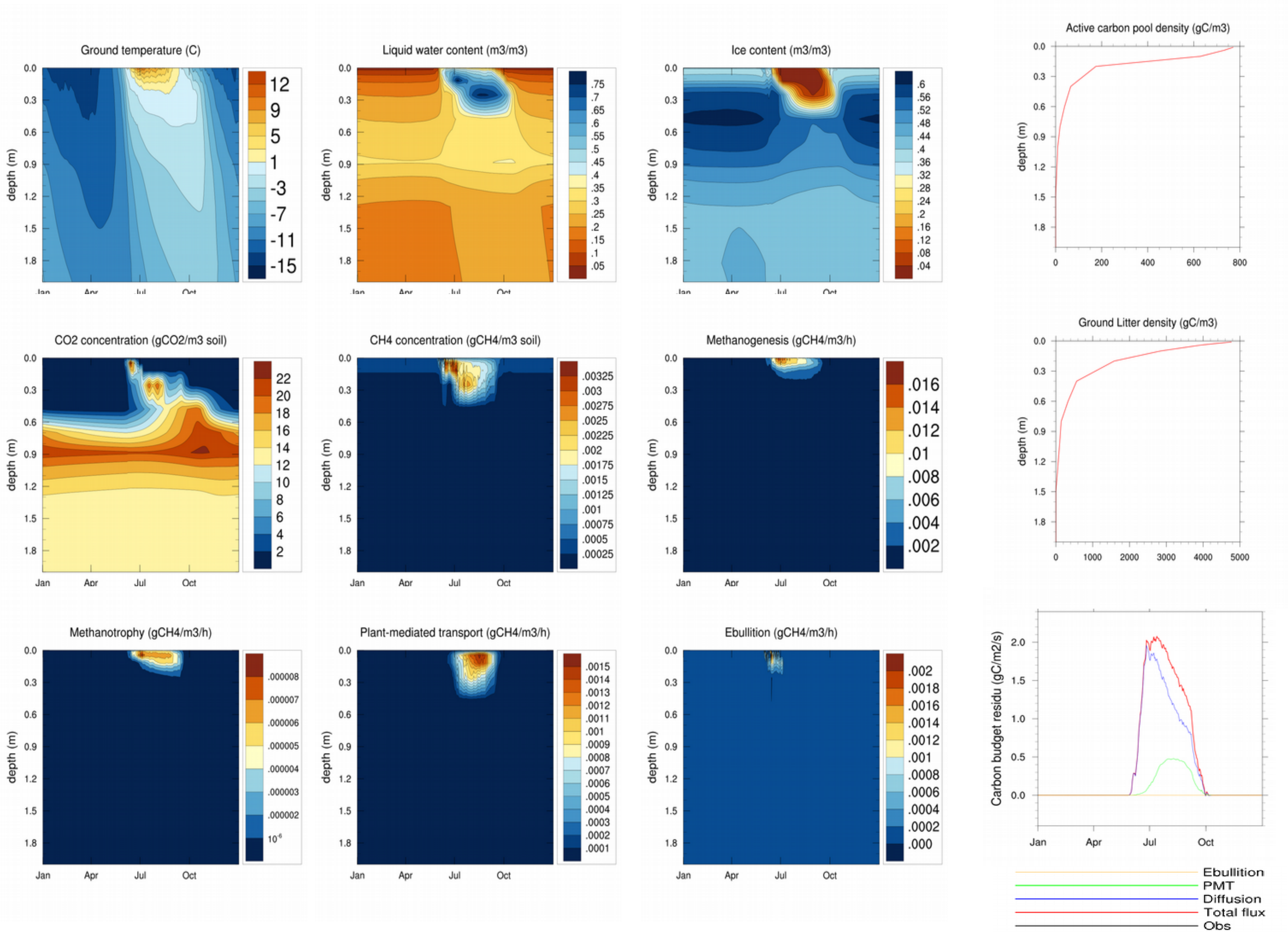
If in the ith layer, $CH_4\geq X_{ebul}$ we set $E_i=V_i\frac{w_g}{w_{sat}}\eta$. Otherwise, $E_i=0$.

Hence, in the ith layer : $$\frac{\Delta(\epsilon_{CH_4}CH_4^i)}{\Delta t}_{ebullition}=-E_i(CH_4{}^i-X_{ebul})\epsilon_{CH_{4i}}+E_{i+1}(CH_4{}^{i+1}-X_{ebul})\epsilon_{CH_{4i+1}}\frac{\Delta z_i}{\Delta z_{i+1}}$$

Finally, ebullition flux F_{ebul} (gCH4/m²/s) is diagnosed at the first layer :

$$F_{ebul}(t)=E_1(CH_4(z=z_1,t)-X_{ebul})\epsilon_{CH_4}(z=z_1,t)\frac{\Delta z_1}{\Delta t}$$

Model behaviour : Zackenberg



Model behaviour : Chokurdakh