Dependence of near-surface permafrost inertia on direction, intensity, and temporal scale of global surface temperature change

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Motivation (1)

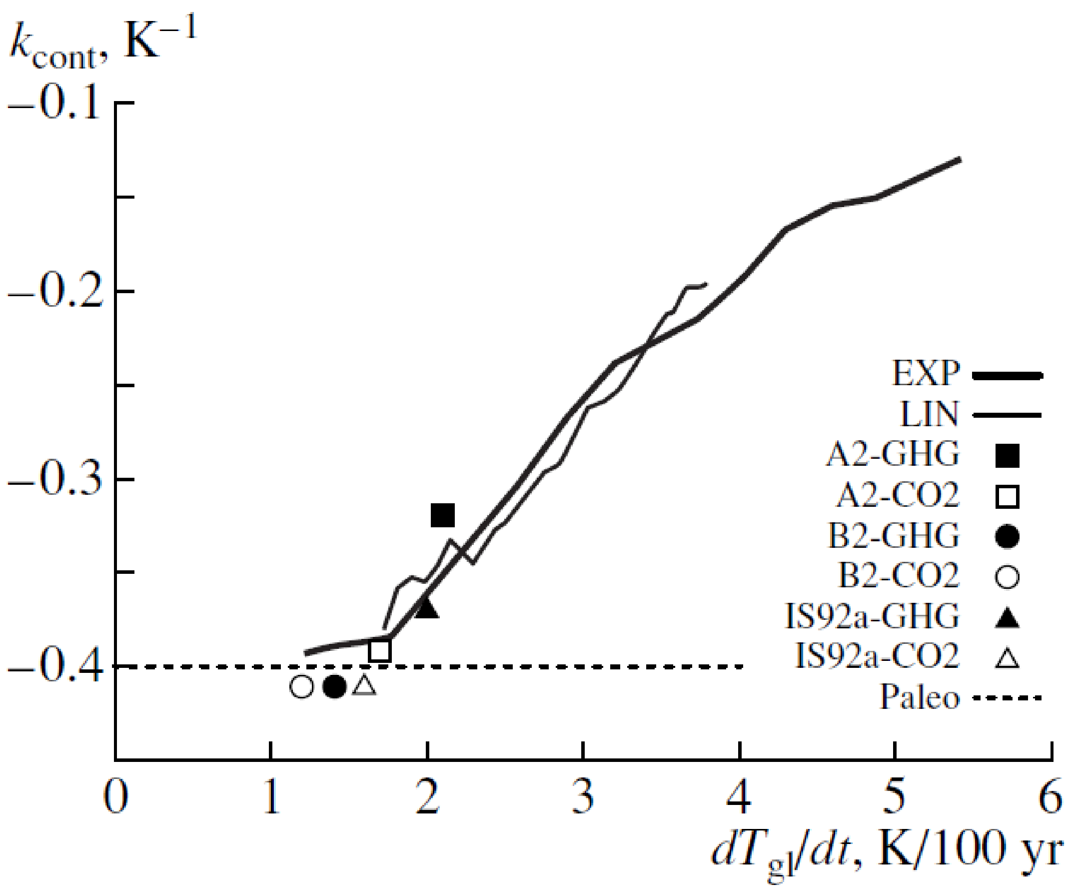
- Global warming, observed in the late 20th century and expected to continue in the 21st century, may lead to degradation of near-surface and deep permafrost. Due to climate inertia, this degradation is able continue during next several centuries provided that anthropogenic GHG emissions are continued and sufficiently strong.

- However, after cessation of these emissions and subsequent decay of anthropogenic forcing agents, climate is expected to return to initial state with respective return to permafrost

Basic question

Is relation between the climate state and permafrost extent depends on direction of climate change? If yes, does this relationship also depend on time scale and intensity of imposed external forcing?

Motivation (2): Dependence of potential continious permafrost extent sensitivity on global warming rate [Demchenko et al., 2006]

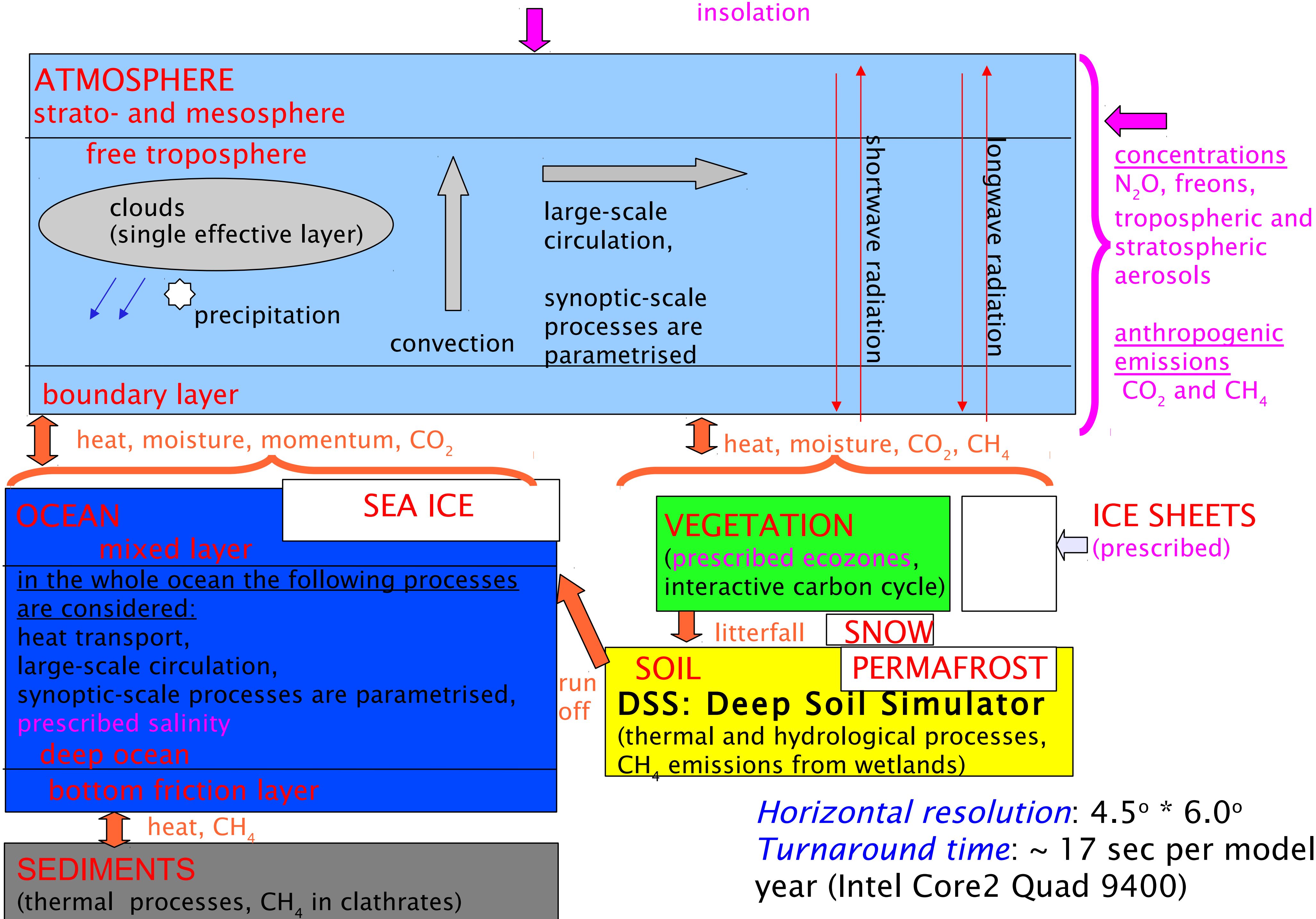


$k_{cont} = S_{cont,0}^{-1}\, dS_{cont} / dT_{gl}$

S_{cont} – extent of potential continious permafrost (calculated based on monthly mean SAT)
$S_{cont,0}$ – reference value of S_{cont}
T_{gl} – globally averaged SAT

EXP, LIN – series of the simulations with the IAP RAS CM forced by the idealised scenarios for q_{CO2}
A2-GHG, A2-CO2, B2-GHG, B2-CO2, IS92a-GHG, IS92a-CO2 – simulations with the IAP RAS CM forced by the anthropogenic scenarios for the 21st century adapted either from the IPCC FAR or from the IPCC TAR
Paleo is derived from the empirically estimated differences between the Holocene Optimum and the Eemian Interglacial [Velichko and Nechaev, 1992]

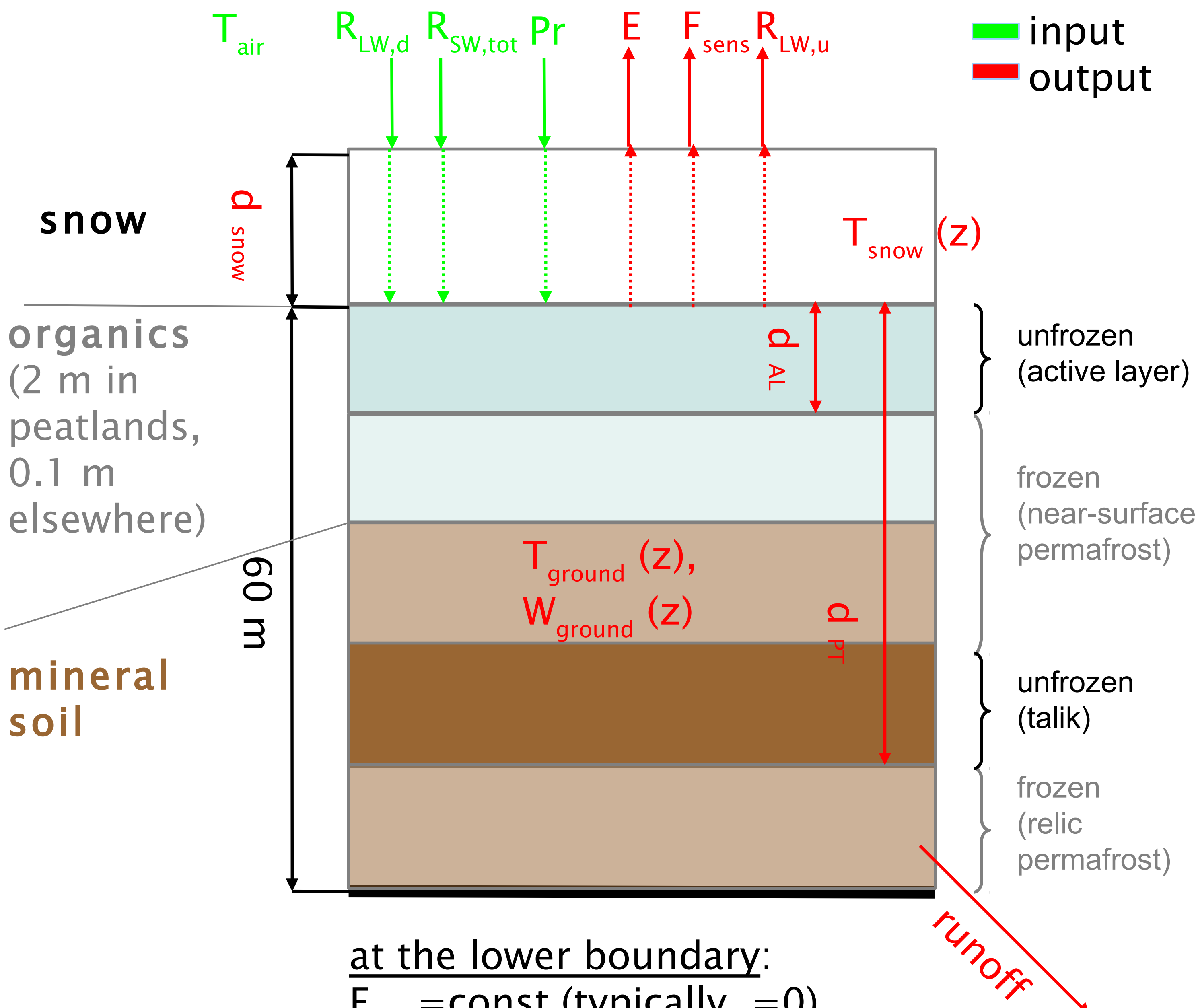
General structure of the IAP RAS CM



Horizontal resolution: 4.5° * 6.0°

Turnaround time: ~ 17 sec per model year (Intel Core2 Quad 9400)

General structure of the DSS [Arzhanov et al., 2009]



Governing equations:
- heat transport (diffusion);
- moisture transport (Richard equation);

Parameters depend on
- soil type,
- soil state (frozen/unfrozen,
- soil moisture content W.

Δz: adaptive grid: = 5 cm in the upper 10 m of soil column; decreased to 1 cm near frost front

at the lower boundary:

F_{heat}=const (typically, =0)

$F_{water}=0$

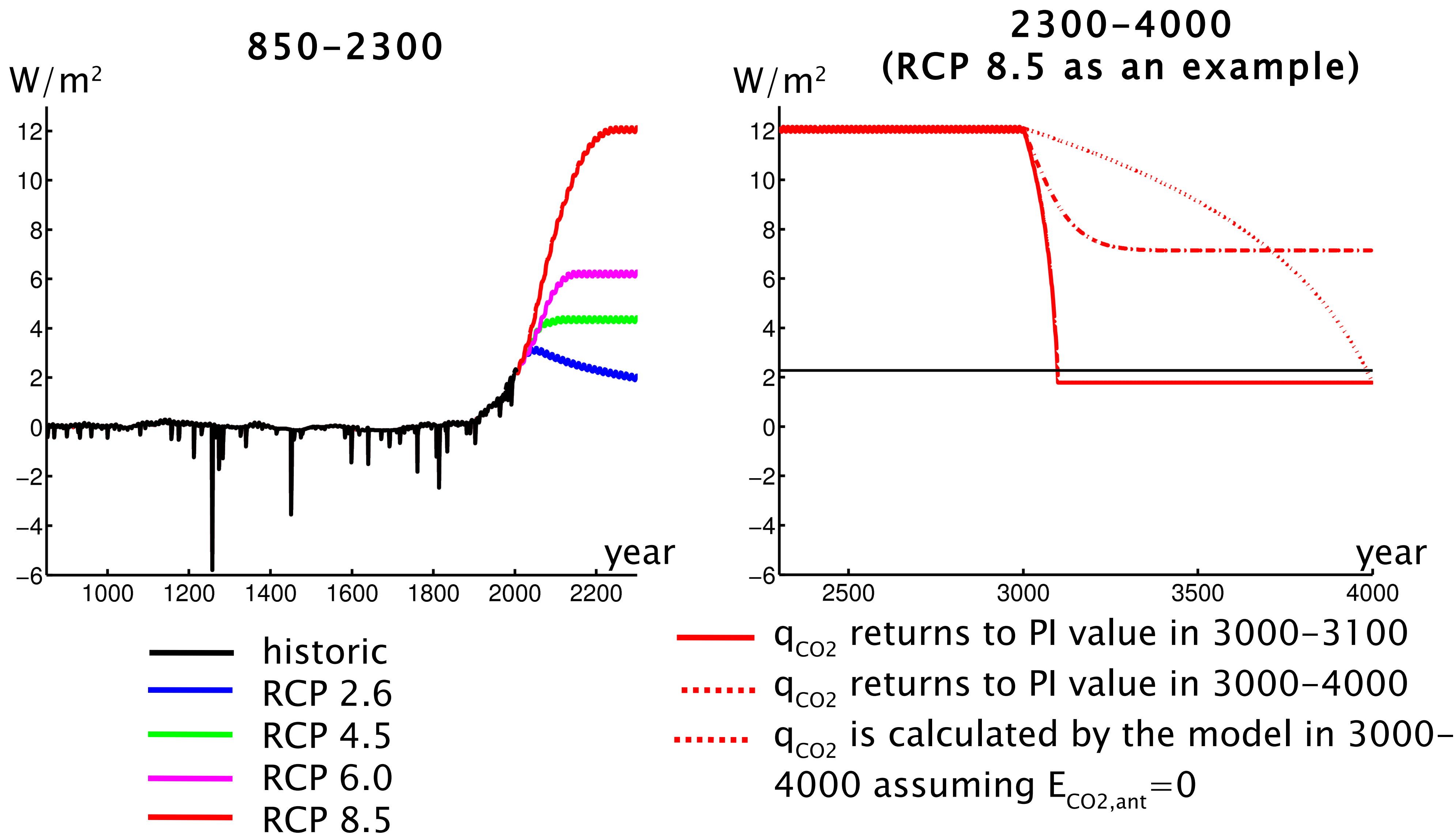
Simulations: AR5 EMIC

Protocol: AR5 EMIC (http://climate.uvic.ca/EMICAR5)

Duration: 850-4000

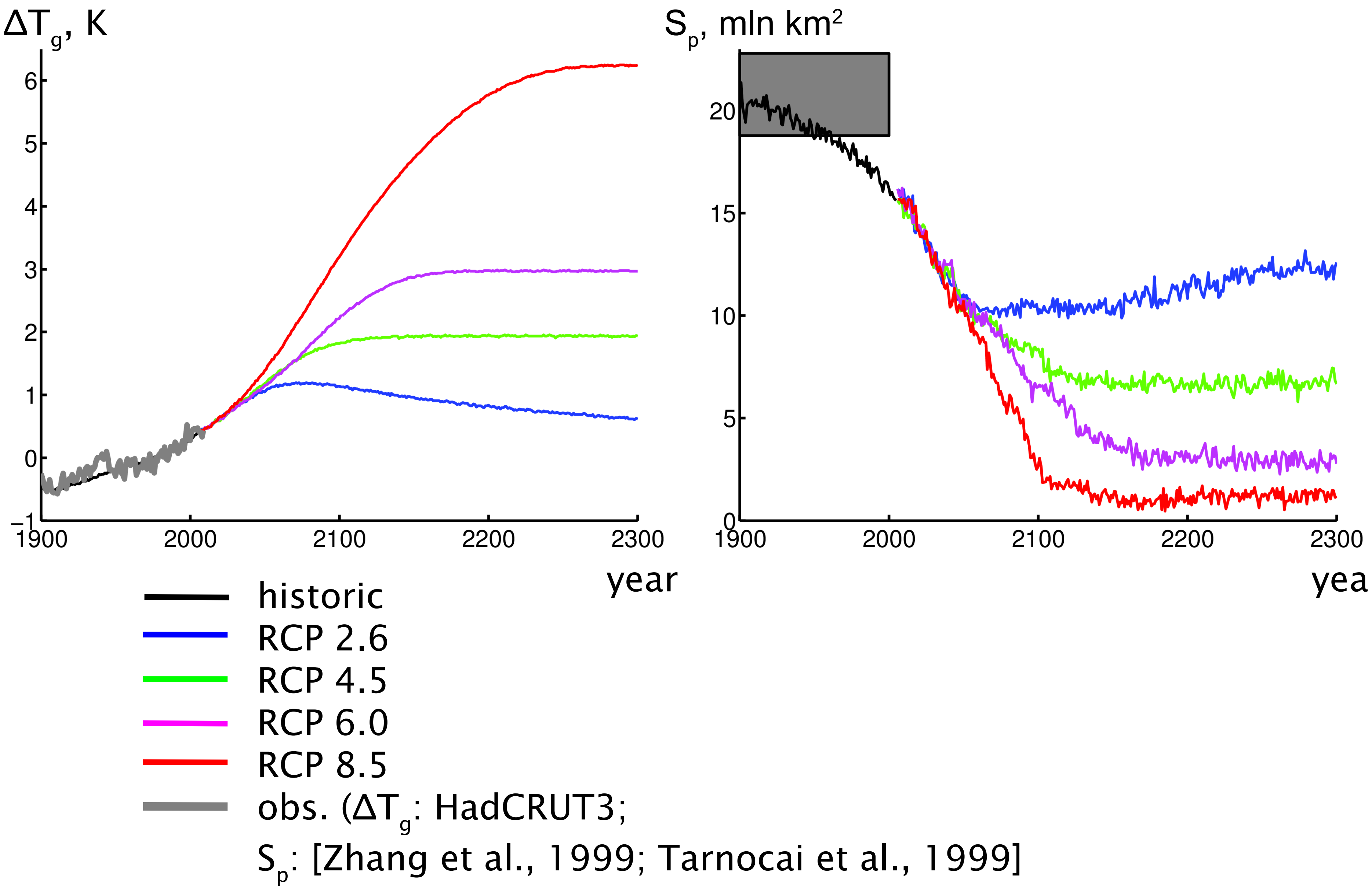
External forcings:
- atmospheric concentrations of CO_2, CH_4, and N_2O;
- tropospheric burdens of sulphate aerosols;
- total solar irradiance;
- stratospheric aerosol optical depth;
- change in surface albedo due to land use.

Globally averaged annual mean TOA radiative forcing

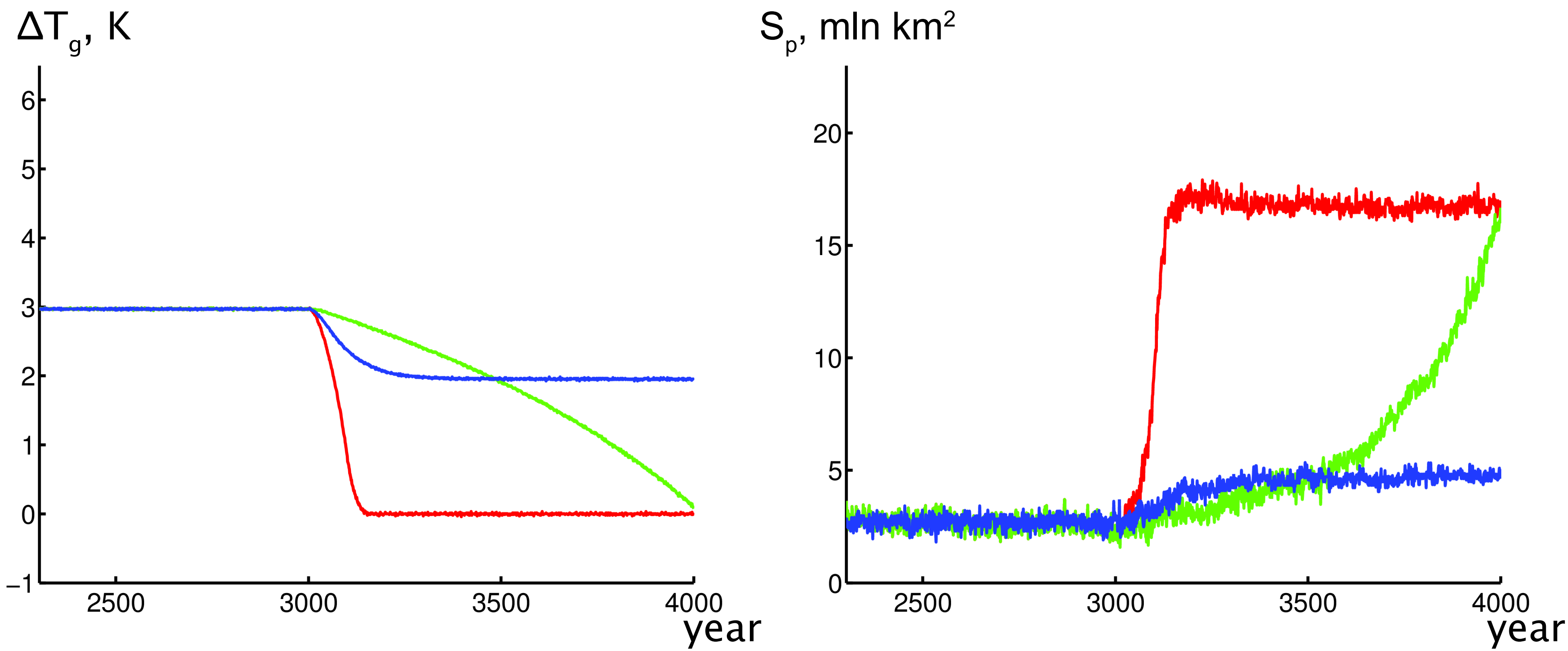


other agents are fixed at the values for year 2300

Globally averaged annual mean SAT and extent of near-surface permafrost: 850–2300

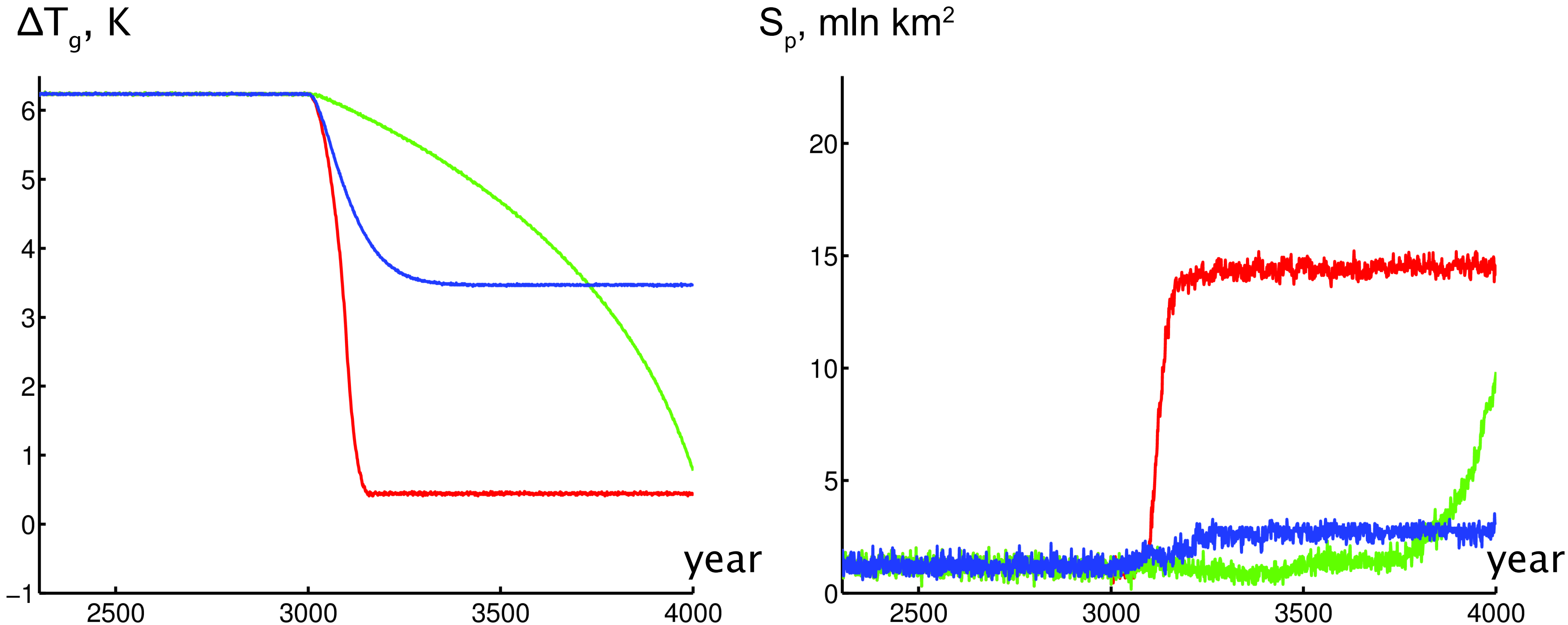


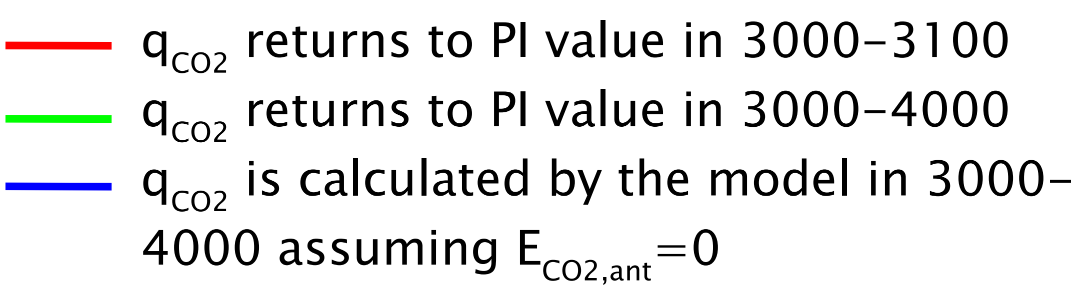
Globally averaged annual mean SAT and extent of near-surface permafrost: RCP 6.0, 2300–4000



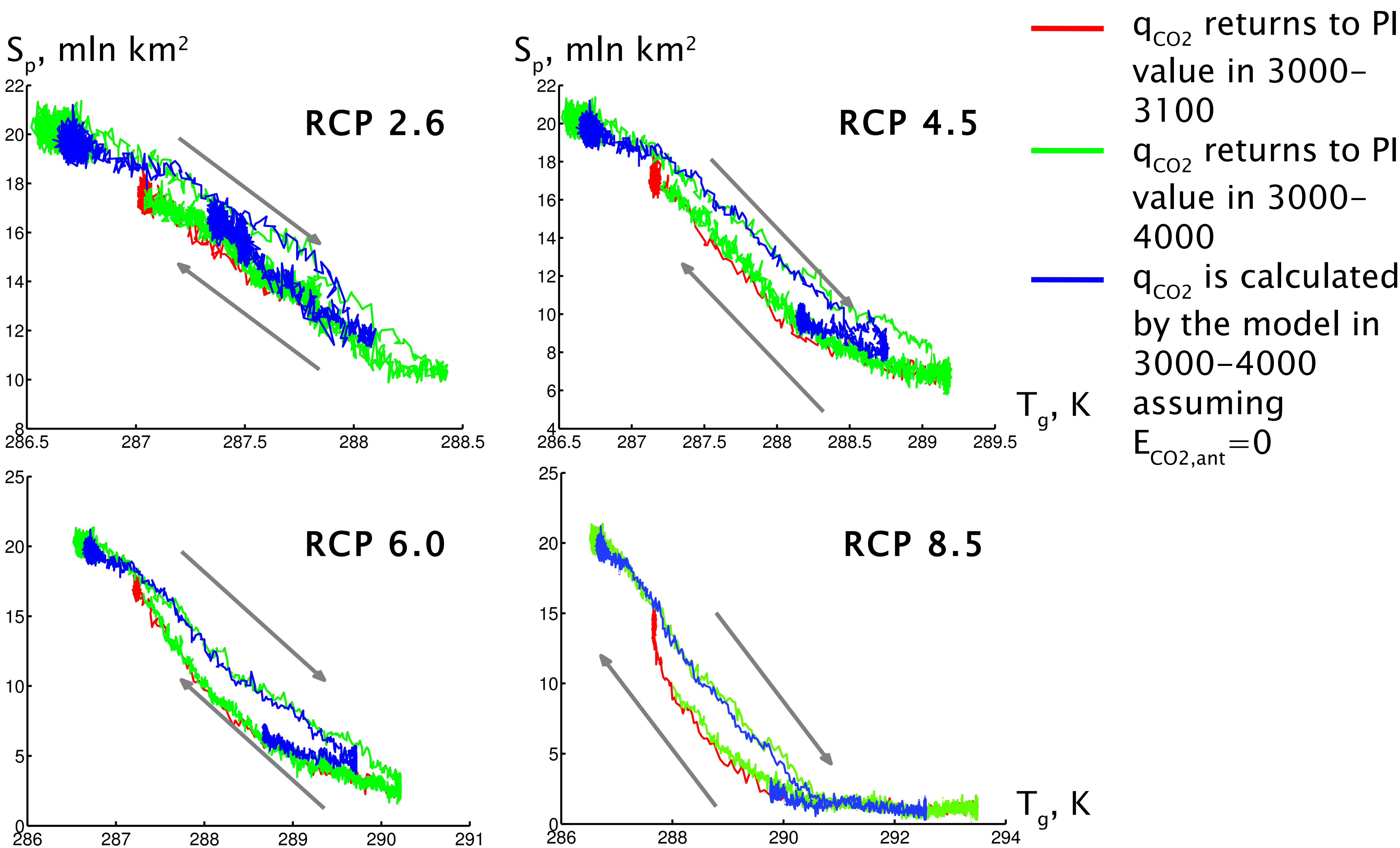
- q_{CO2} returns to PI value in 3000–3100
- q_{CO2} returns to PI value in 3000–4000
- q_{CO2} is calculated by the model in 3000–4000 assuming $E_{CO2,ant}=0$

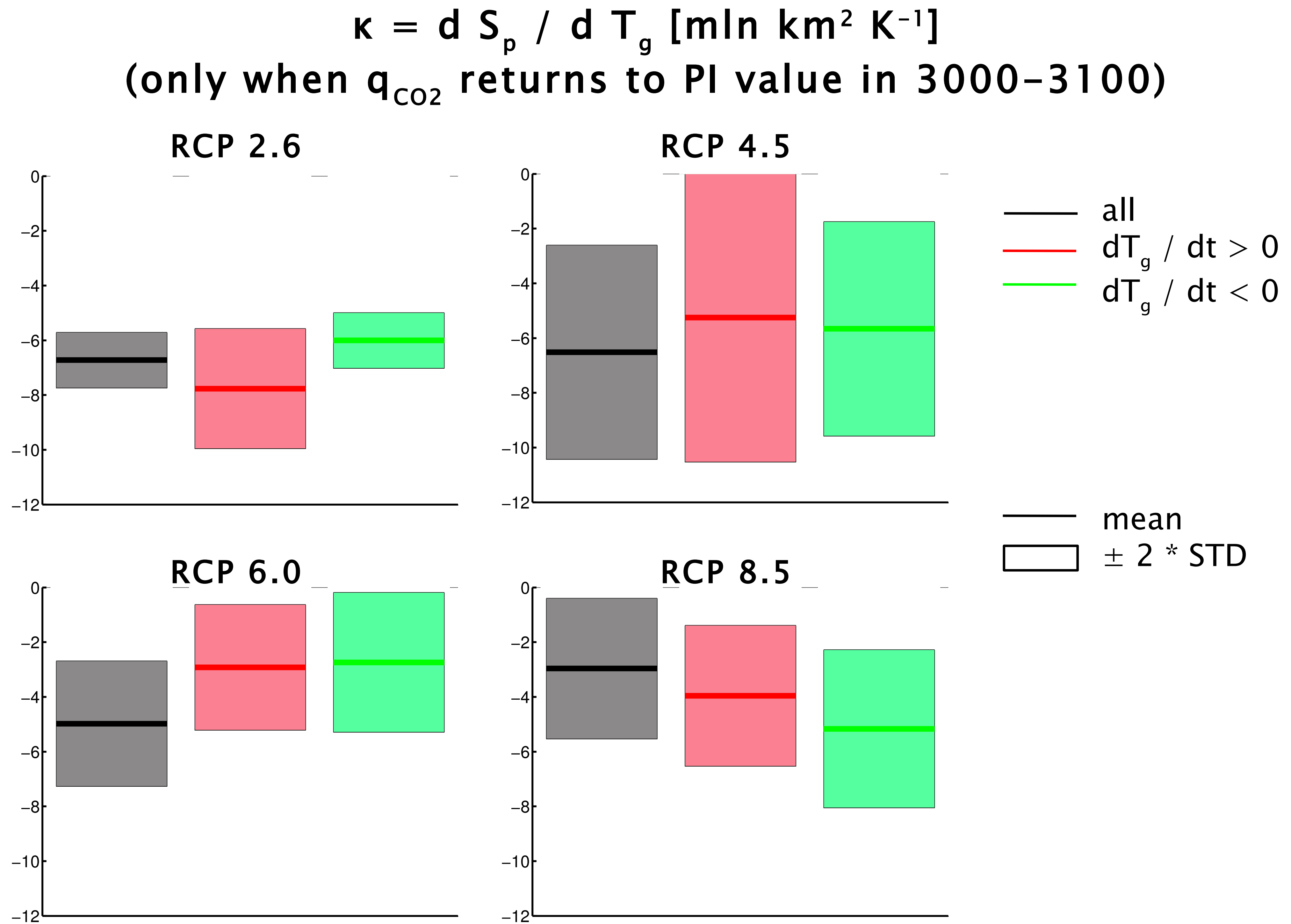
Globally averaged annual mean SAT and extent of near-surface permafrost: RCP 8.5, 2300–4000



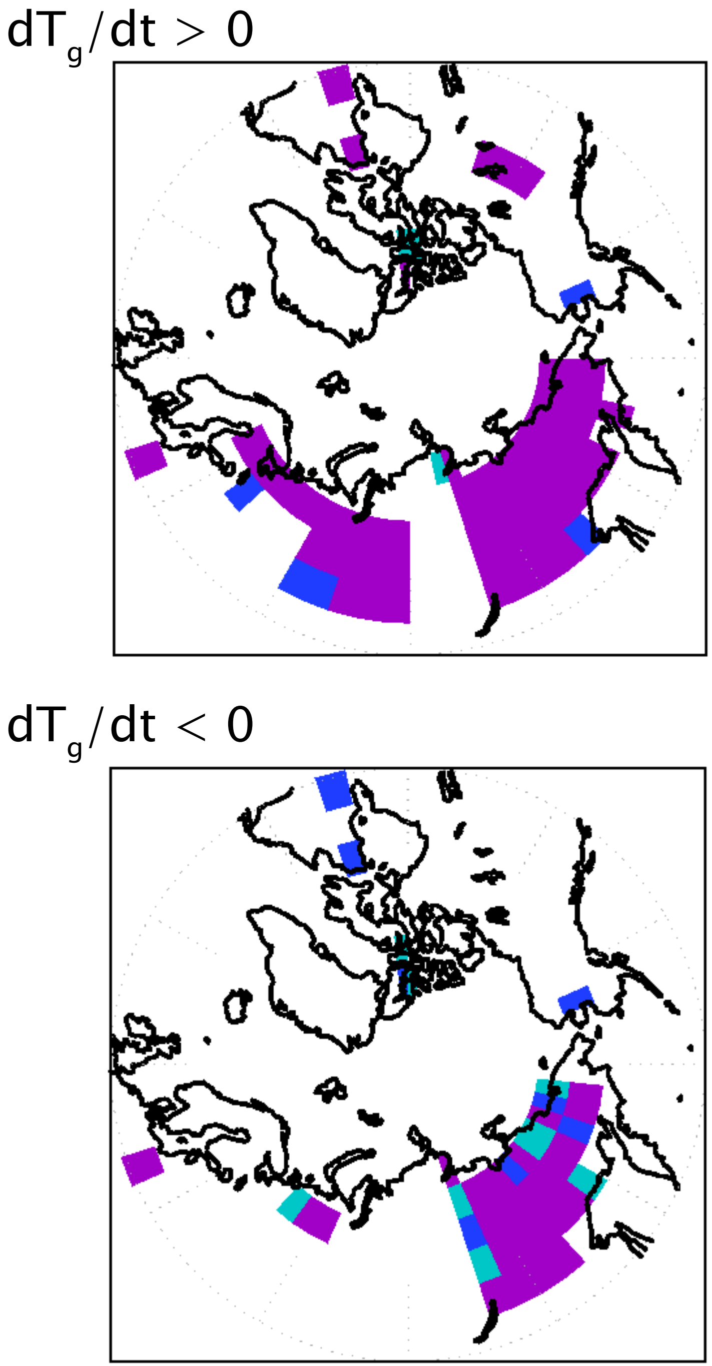


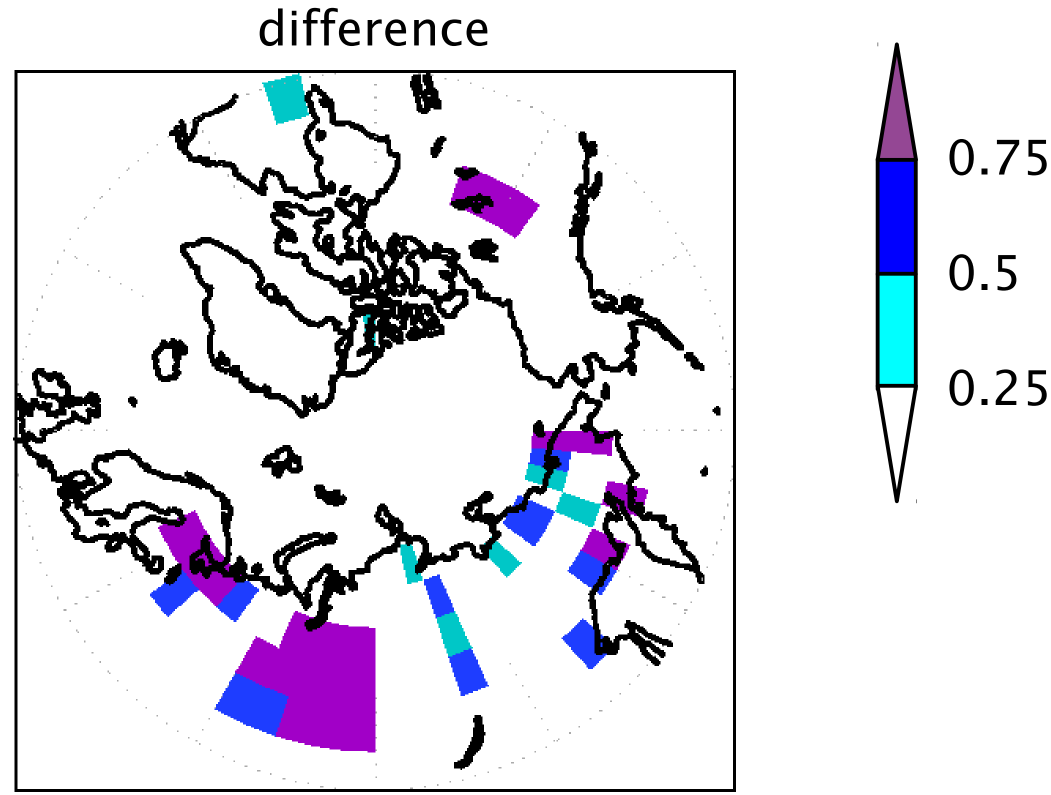
Modelled near-surface permafrost-covered area *vs*. globally averaged annual mean SAT




κ = d S_p / d T_g [mln km² K⁻¹]
(only when q_CO2 returns to PI value in 3000–3100)
RCP 2.6
RCP 4.5
RCP 6.0
RCP 8.5
0
−2
−4
−6
−8
−10
−12
all
dT_g / dt > 0
dT_g / dt < 0
mean
± 2 * STD

Near-surface permafrost mask
(RCP 8.5; q_{CO2} returns to PI value in 3000–3100)



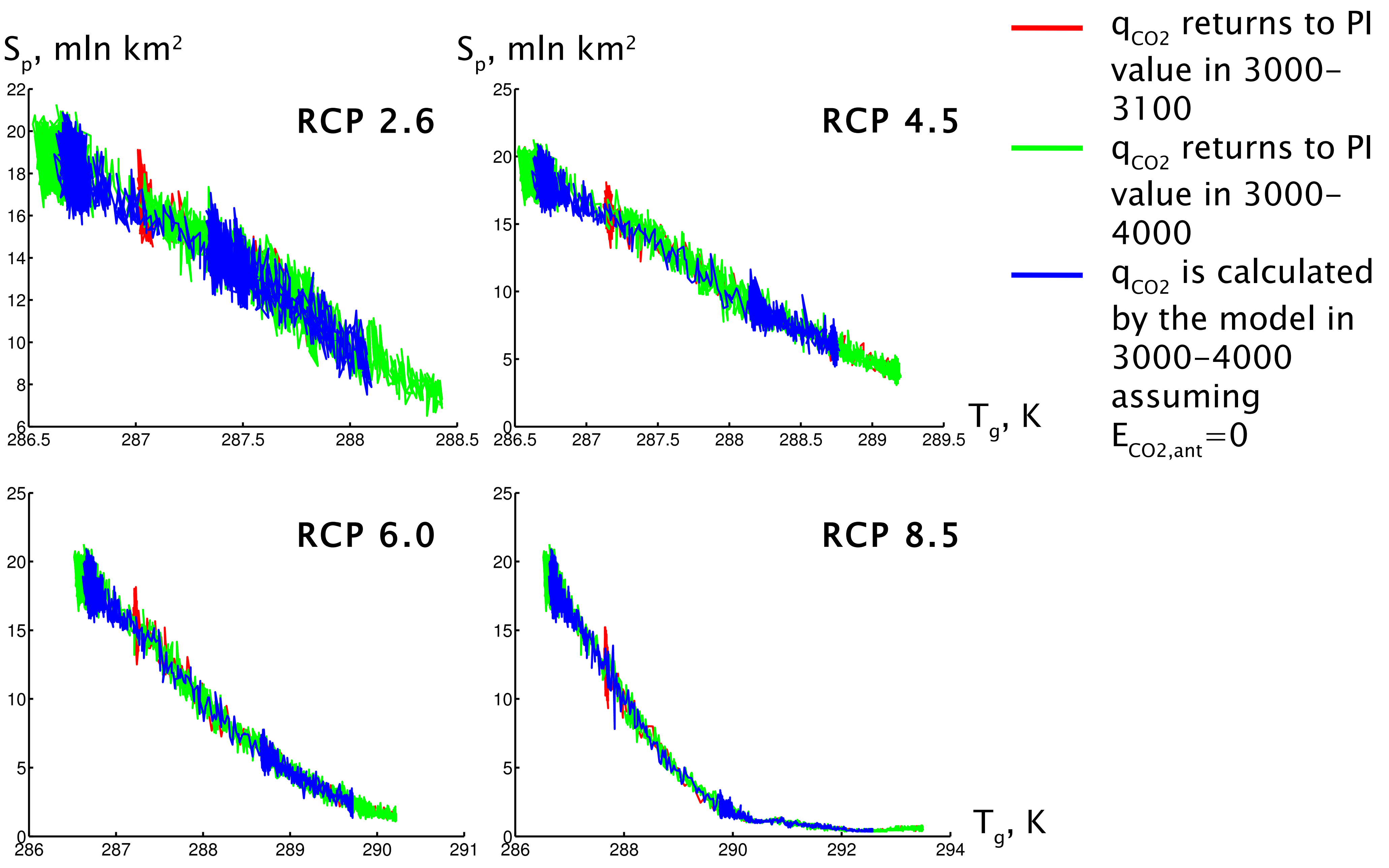


For every individual year in every grid cell:

- M=1 if permafrost is diagnosed,
- M=0 otherwise.

Then composites of M are constructed by averaging in $288.4\ K < T_g < 290.0\ K$ (this range depends on the RCP scenario) when hysteresis branches in coordinates (T_g, S_p) are separated.

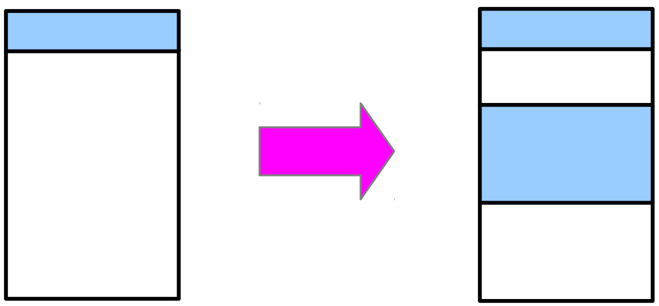
Area covered by continious potential permafrost (as calculated based on monthly mean local SAT) *vs*. globally averaged annual mean SAT

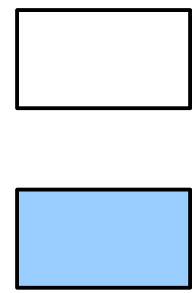


Tentative mechanism for permafrost hysteresis

1. $dT_g/dt > 0$

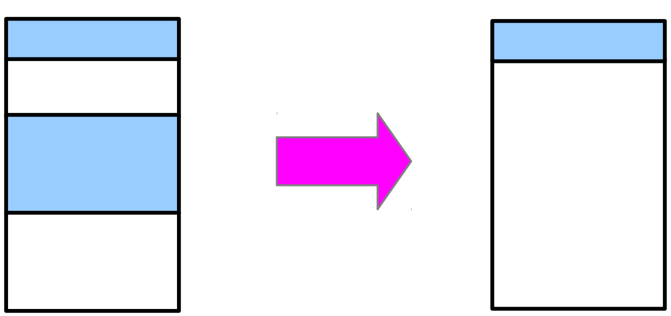
seasonal thaw　　talik develops





2. $dT_g/dt < 0$

talik exists　　talik disappears



Talik generally delays soil response to atmospheric forcing

Longer impact of talik on soil state in the case of global cooling in comparison to the case of global warming

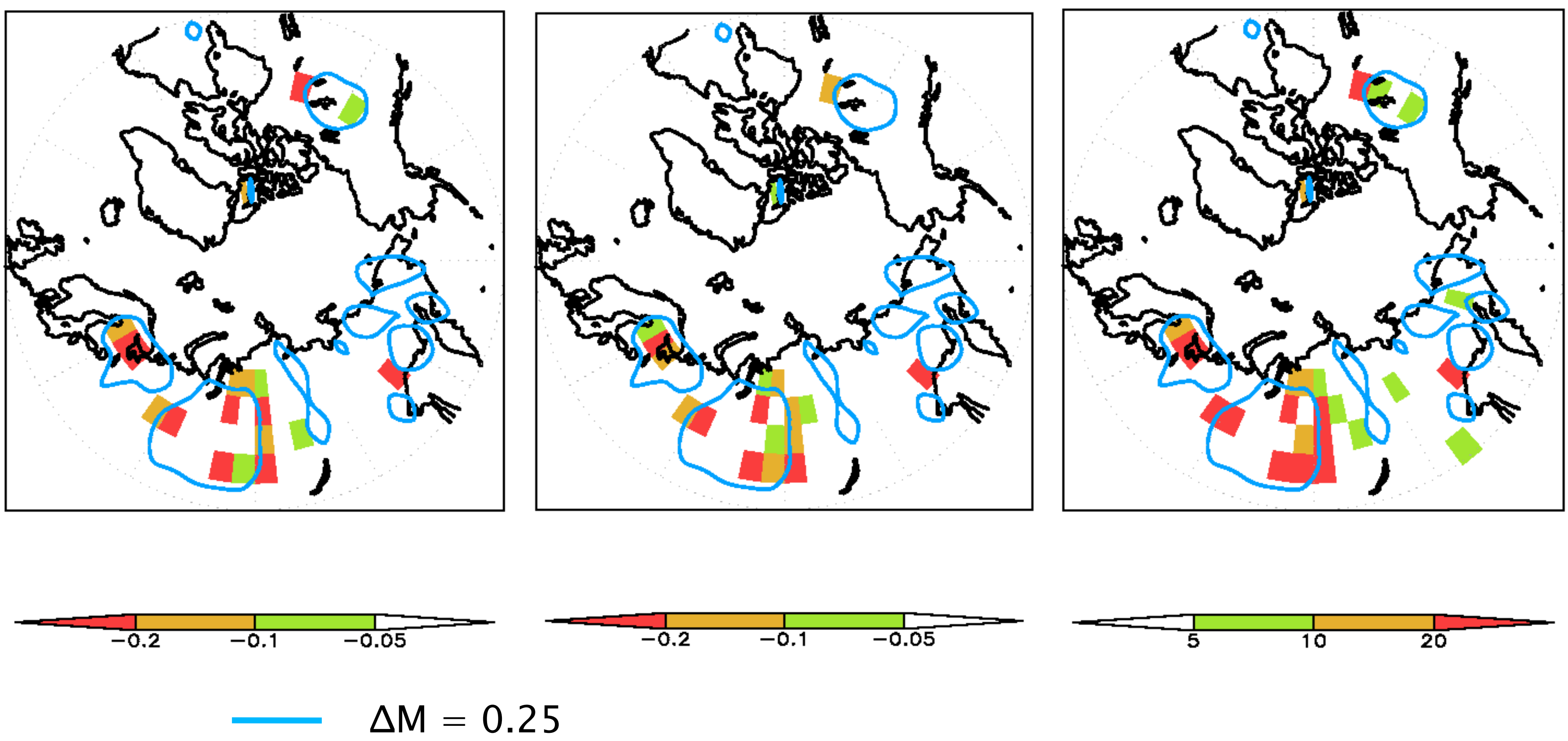
Permafrost hysteresis

Amplification through hydrological cycle: Composite differences for July (RCP 8.5; q_{CO2} returns to PI value in 3000–3100)

soil moisture content in the upper 7 cm of soil column [m/m]

cloud amount []

radiation budget at the surface [W/m²]



Therefore:

- The relationship between globally averaged surface air temperature T_g and the near-surface permafrost extent S_p is multivalued.

- This transient permafrost hysteresis is visible more clearly for more aggressive anthropogenic scenarios. In contrast, it does not depend on the way how q_{CO2} returns to the PI value, at least among studied here scenarios.

- It is likely to related to the impact of phase transitions of soil moisture on apparent heat capacity of soil. This mechanism is amplified via atmospheric hydrological feedbacks and radiative budget at the surface.

⇩

It is tempting to study this mechanism in a systematic way

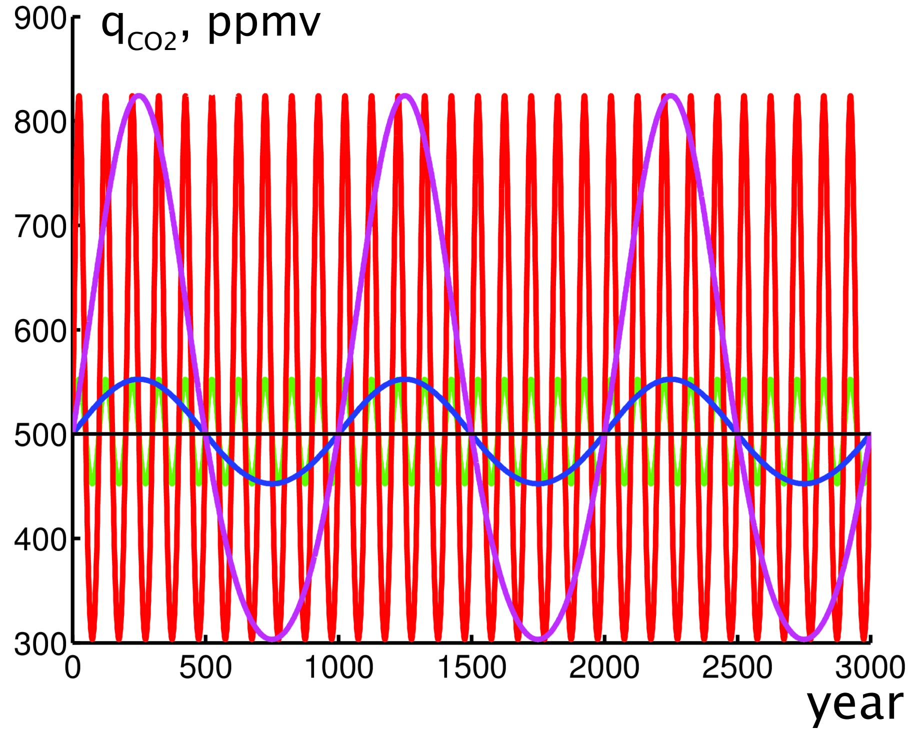
Simulations: Idealised

Duration: (45 simulations) * (model years 1-3000) = 135,000 years

External forcings: periodically varying q_{CO2}:

$q_{CO2} = q_{CO2,0} \exp [A \sin (2 \pi t / P)]$,

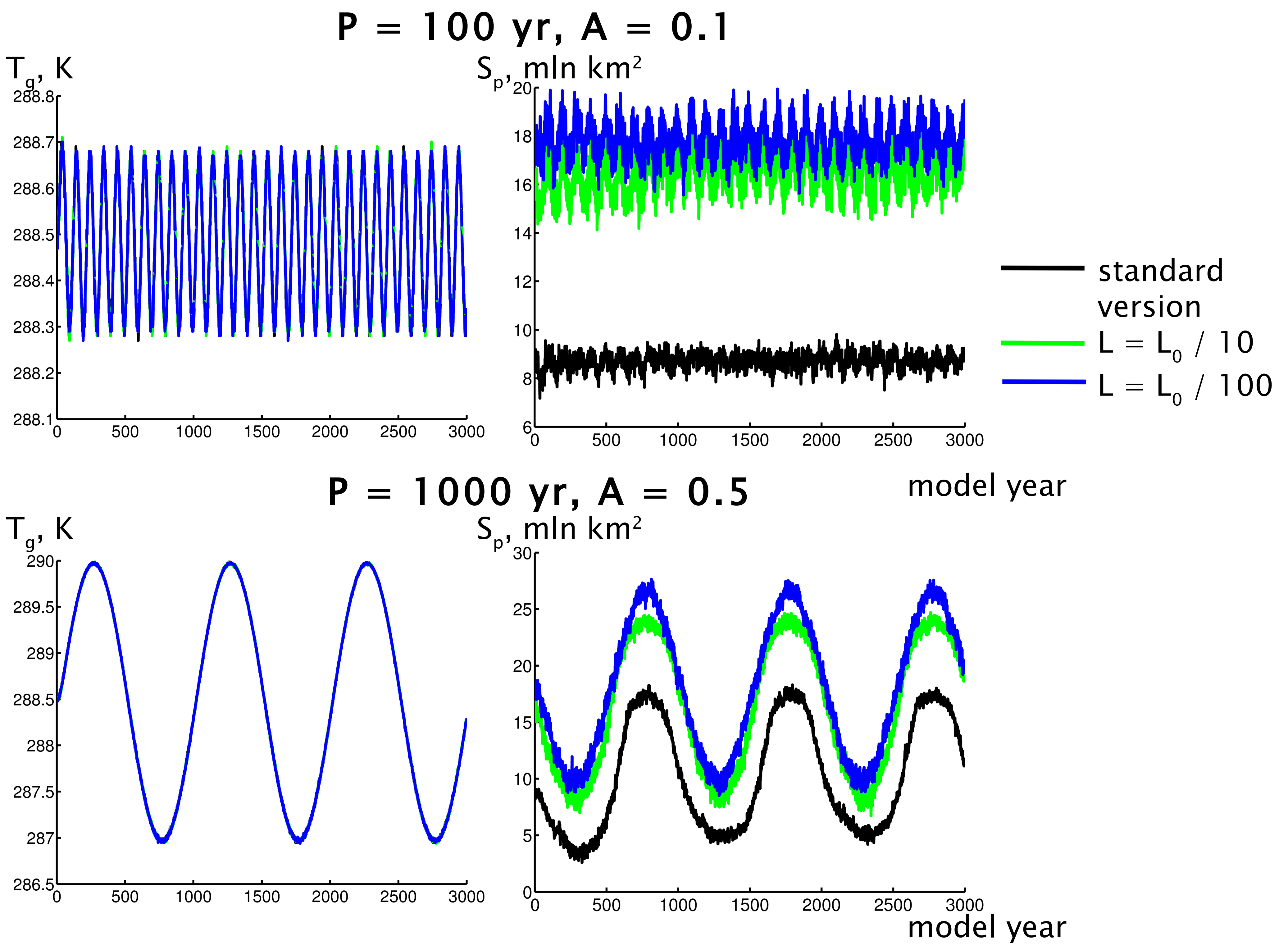
$q_{CO2,0} = 500$ ppmv



- A = 0.1, P = 100 yr
- A = 0.1, P = 1000 yr
- A = 0.5, P = 100 yr
- A = 0.5, P = 1000 yr

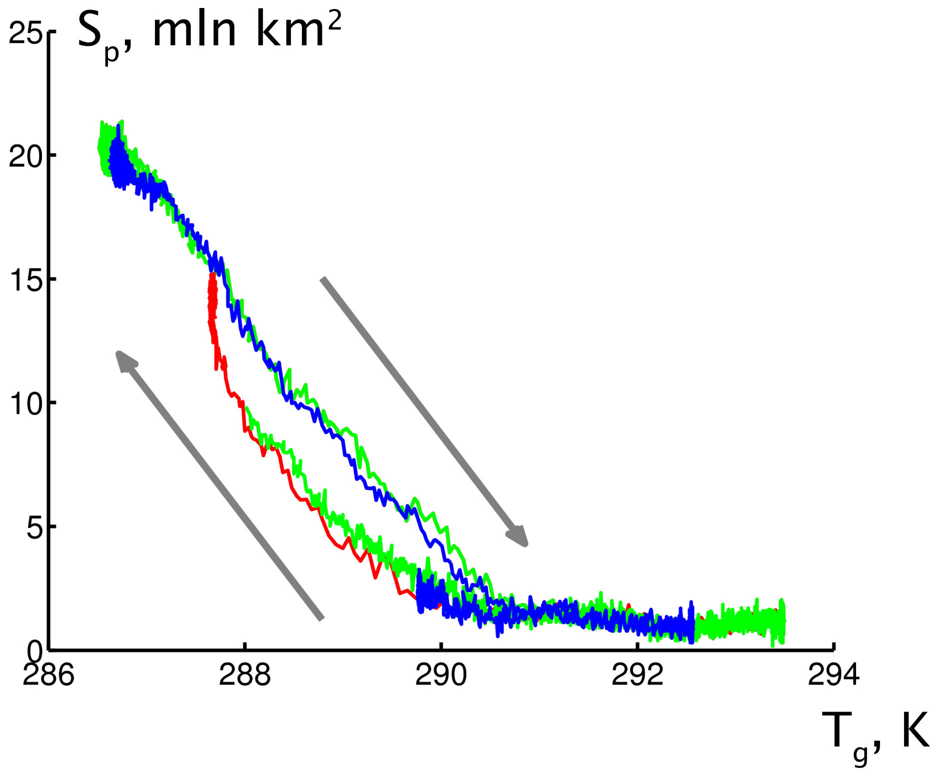
Model versions:

- standard, specific latent heat of freezing $L = L_0 = 3.34 \cdot 10^5$ J / kg;
- $L = L_0 / 10$ in soil;
- $L = L_0 / 100$ in soil;

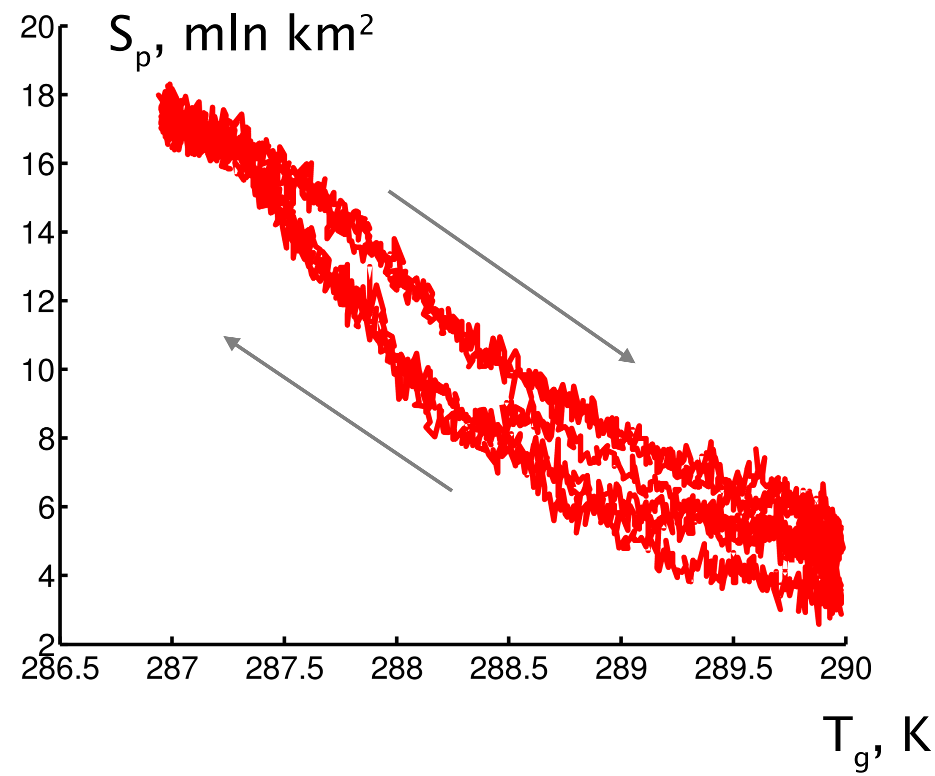

P = 100 yr, A = 0.1
T_g, K
S_p, mln km²
standard version
L = L_0 / 10
L = L_0 / 100
P = 1000 yr, A = 0.5
model year
T_g, K
S_p, mln km²
model year

Hysteresis of near-surface permafrost: dependence on type of external forcing (standard model version)

RCP 8.5

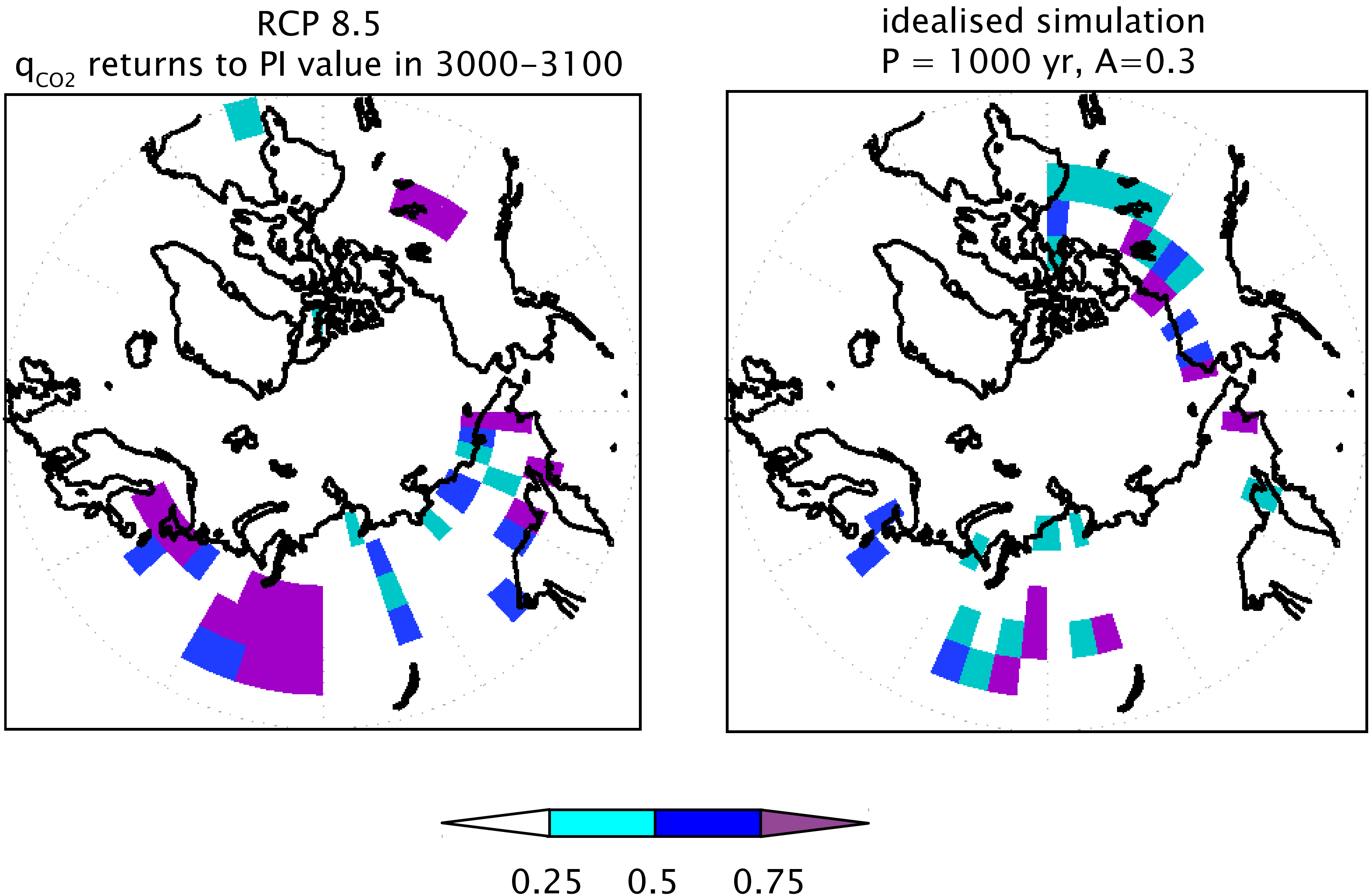


idealised: P = 1000 yr, A = 0.5



- (red) q_{CO2} returns to PI value in 3000–3100
- (green) q_{CO2} returns to PI value in 3000–4000
- (blue) q_{CO2} is calculated by the model in 3000–4000 assuming $E_{CO2,ant}$=0

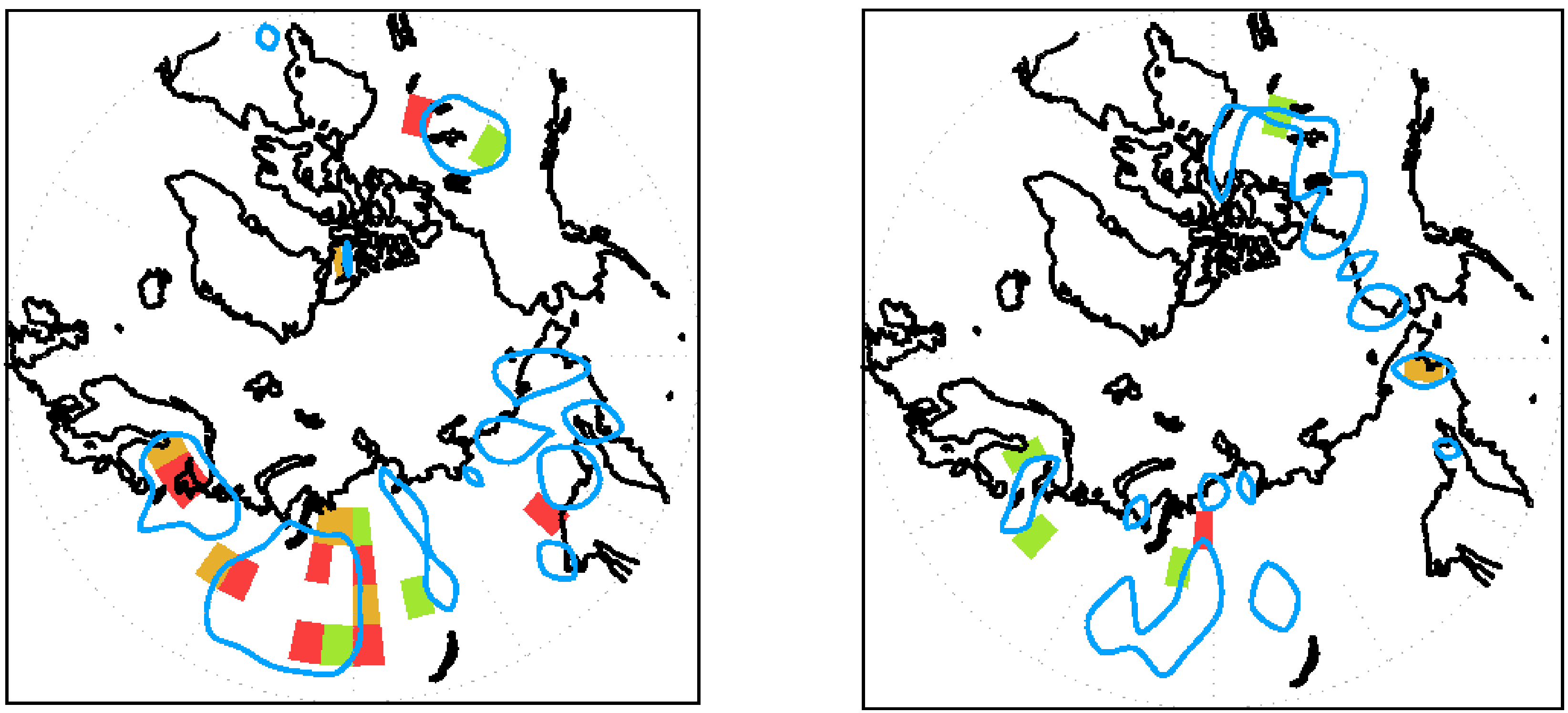
Between-branches difference of near-surface permafrost mask (standard version)

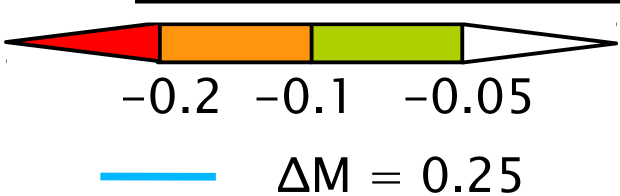


Amplification mechanism via hydrological cycle: dependence on type of external forcing. Moisture content in the upper 7 cm of soil column [m/m] (standard model version)

RCP 8.5
q_{CO2} returns to PI value in 3000–3100

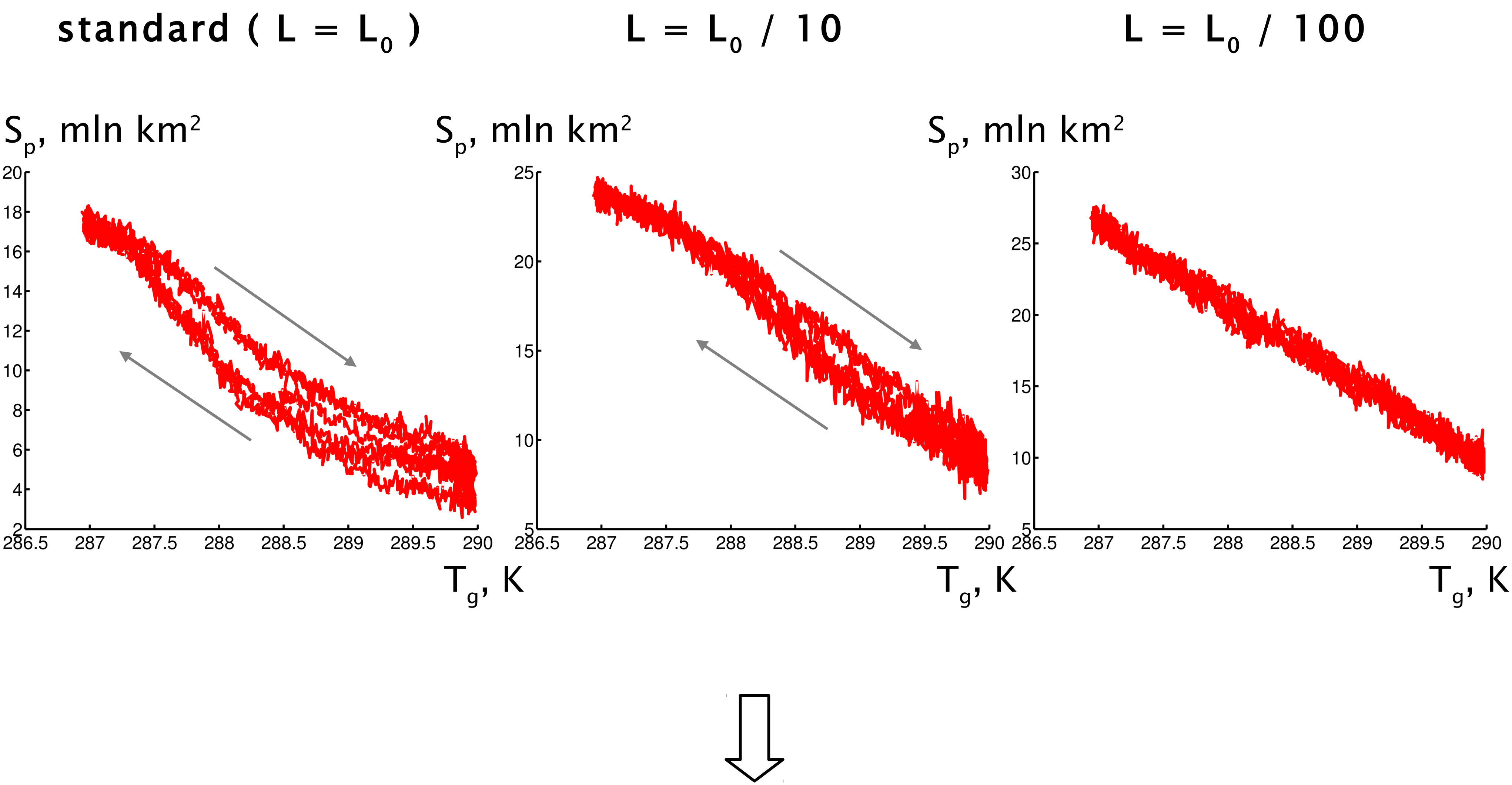
idealised simulation
P = 1000 yr, A=0.3





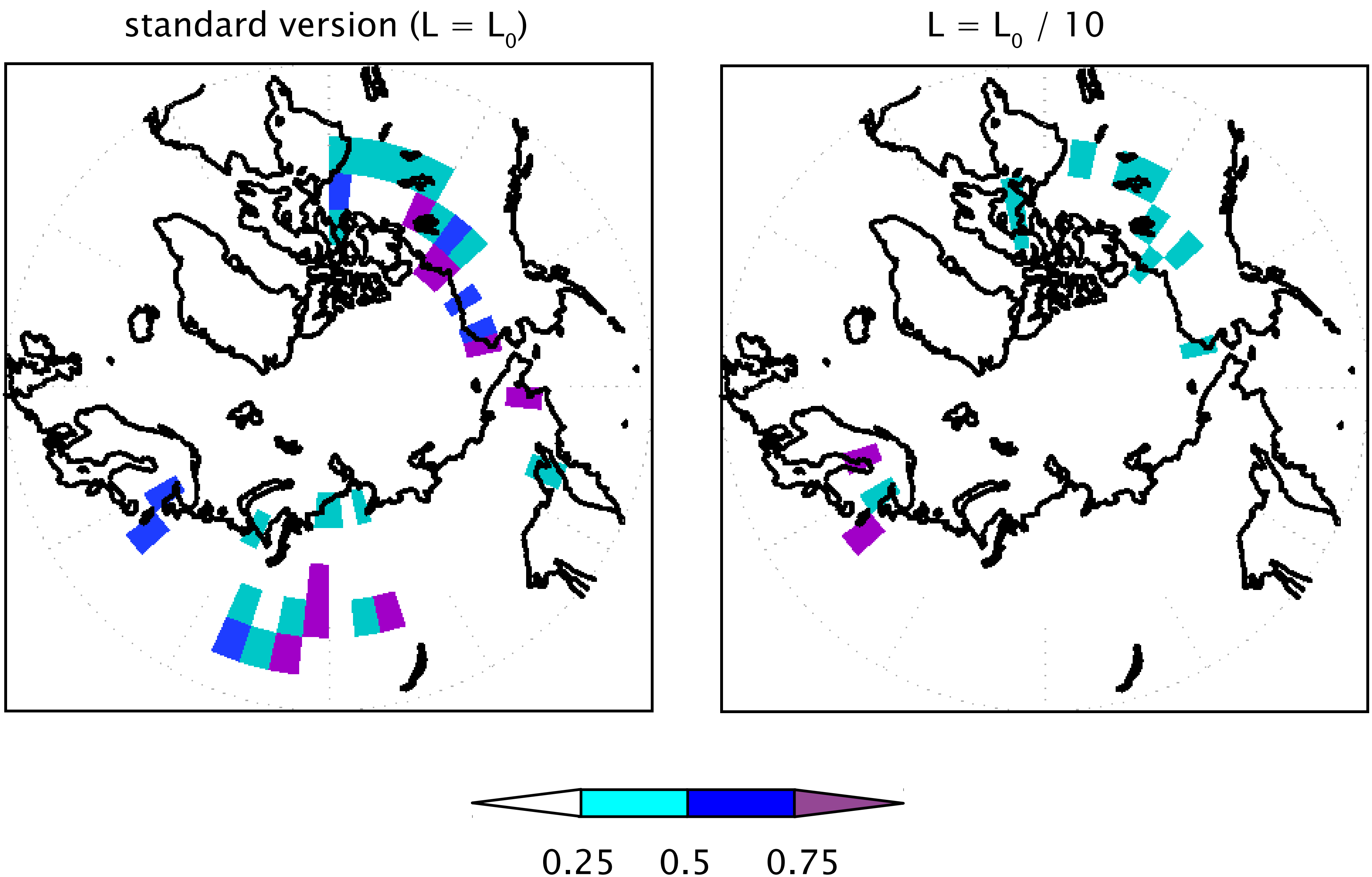
This mechanism is likely not important for permafrost hysteresis. However, it does amplify the separation between the hysteresis branches.

Hysteresis of near-surface permafrost: dependence on model version (P = 1000 yr, A = 0.5)



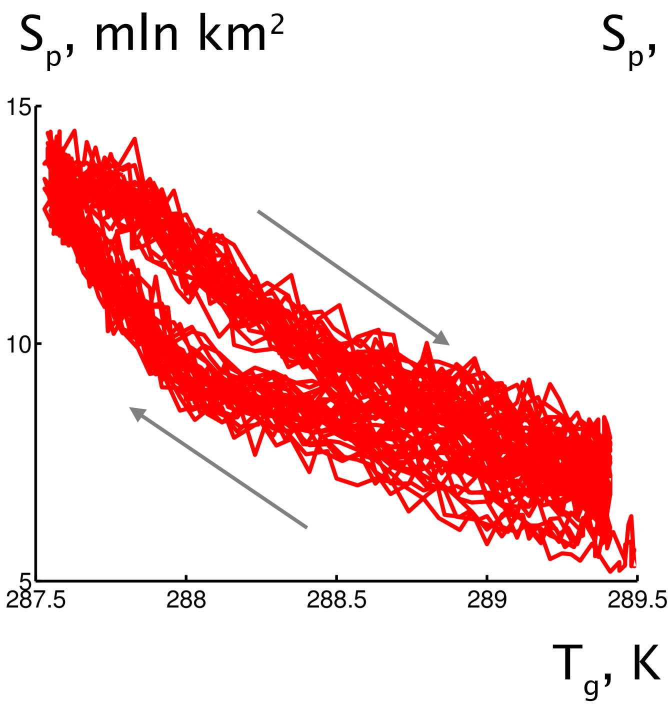
Consistent with the tentative mechanism proposed above

Between-branches difference of near-surface permafrost mask
(P = 1000 yr, A = 0.5)

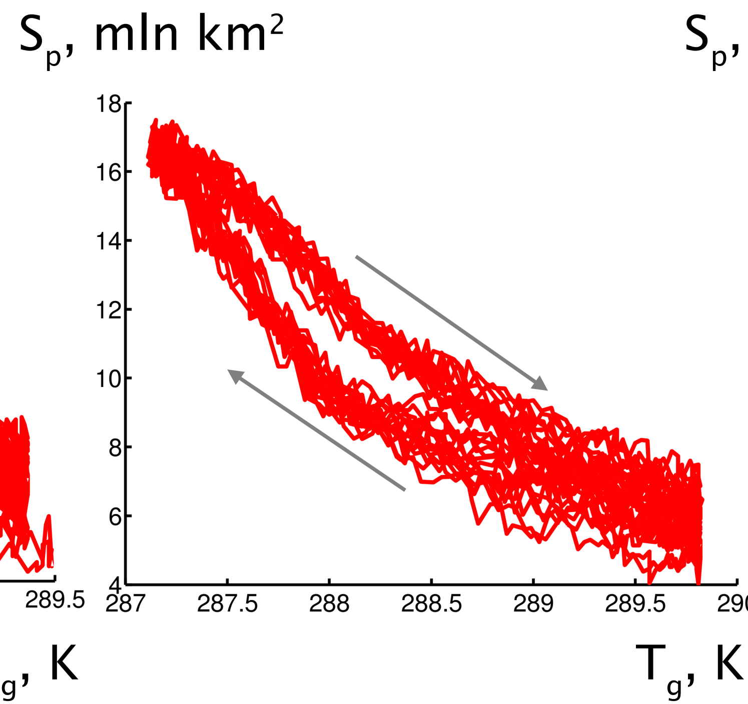


Hysteresis of near-surface permafrost: dependence on time scale of external forcing (standard version of the model, A = 0.5)

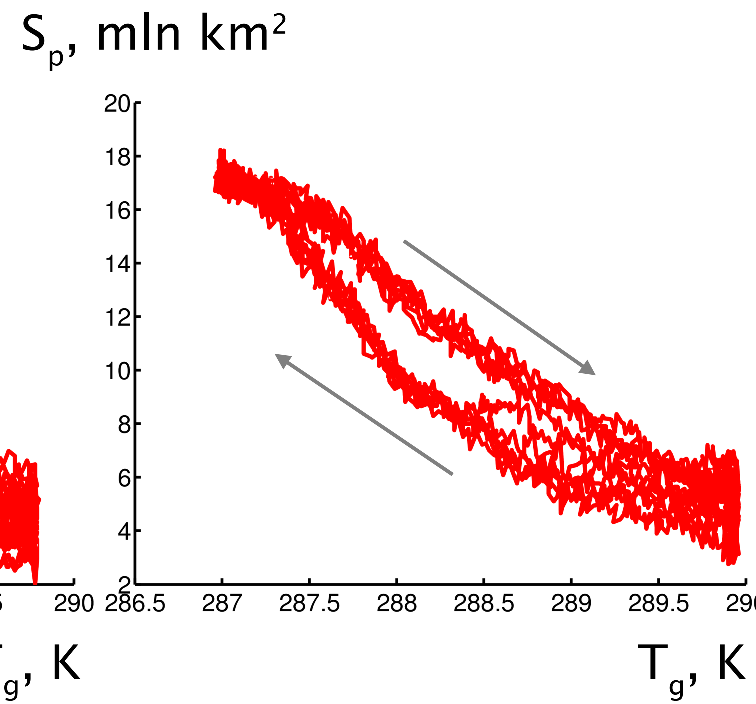
P = 100 yr



P = 200 yr

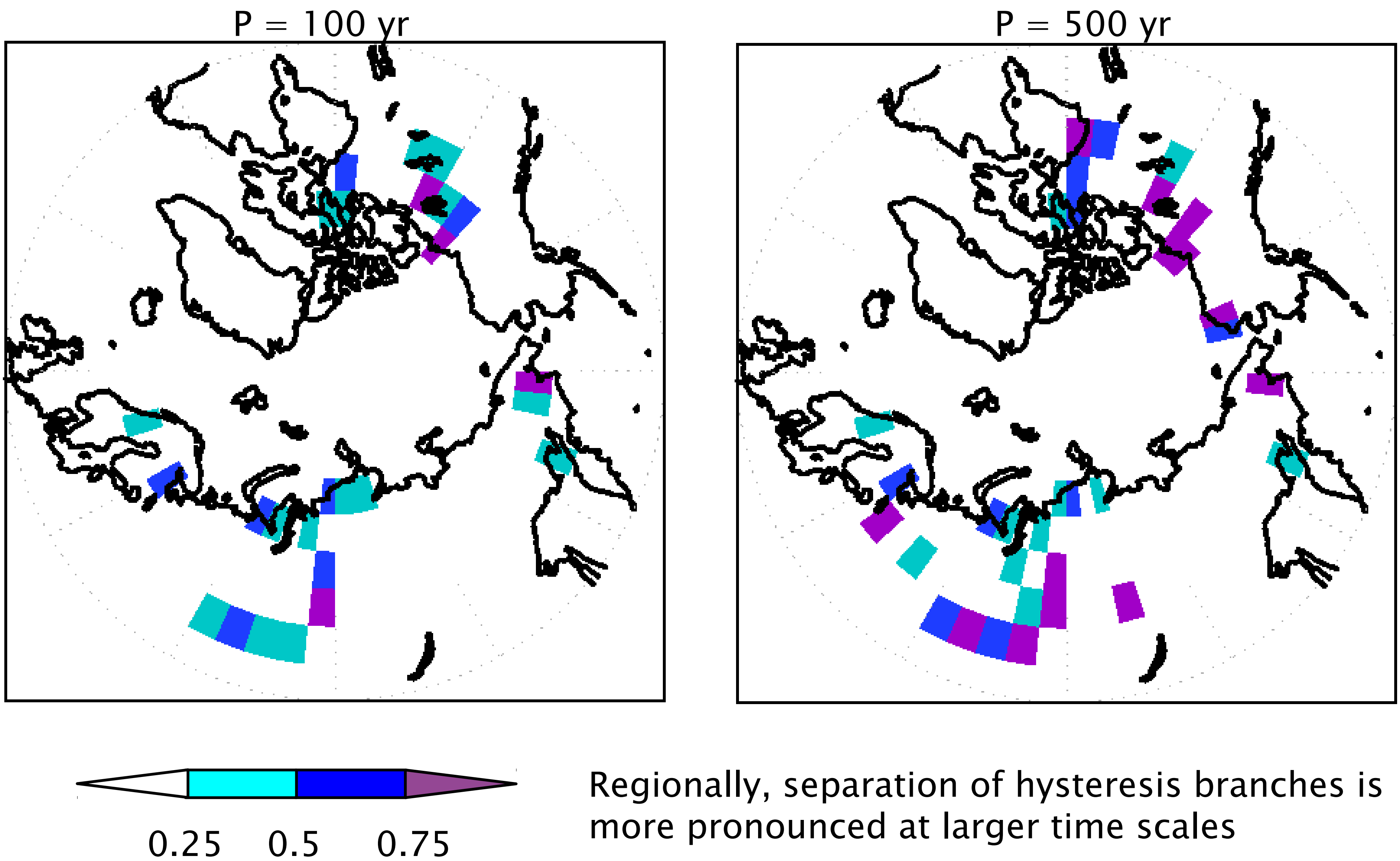


P = 500 yr



For total area, relatively weak dependence on time scale

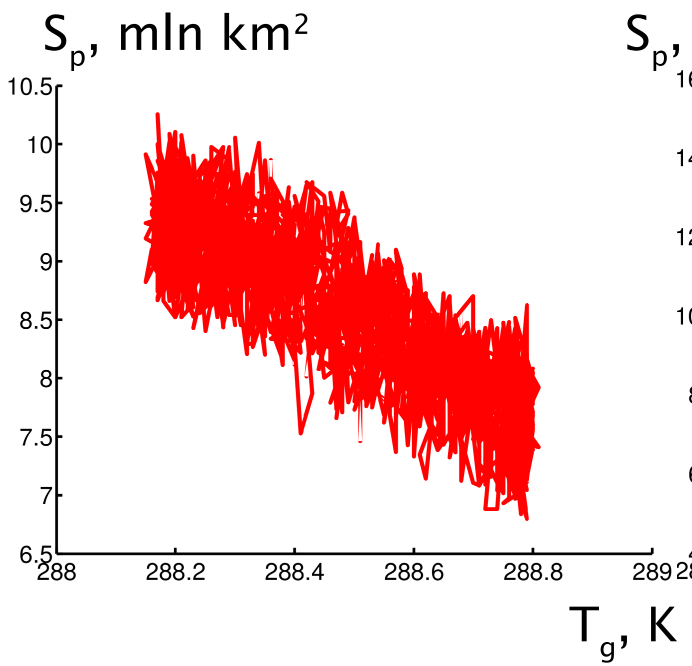
Between-branches difference of near-surface permafrost mask: (standard version of the model, A = 0.5)



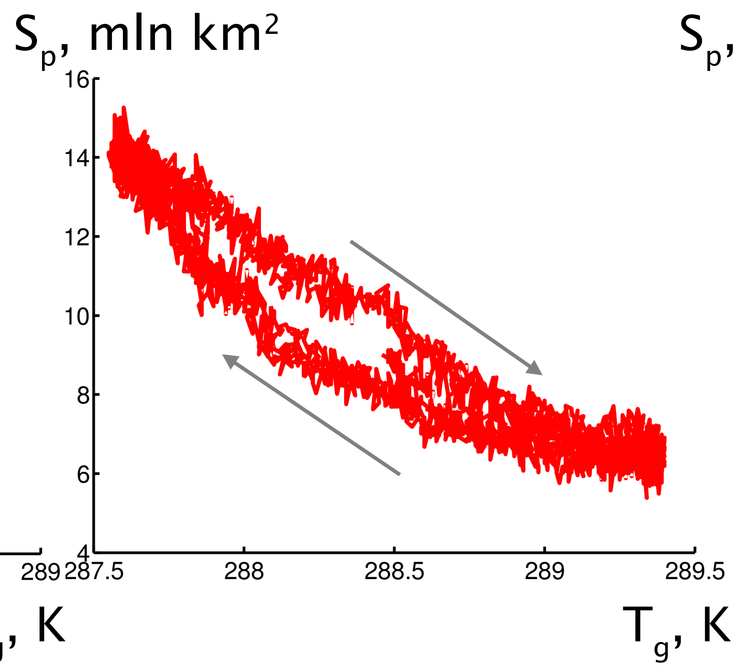
Regionally, separation of hysteresis branches is more pronounced at larger time scales

Hysteresis of near-surface permafrost: dependence on amplitude of external forcing (standard version of the model, P = 1000 yr)

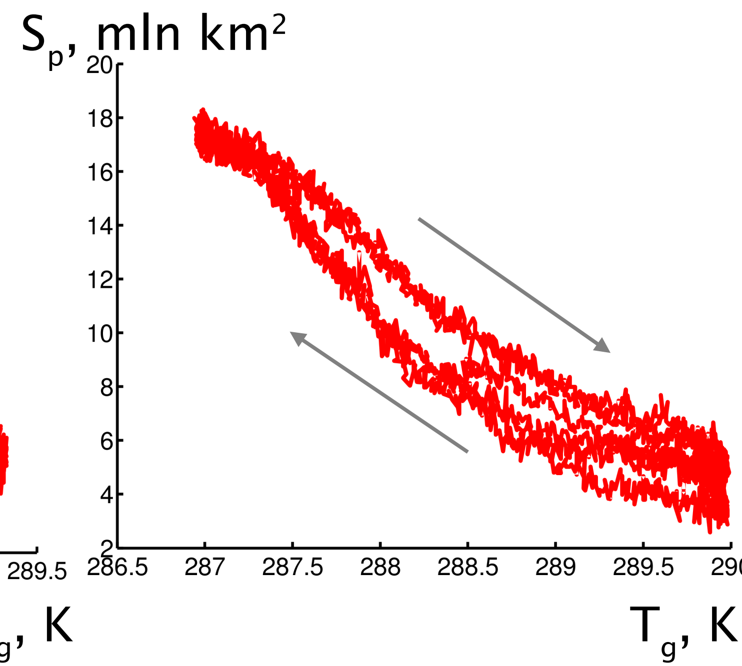
A = 0.1



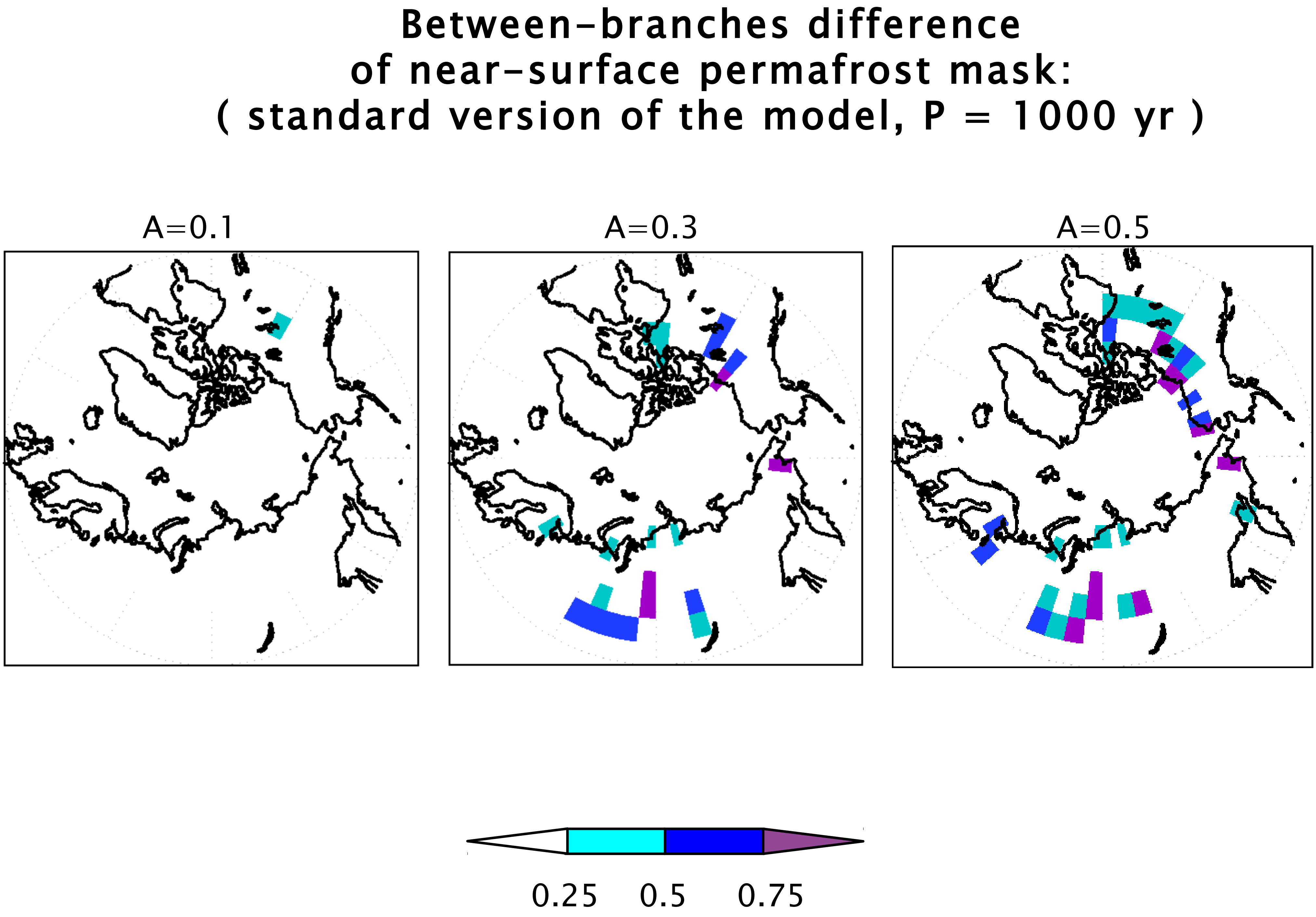
A = 0.3



A = 0.5



Separation of hysteresis branches becomes more pronounced at larger amplitudes

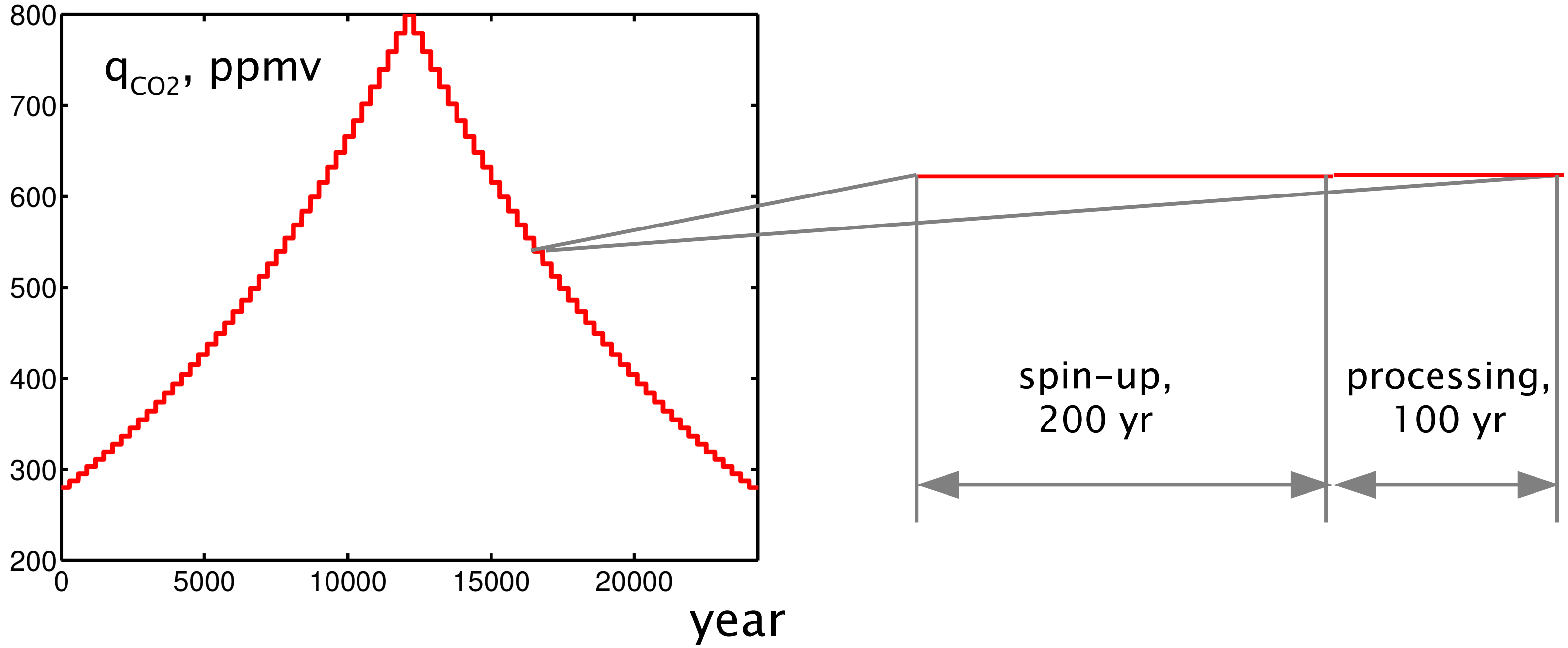


Between-branches difference
of near-surface permafrost mask:
(standard version of the model, P = 1000 yr)
A=0.1
A=0.3
A=0.5
0.25
0.5
0.75

Is transience important ? Additional simulations.

Duration: (3 simulations) * (model years 1-24,300) = 72,900 years

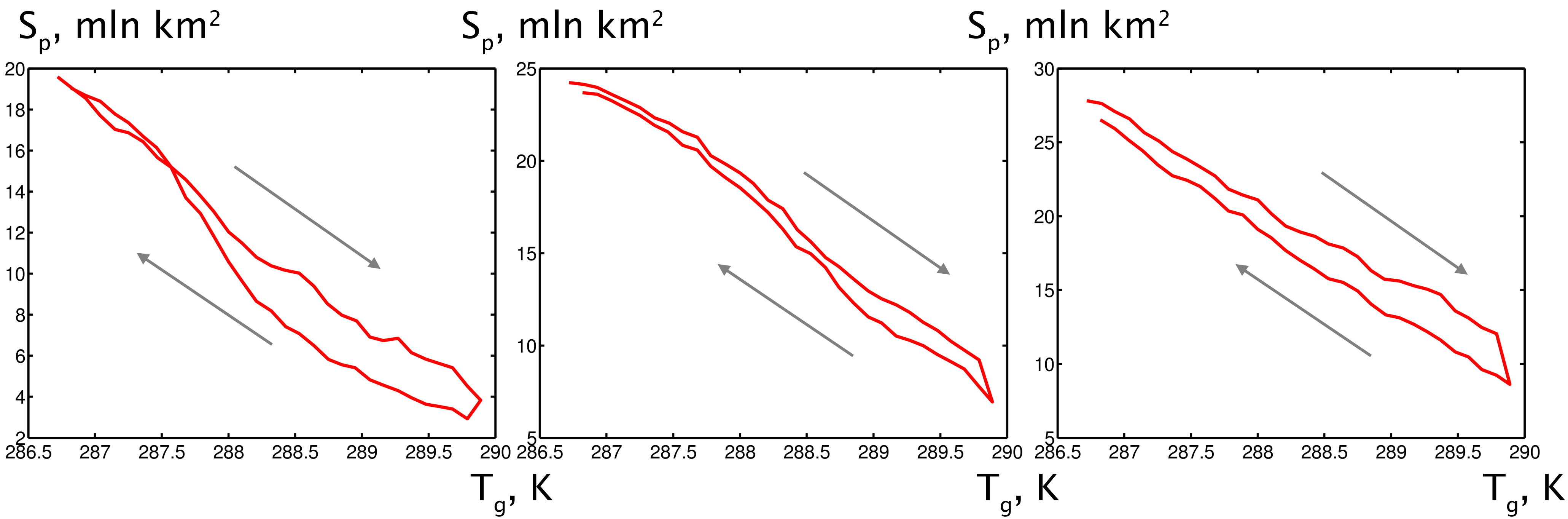
External forcing: stepwise varying q_{CO2}:



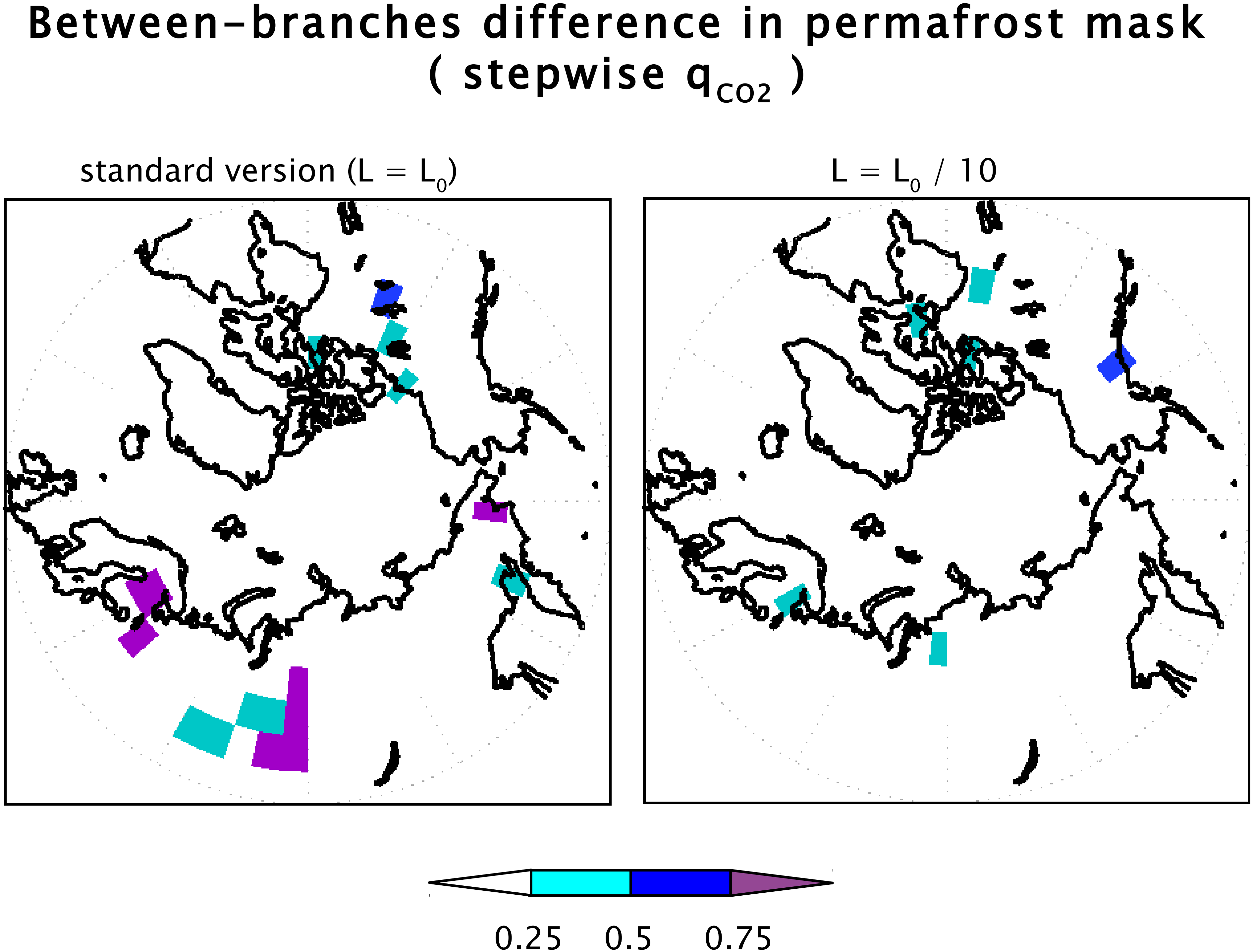
Model versions:
- standard, specific latent heat of freezing $L = L_0 = 3.34*10^5$ J / kg;
- $L = L_0$ / 10 in soil;
- $L = L_0$ / 100 in soil;

Hysteresis of near-surface permafrost: dependence on model version (stepwise q_{CO2})

standard ($L = L_0$) | $L = L_0 / 10$ | $L = L_0 / 100$

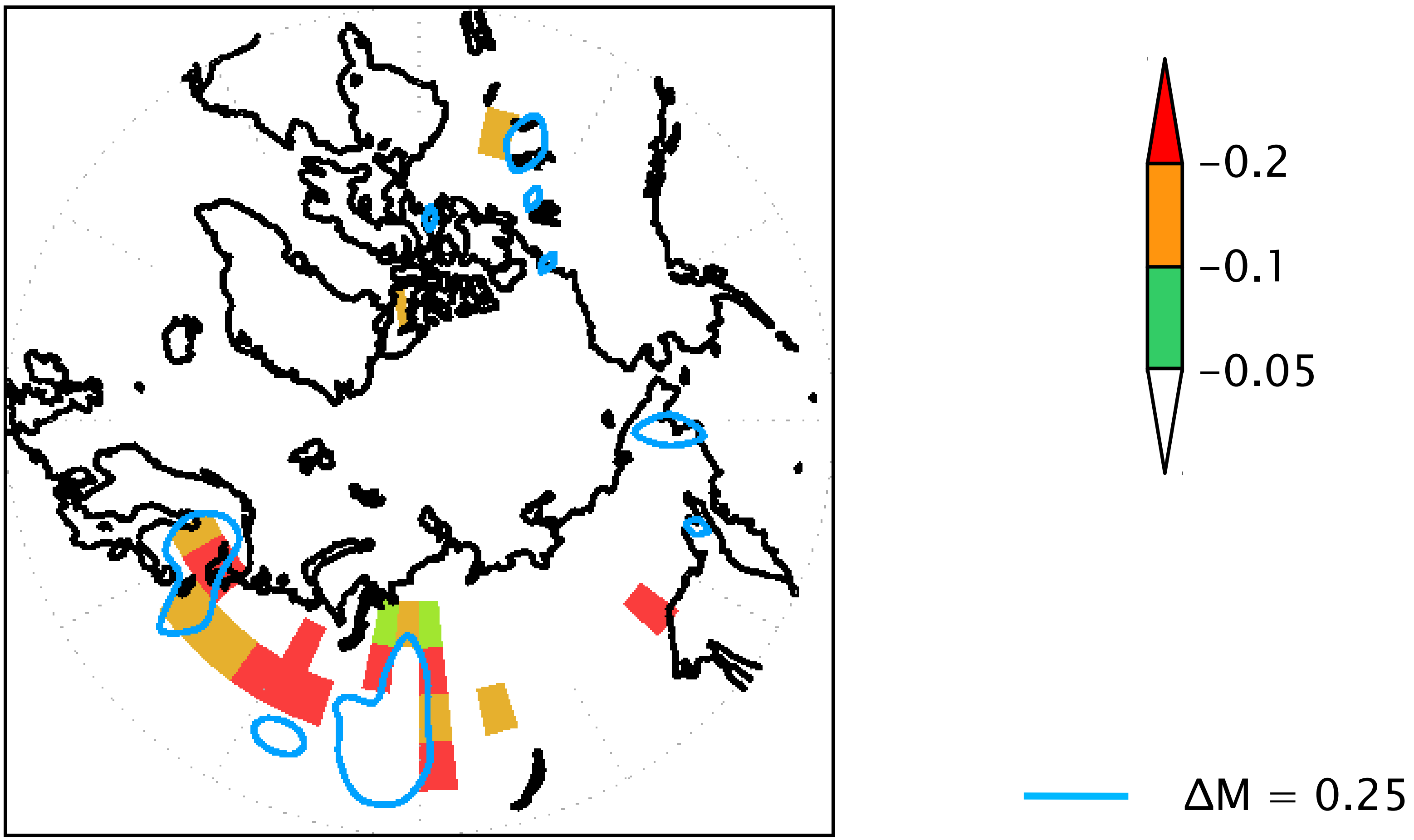


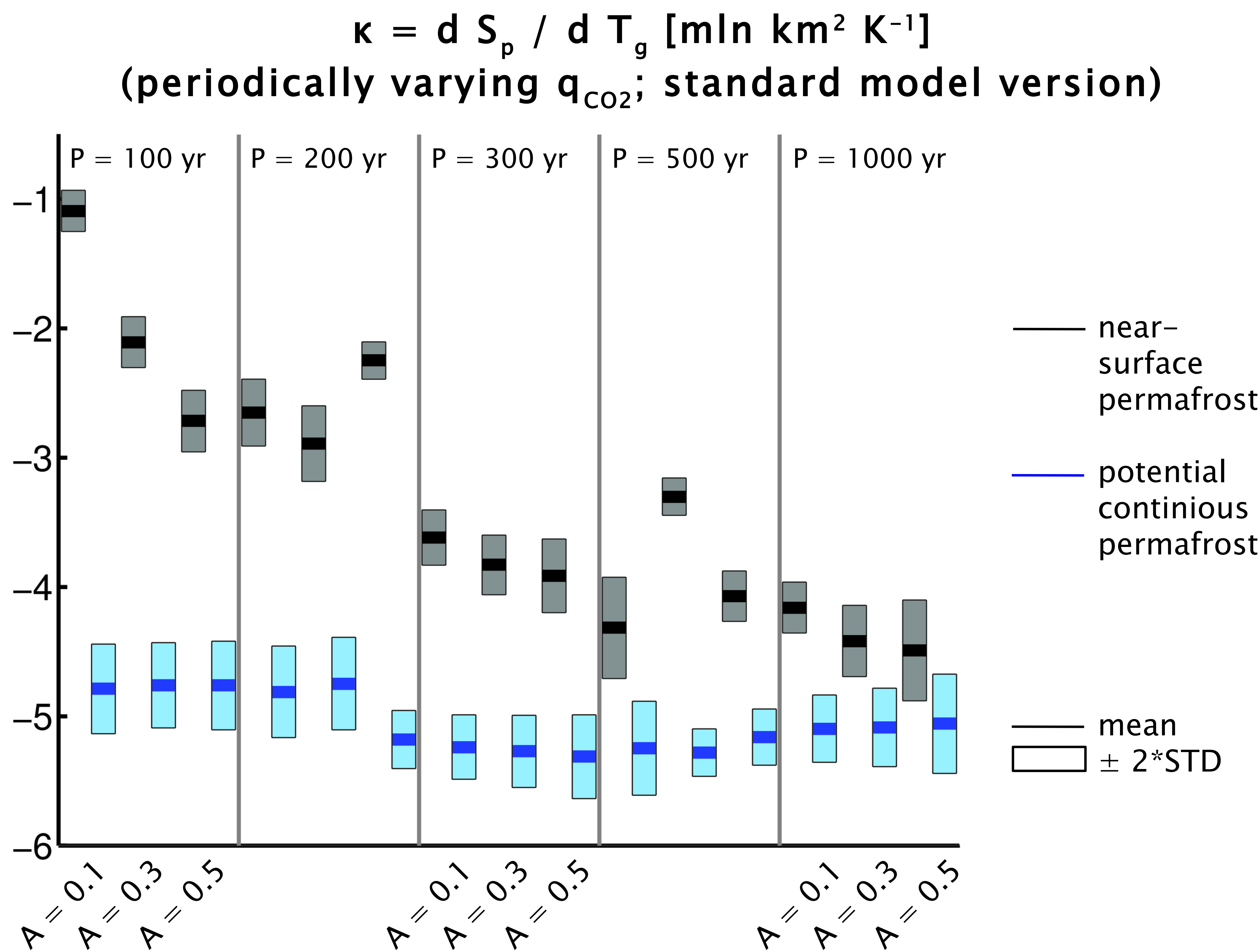
For total area, transience suppresses hysteresis



Between-branches difference in permafrost mask
(stepwise q_{CO2})
standard version ($L = L_0$)
$L = L_0 / 10$
0.25
0.5
0.75

Between-branches difference in soil moisture content in the upper 7 cm of soil column [m/m] (stepwise q_{CO2} ; standard model version)




κ = d S_p / d T_g [mln km^2 K^{-1}]
(periodically varying q_{CO2}; standard model version)
P = 100 yr
P = 200 yr
P = 300 yr
P = 500 yr
P = 1000 yr
−1
−2
−3
−4
−5
−6
near-surface permafrost
potential continious permafrost
mean
± 2*STD
A = 0.1
A = 0.3
A = 0.5
A = 0.1
A = 0.3
A = 0.5
A = 0.1
A = 0.3
A = 0.5

Conclusions

- In the IAP RAS CM simulations forced by the return-to-preindustrial continuations of the RCP scenarios, a possibility of hysteresis in dependence of near-surface permafrost (NSP) extent S_p on global temperature T_g is shown: in some temperature range which depends on imposed scenario of external forcing, for a given value of T_g, NSP area is larger in the case of warming climate than in the case when climate cools. This hysteresis is due to dependence of soil state in the regions of extra-tropical wetlands and near the contemporary NSP boundaries on sign of climatic external forcing.

- In the simulations forced by the periodically-varying q_{CO2}, it is exhibited that multivalued dependence of S_p on T_g is related to the impact of phase transitions of soil water on apparent inertia of the system owing to talik formation. This mechanism is amplified by the respective changes in soil and atmospheric hydrological cycle and associated radiation transfer in the atmosphere. Transience is not important for the NSP hysteresis.

- In addition, it is shown that potential permafrost may approximate the real permafrost only at millennia and longer time scale. At centennial and shorter scales, sensitivity of potential permafrost drastically overestimate those for real permafrost. This poses limitations on palaeoclimate permafrost reconstructions based only on SAT.