Влияние изменения климата на вечную мерзлоту: наблюдения, моделирование, прогноз.

Impacts of changing climate on permaprost: observations and predictive modeling

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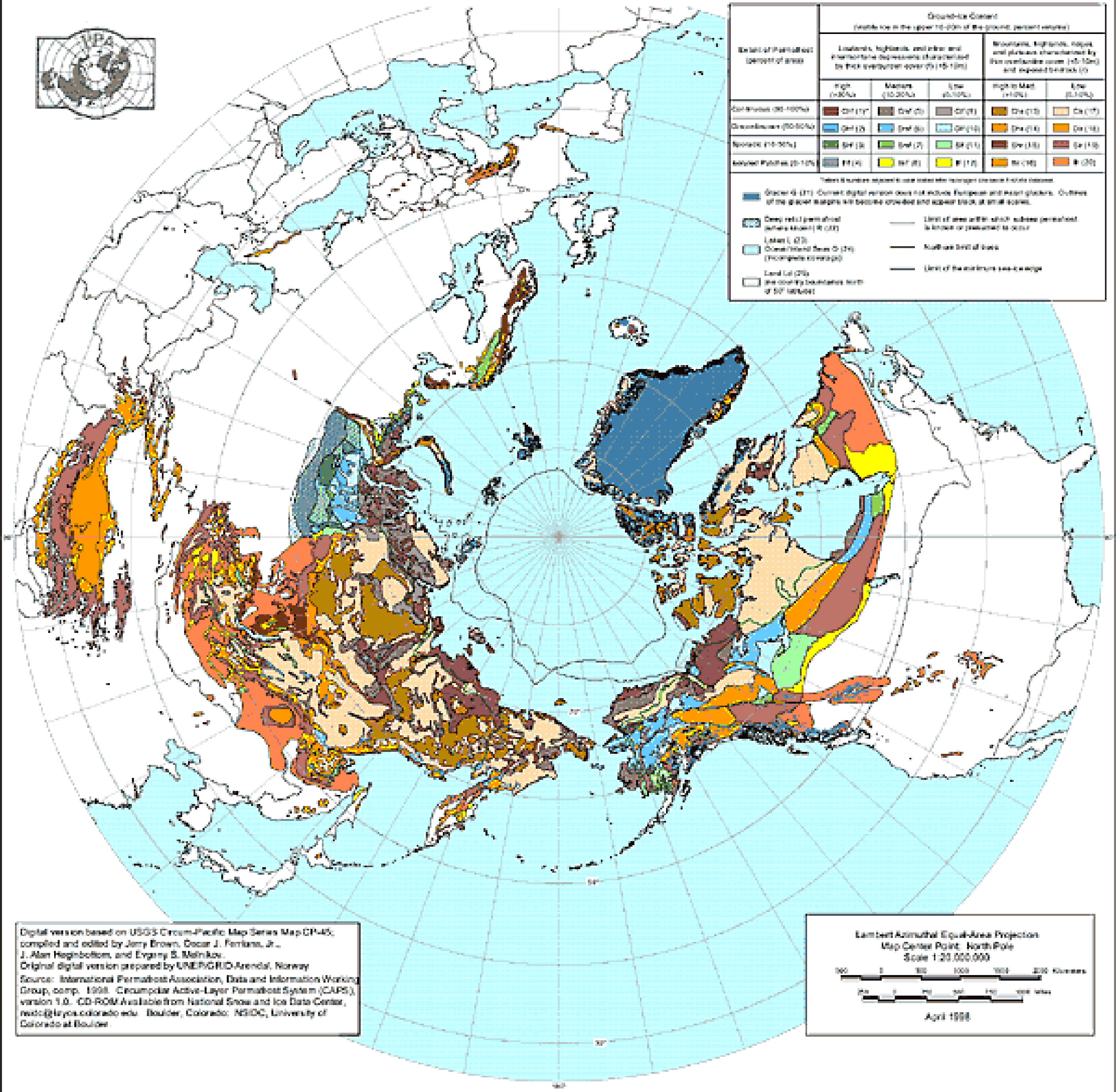
STATE HYDROLOGICAL INSTITUTE

CIRCUM-ARCTIC MAP OF PERMAFROST AND GROUND-ICE CONDITIONS

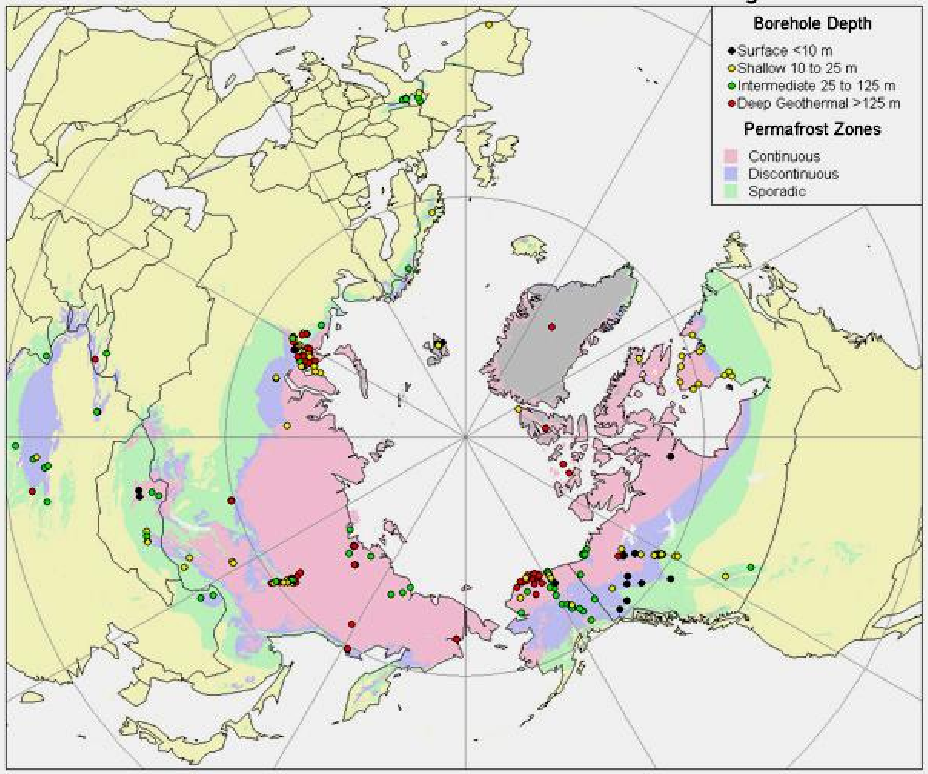


Permafrost observational programs

GTN-P
Global Terrestrial Network for Permafrost

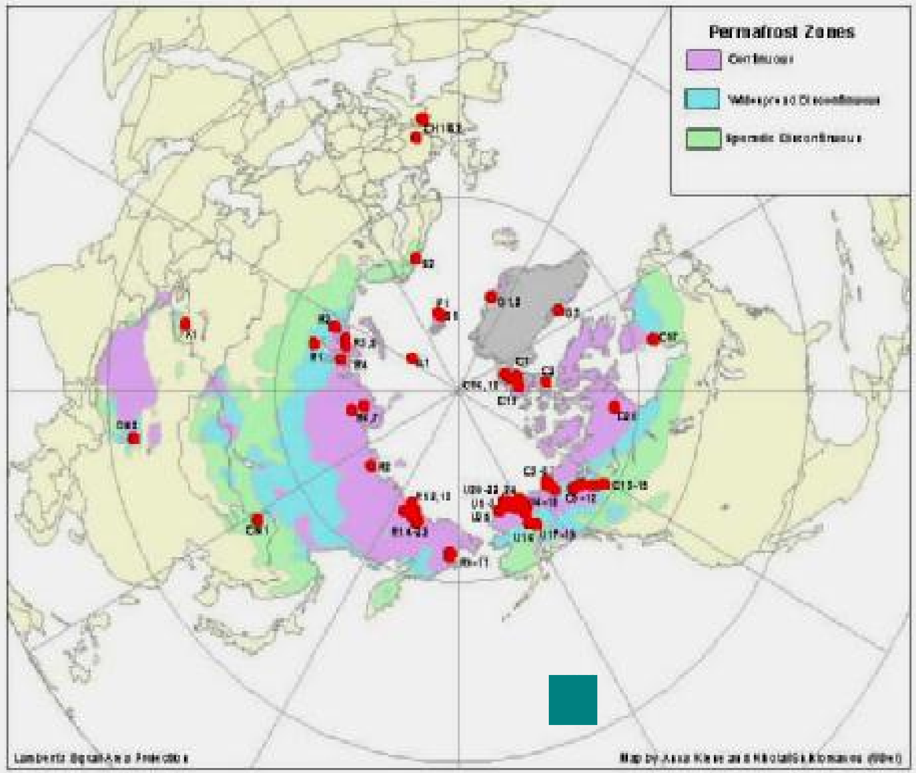
CALM
Circumpolar Active Layer Monitoring

Candidate Boreholes for Permafrost Thermal Monitoring

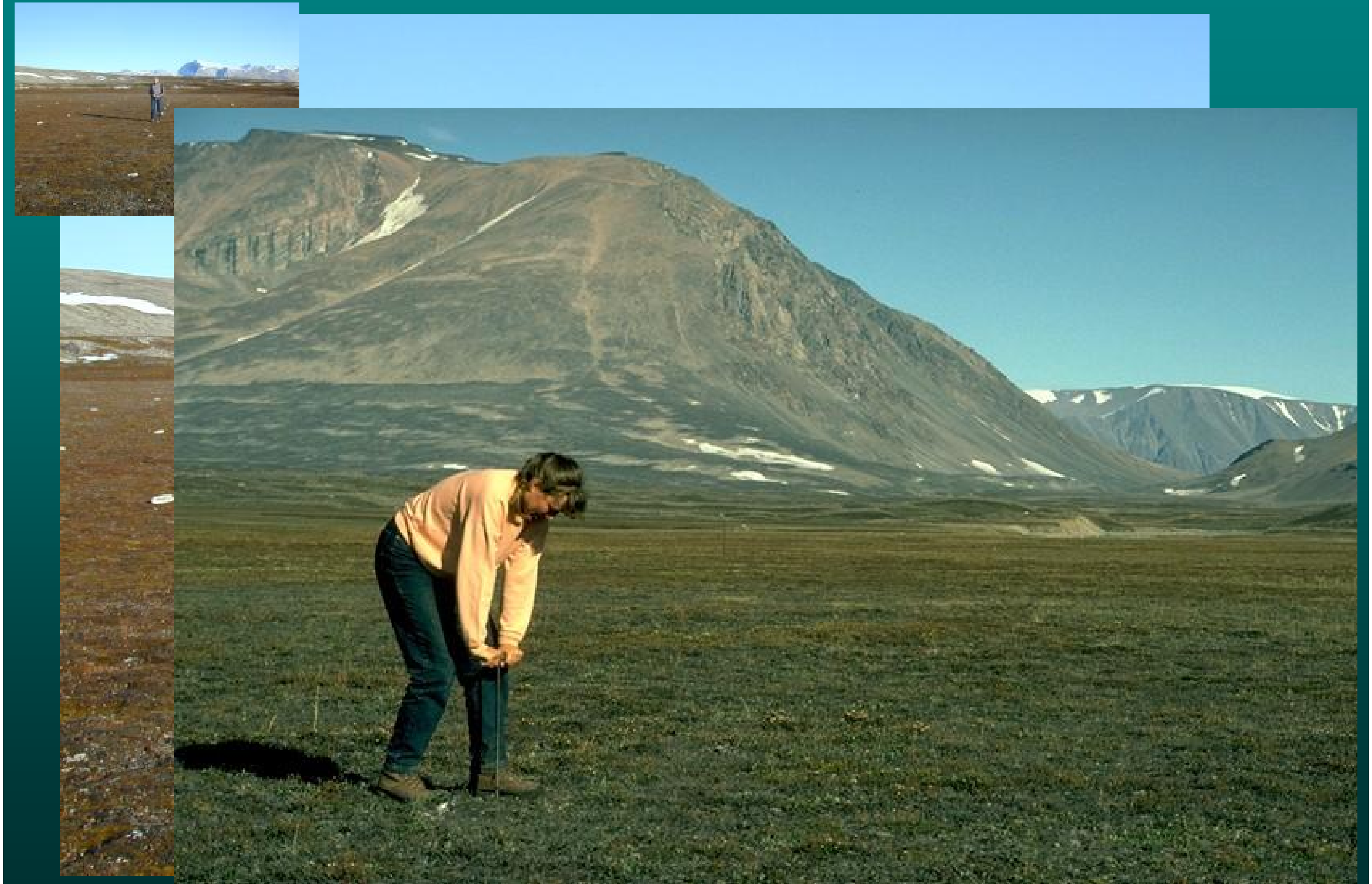


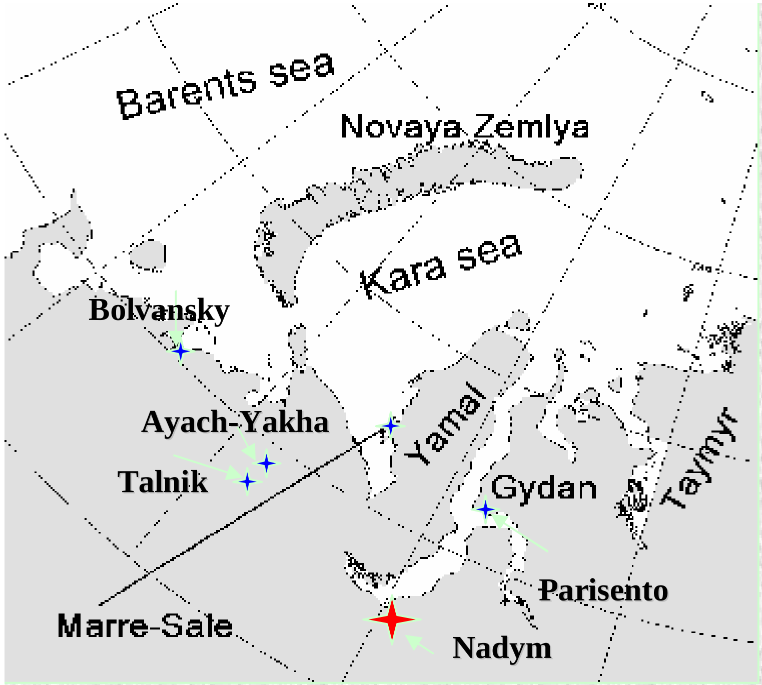
Map compiled by S.L. Smith, Geological Survey of Canada, March, 2001

Circumpolar Active Layer Monitoring (CALM) Network

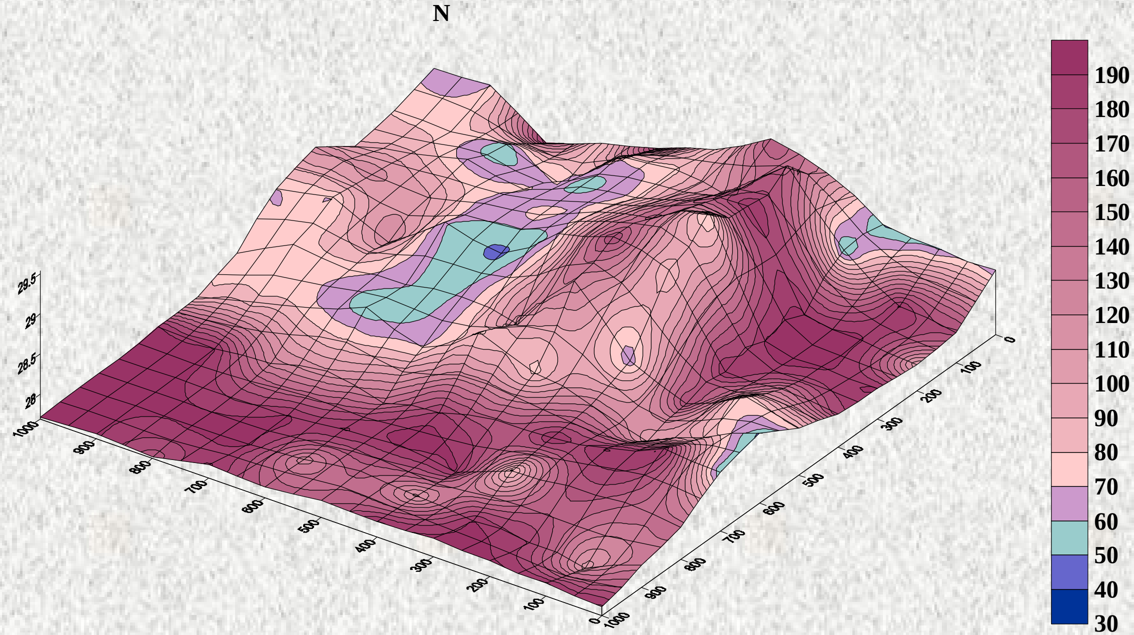


Permafrost measurements at CALM site on Svalbard

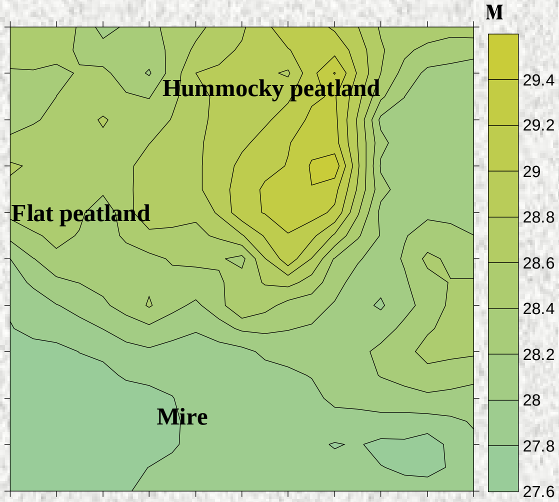




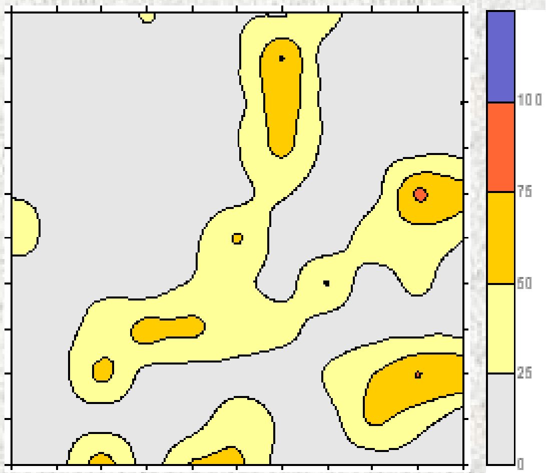
NADYM GRID: AVERAGE THAW DEPTH (130 cm) AND TERRAIN



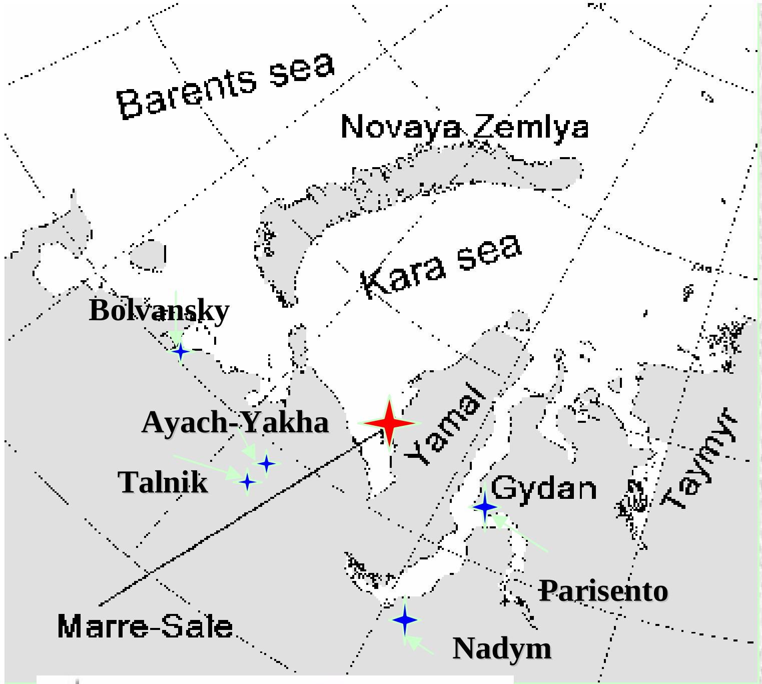
NADYM TERRAIN

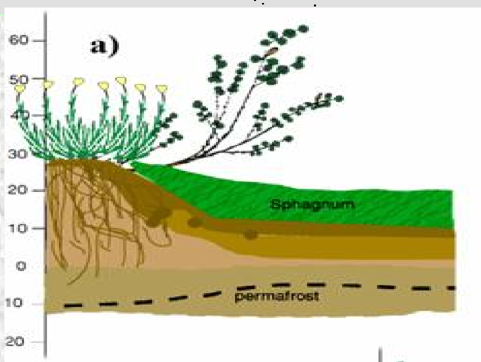


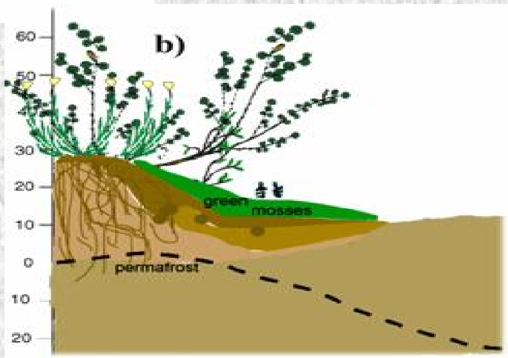
NADYM INV (20%)

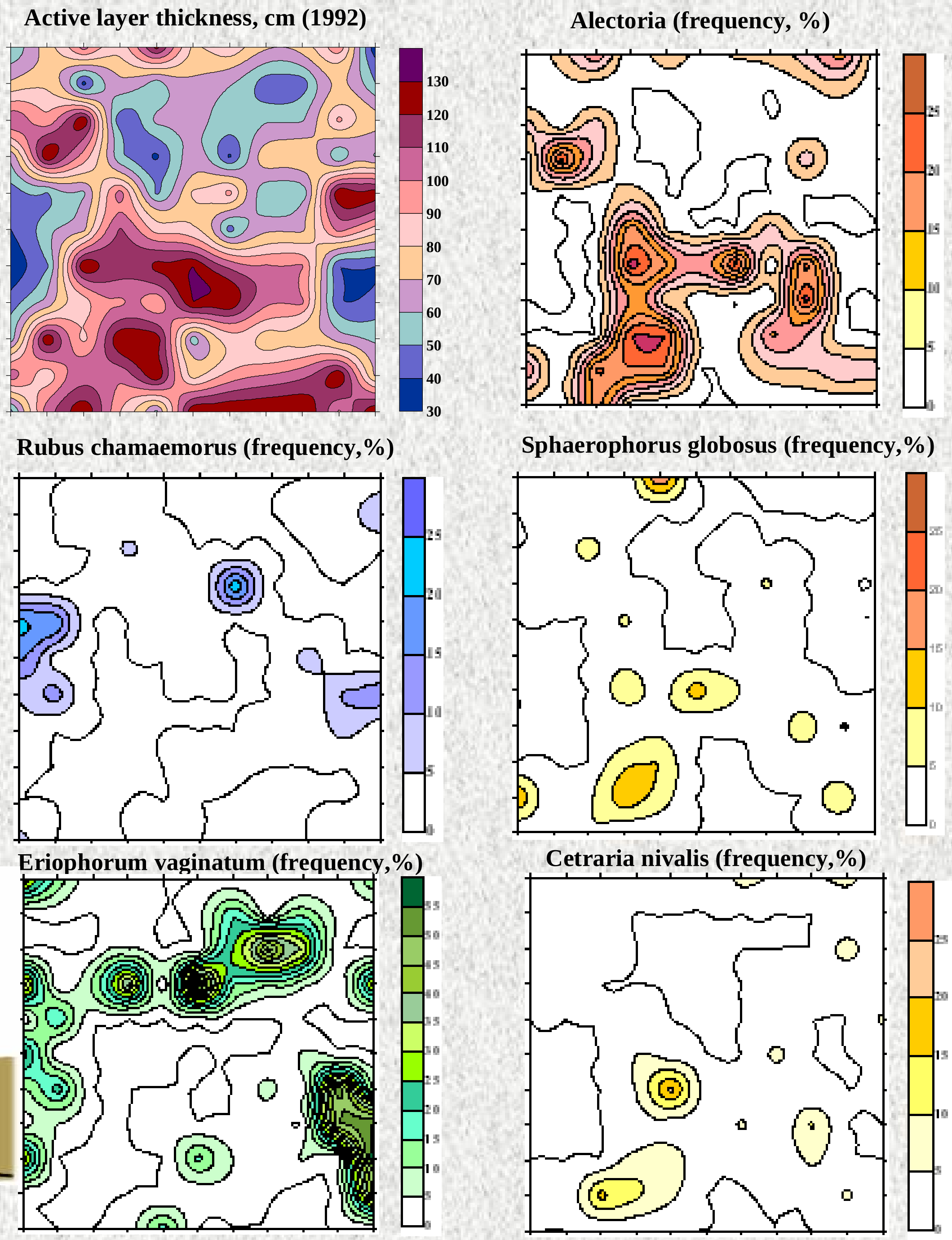


Vasiliev et al., 2005





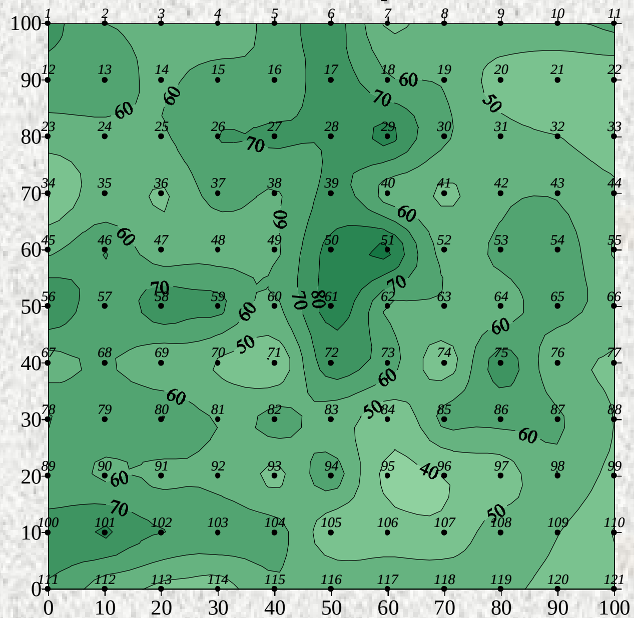




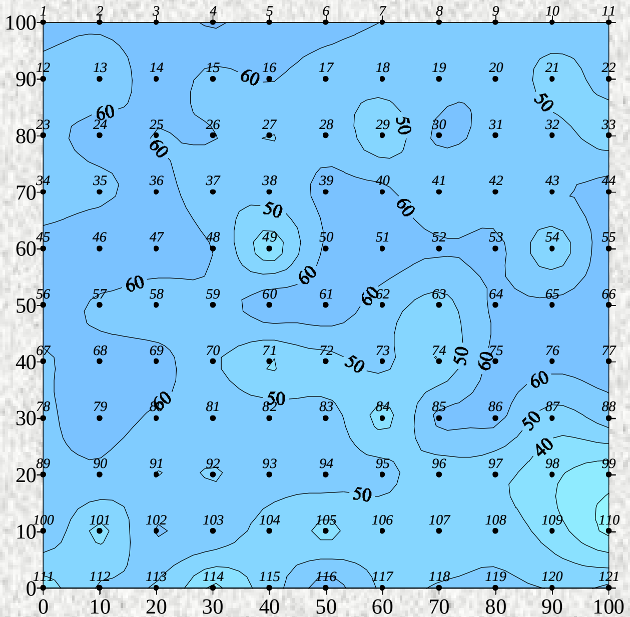
Malkova et al., 2005

Cape Lavrentia

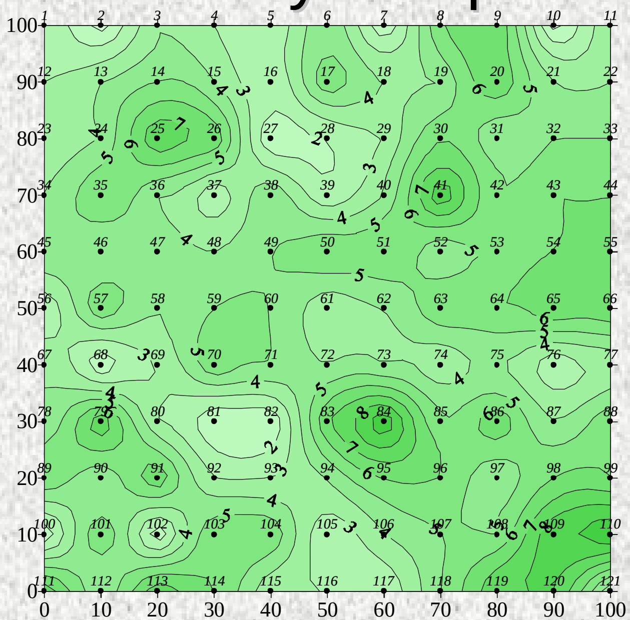
Thaw depth



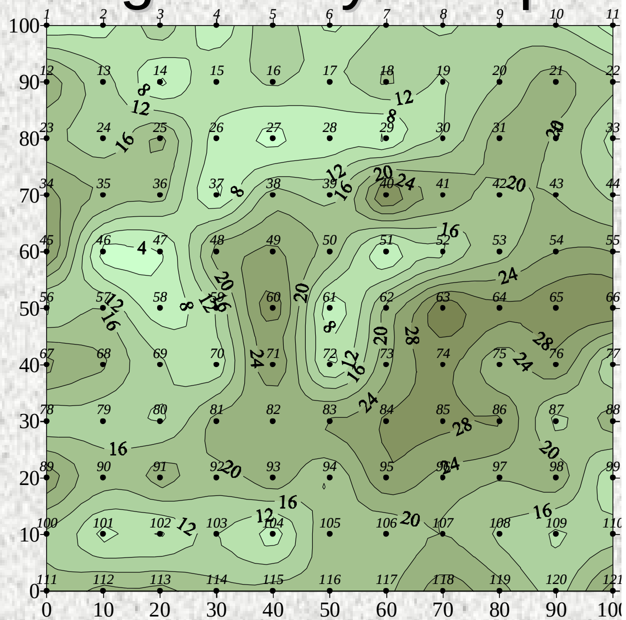
Soil moisture

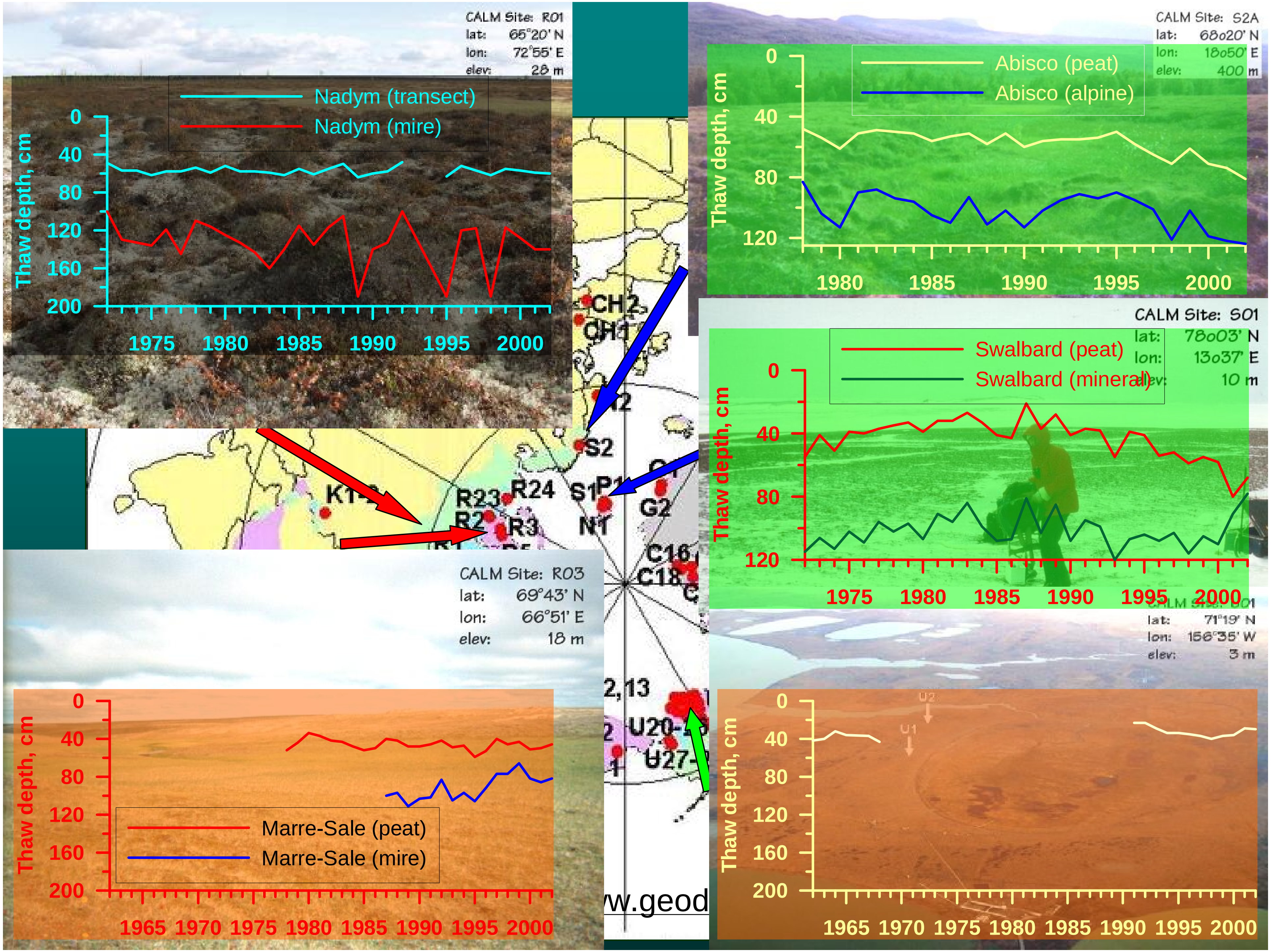


Moss layer depth

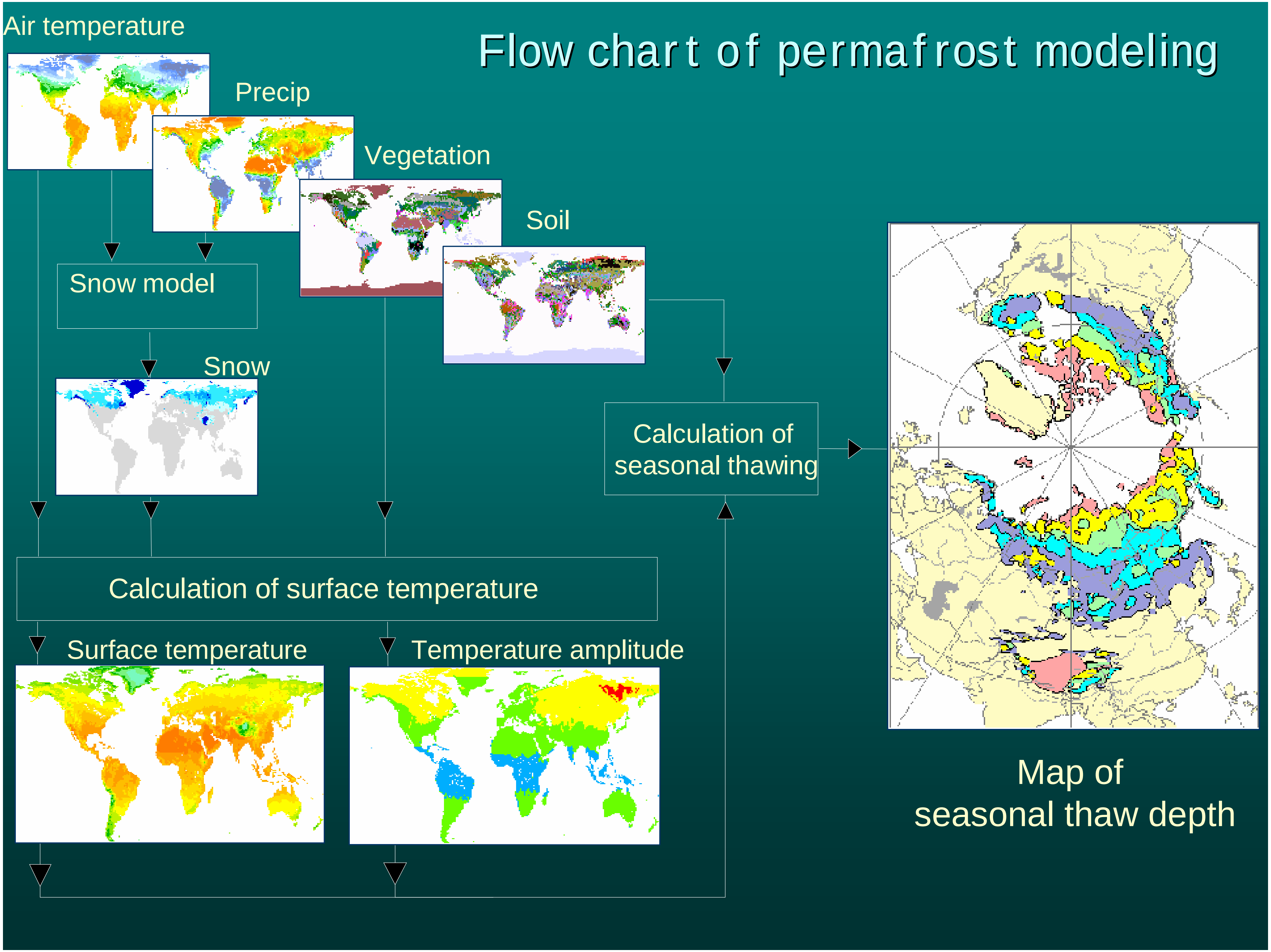


Organic layer depth

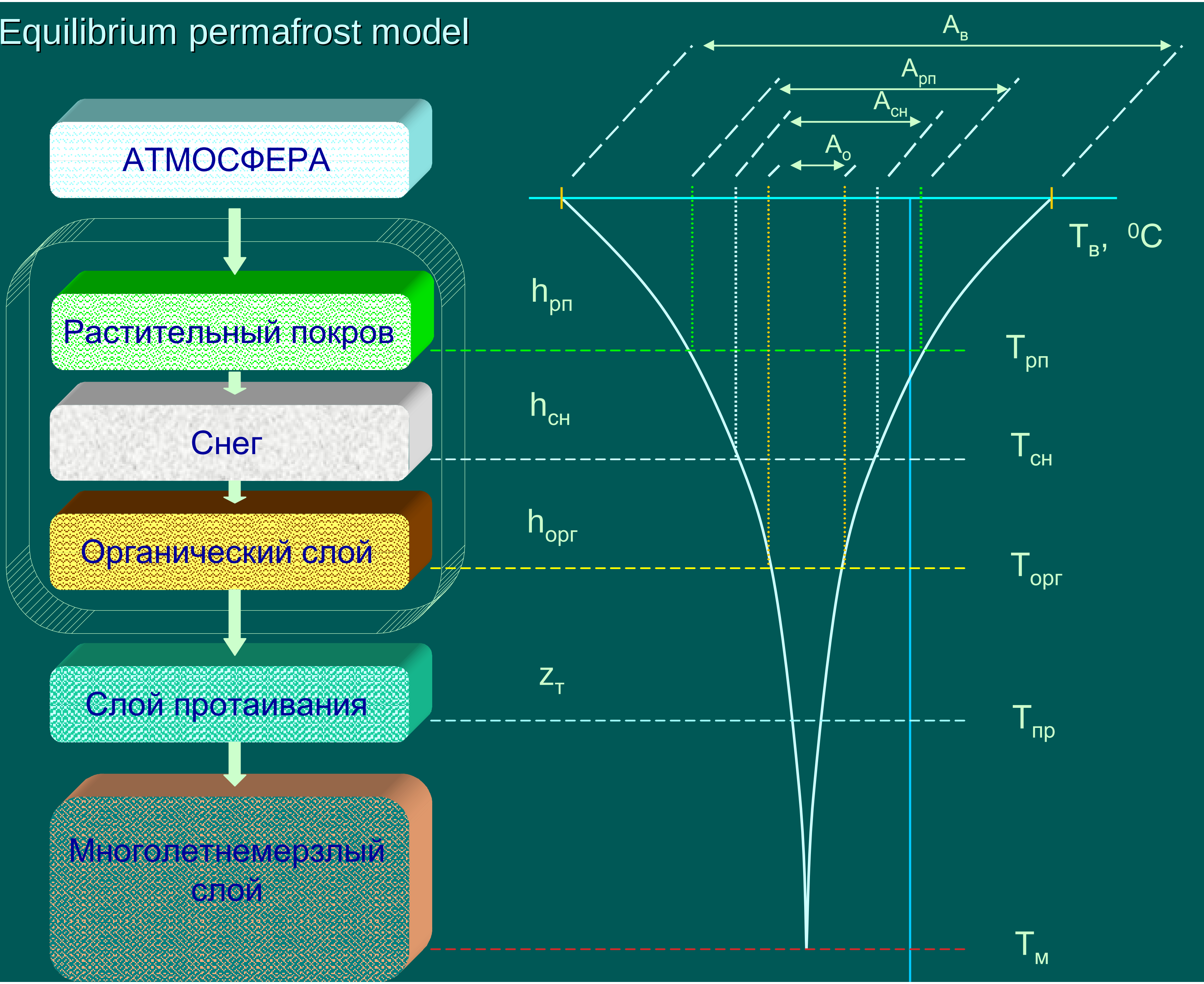


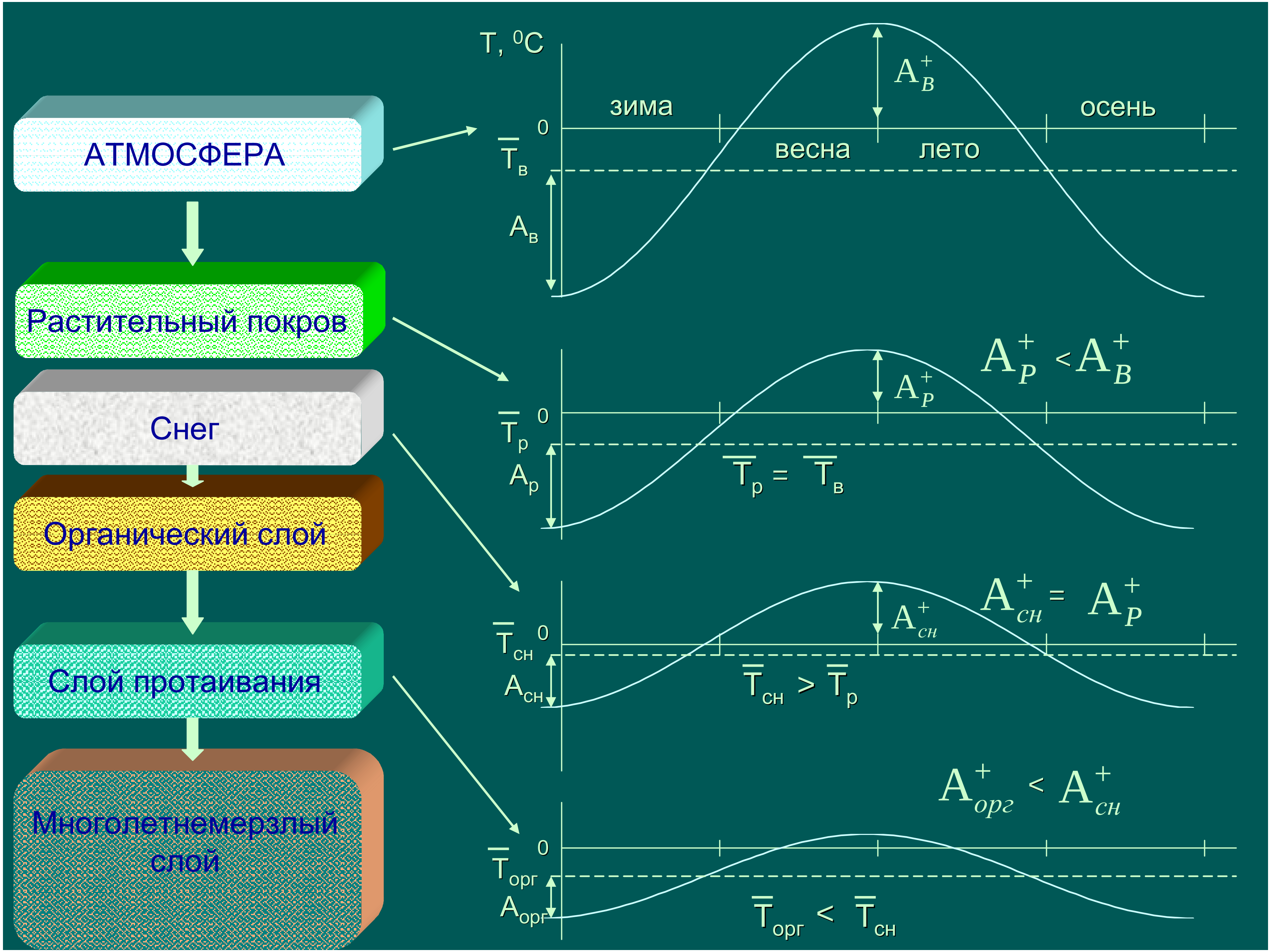


CALM Site: R01
lat: 65°20' N
lon: 72°55' E
elev: 28 m
Nadym (transect)
Nadym (mire)
Thaw depth, cm
0
40
80
120
160
200
1975
1980
1985
1990
1995
2000
CALM Site: S2A
lat: 68o20' N
lon: 18o50' E
elev: 400 m
Abisco (peat)
Abisco (alpine)
Thaw depth, cm
0
40
80
120
1980
1985
1990
1995
2000
CALM Site: S01
lat: 78o03' N
lon: 13o37' E
elev: 10 m
Swalbard (peat)
Swalbard (mineral)
Thaw depth, cm
0
40
80
120
1975
1980
1985
1990
1995
2000
CH2
CH1
S2
S1
P1
N1
G2
K1
R23
R24
R2
R3
C16
C18
U20
U27
CALM Site: R03
lat: 69°43' N
lon: 66°51' E
elev: 18 m
Marre-Sale (peat)
Marre-Sale (mire)
Thaw depth, cm
0
40
80
120
160
200
1965
1970
1975
1980
1985
1990
1995
2000
lat: 71°19' N
lon: 156°35' W
elev: 3 m
Thaw depth, cm
0
40
80
120
160
200
1965
1970
1975
1980
1985
1990
1995
2000
w.geod


Flow chart of permafrost modeling
Air temperature
Precip
Vegetation
Soil
Snow model
Snow
Calculation of seasonal thawing
Calculation of surface temperature
Surface temperature
Temperature amplitude
Map of seasonal thaw depth

Equilibrium permafrost model




АТМОСФЕРА
Растительный покров
Снег
Органический слой
Слой протаивания
Многолетнемерзлый слой
T, 0C
0
зима
весна
лето
осень
$\overline{T}_в$
$A_в$
A_B^+
$\overline{T}_р$
$A_р$
A_P^+
$A_P^+ < A_B^+$
$\overline{T}_р = \overline{T}_в$
$\overline{T}_{сн}$
$A_{сн}$
$A_{сн}^+$
$A_{сн}^+ = A_P^+$
$\overline{T}_{сн} > \overline{T}_р$
$\overline{T}_{орг}$
$A_{орг}$
$A_{орг}^+ < A_{сн}^+$
$\overline{T}_{орг} < \overline{T}_{сн}$

$$T_п = T_в + \Delta T_{сн} + \Delta T_р, \quad A_п = A_в - \Delta A_{сн} - \Delta A_р, \quad Z_{сн} = \sin^2 f\ \frac{1}{k}\left\{\sum_{i=1}^{k} h_i\left(k - (i-1)\right)\right\}$$

$$DT_{сн} = A_в\left(1 - \exp\left(-Z_{сн}\left(\frac{p \cdot c_{сн} \cdot r_{сн}}{P \cdot l_{сн}}\right)^{1/2}\right)\right) \qquad DA_{сн} = A_в\left(1 - \exp\left(-Z_{сн}\left(\frac{p \cdot c_{сн} \cdot r_{сн}}{P \cdot l_{сн}}\right)^{1/2}\right)\right)$$

$$DT_р = \frac{DA_1 t_1 + DA_2 t_2}{P} \cdot \frac{2}{p} \qquad DA_р = \frac{DA_1 t_1 + DA_2 t_2}{P}$$

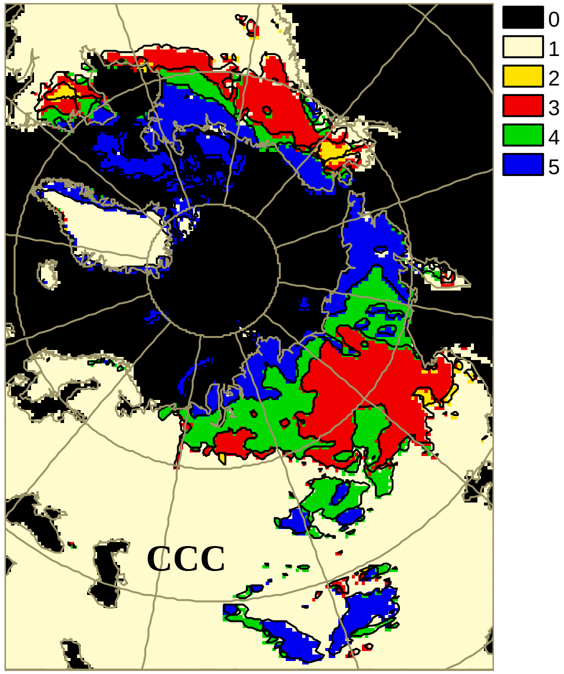
$$DA_1 = \left(A_р - T_р\right)\left(1 - \exp\left(-Z_р\left(\frac{p}{K_р^- \cdot 2t_1}\right)^{1/2}\right)\right) \qquad DA_2 = \left(A_р + T_р\right)\left(1 - \exp\left(-Z_р\left(\frac{p}{K_р^+ \cdot 2t_2}\right)^{1/2}\right)\right)$$

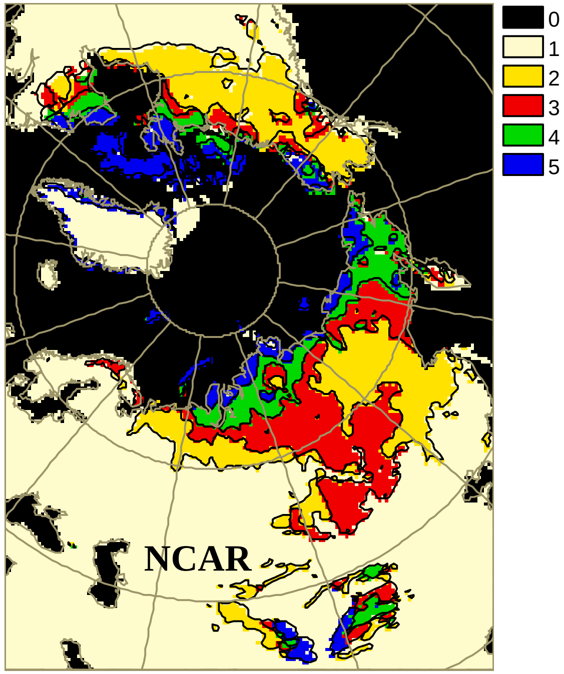
$$T_р = T_в + DT_{сн},$$

$$A_р = A_в - \Delta A_{сн},$$

$$T_м = \frac{0.5 \cdot T_п \cdot \left(l_м + l_т\right) + A_п \frac{l_т - l_м}{p}\left(\frac{T_п}{A_п}\arcsin\frac{T_п}{A_п} + \left(1 - \frac{T_п^2}{A_п^2}\right)^{1/2}\right)}{l^*}$$

$$Z = \frac{2\left(A_п - T_м\right) \cdot \left(\frac{l \cdot P \cdot C}{p}\right)^{1/2} + \frac{\left(2A_м \cdot C \cdot Z_м + Q_ф \cdot Z\right) \cdot Q_ф \cdot \left(\frac{l \cdot P \cdot}{p \cdot C}\right)^{1/2}}{2A_м \cdot C \cdot Z_м + Q_ф \cdot Z + \left(2A_м \cdot C + Q_ф\right) \cdot \left(\frac{l \cdot P \cdot}{p \cdot C}\right)^{1/2}}}{2A_м \cdot C + Q_ф}$$

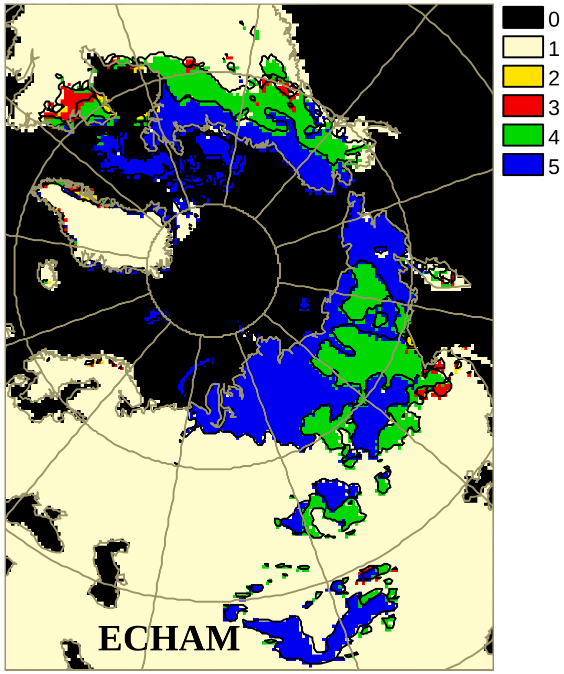


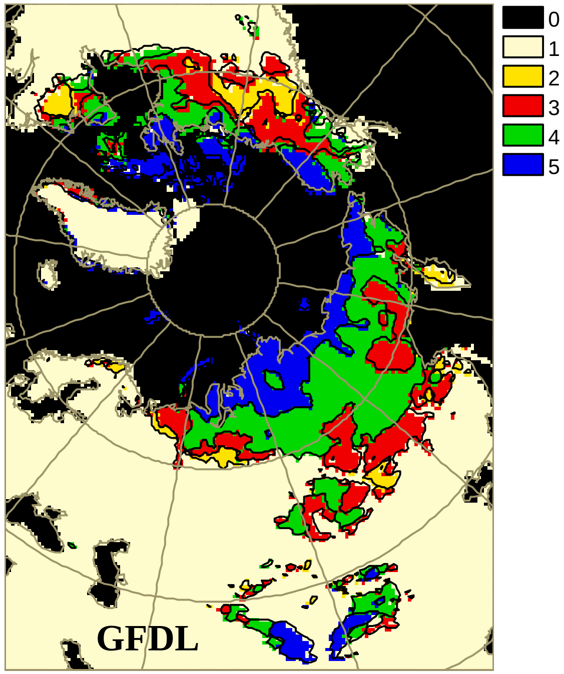


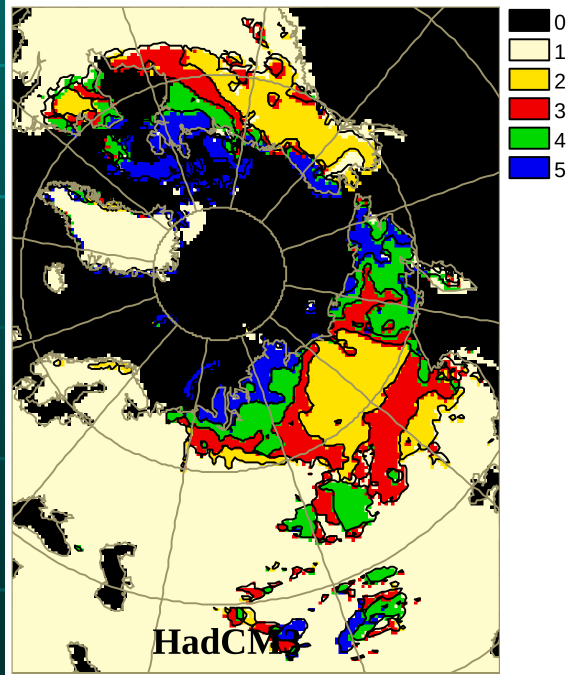
Projected for 2050 changes of seasonal thaw depth (relative to 2000)

0 – ocean
1 – permafrost-free land

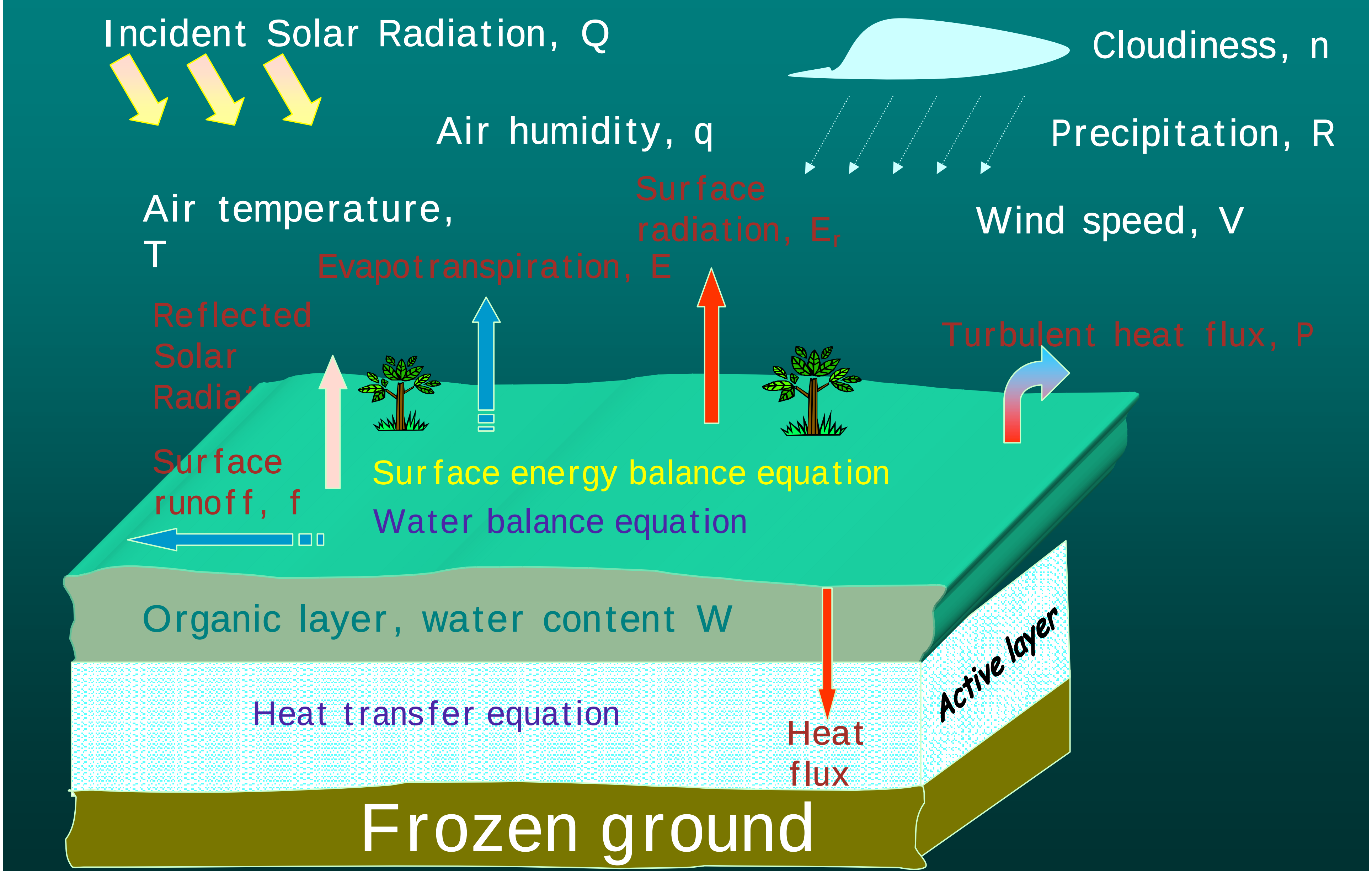
2 – 0% - 20% increase
3 – 20% - 30% increase
4 – 30%-50% increase
5 – >50% increase







Dynamical permafrost modeling



Surface energy balance equation

$$Q(1-\alpha) - E_r(T_s) - P(T_s) - B(T_s) - LE(T_s) = 0$$

$E_r(T_s) = E_r^{o}(T_s)\,(1\text{-}0.79\ n) + 4\ ds\ T^3(T_s\text{-}T)$; $E_r^{o}(T_s) = ds\ T^4(0.39 - 0.058\ e^{1/2})$;

$P(T_s) = r_a\, c_a vD_t\,(T_s\text{-}T)$; $B = l \dfrac{dT}{dz}$ $E = E_o$, if $w > w_k$; $E = E_o\, w/w_k$, if w £ w_k $E_o = r_a\, vD_t\,(e_o\text{-}e)$

Heat transfer equation

$$r c \frac{dT}{dt} = \frac{d}{dz}\left(l \frac{dT}{dz} \right)$$

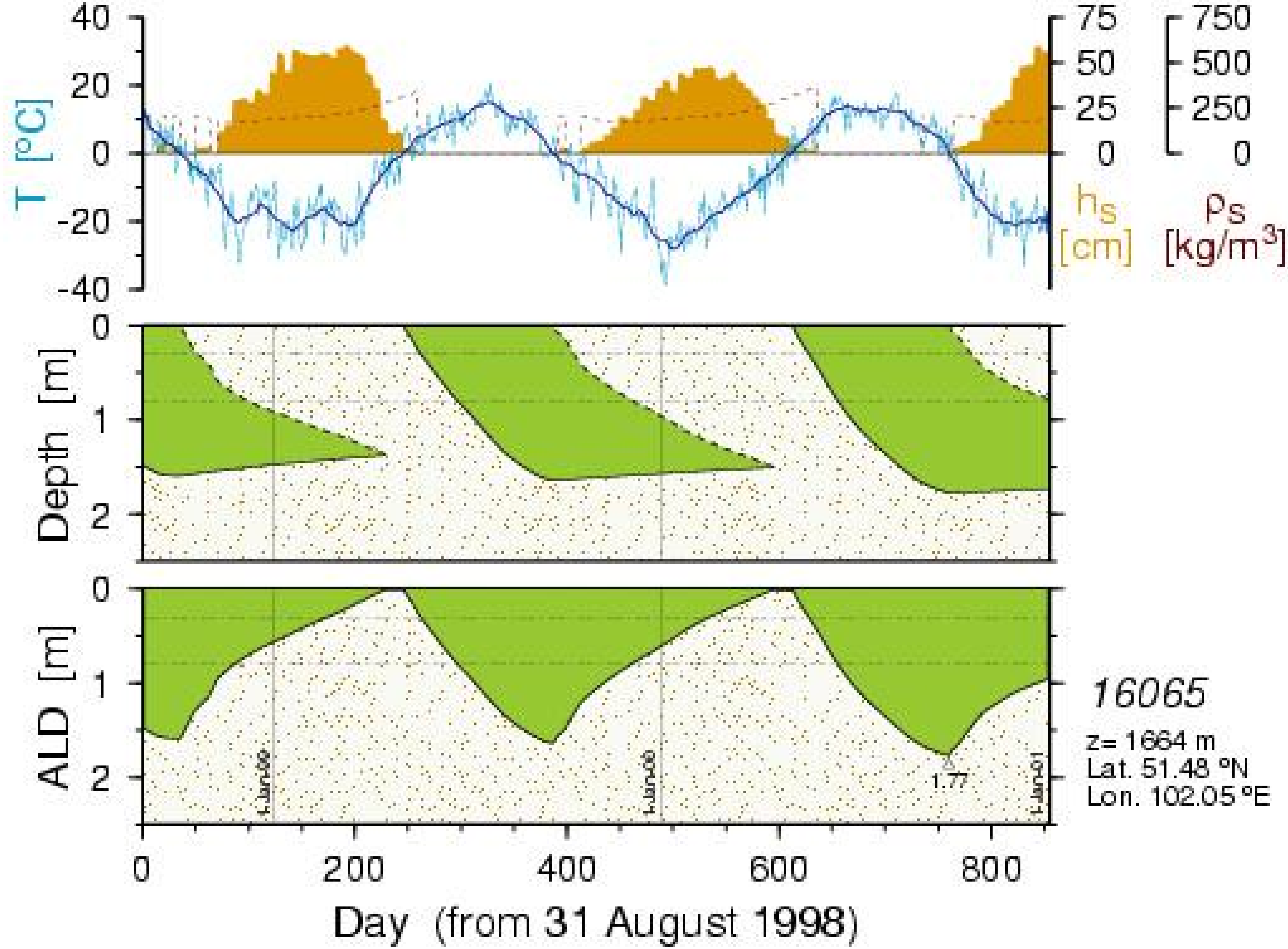
$$\frac{dz_j}{dt} = (-1)^{j+1} \frac{1}{wL} \left(l_{\square} \frac{dT}{dz}\Big|_{z=z_j+0} - l_{\text{„}} \frac{dT}{dz}\Big|_{z=z_j-0} \right)$$

Water balance equation

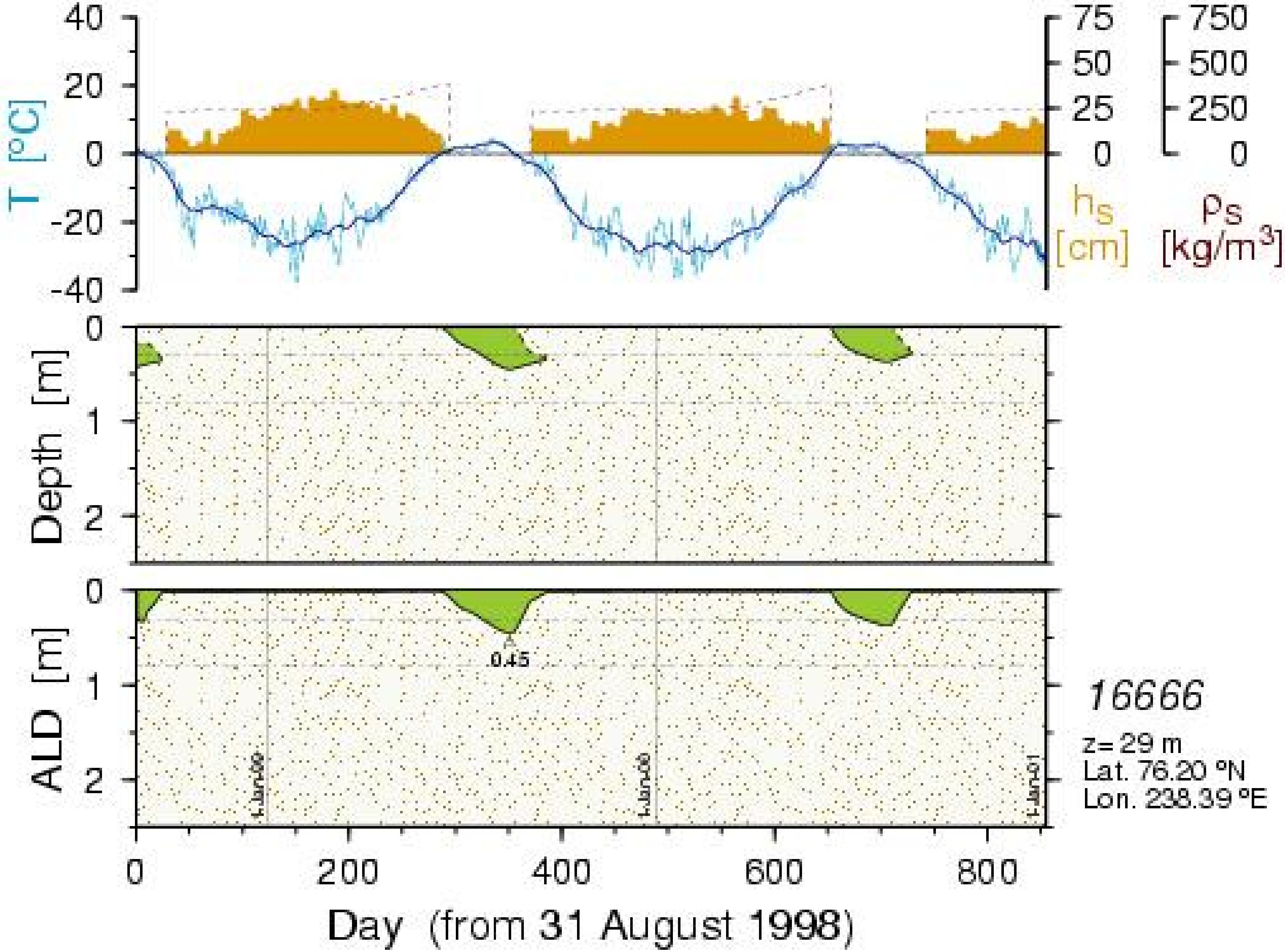
$$z_t \frac{dw}{dt} = R - E - f$$

$$f = R \frac{w}{w_k} \sqrt{m^2\left[1-\left(1-\frac{E_0}{R}\right)^2\right] + \left(1-\frac{E_0}{R}\right)^2}$$, if $R > E_o$

$f = m\ R\ w/w$, if $R \le E_o$



T [°C]
40
20
0
-20
-40
75
50
25
0
750
500
250
0
hs [cm]
ρs [kg/m3]
Depth [m]
ALD [m]
0
1
2
1.77
16065
z= 1664 m
Lat. 51.48 °N
Lon. 102.05 °E
0
200
400
600
800
Day (from 31 August 1998)



T [°C]
40
20
0
-20
-40
75
50
25
0
750
500
250
0
h_s [cm]
ρ_s [kg/m^3]
Depth [m]
ALD [m]
0
1
2
0.45
16666
z= 29 m
Lat. 76.20 °N
Lon. 238.39 °E
0
200
400
600
800
Day (from 31 August 1998)

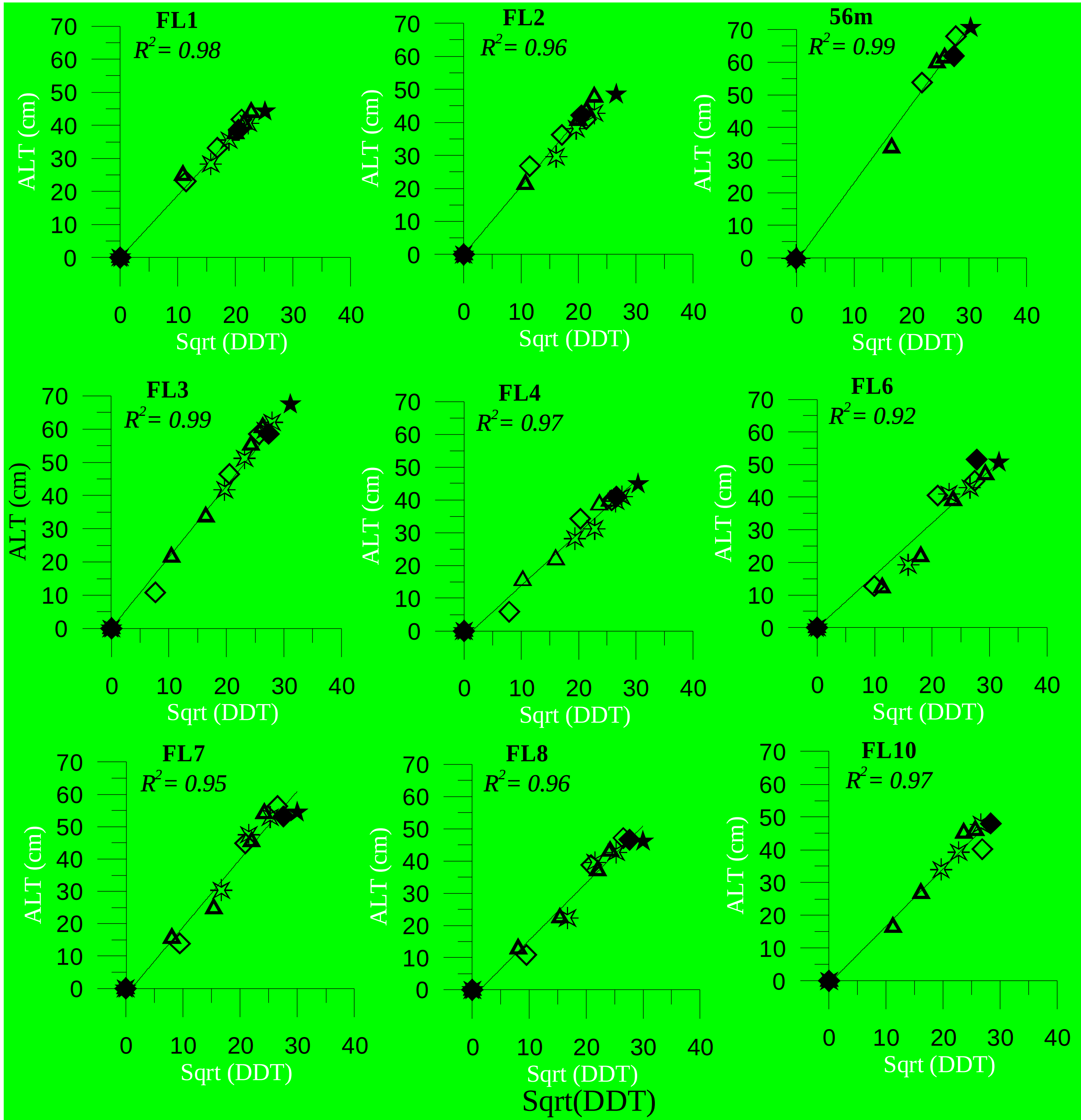
Stochastic permafrost modeling

Stefan Solution for Depth of Thaw:

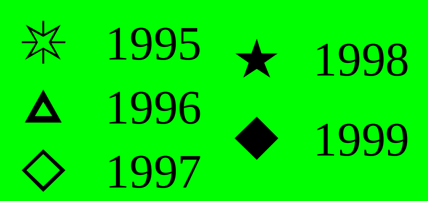
$$z = \sqrt{\frac{2ks(nDDT)}{rwL}}$$

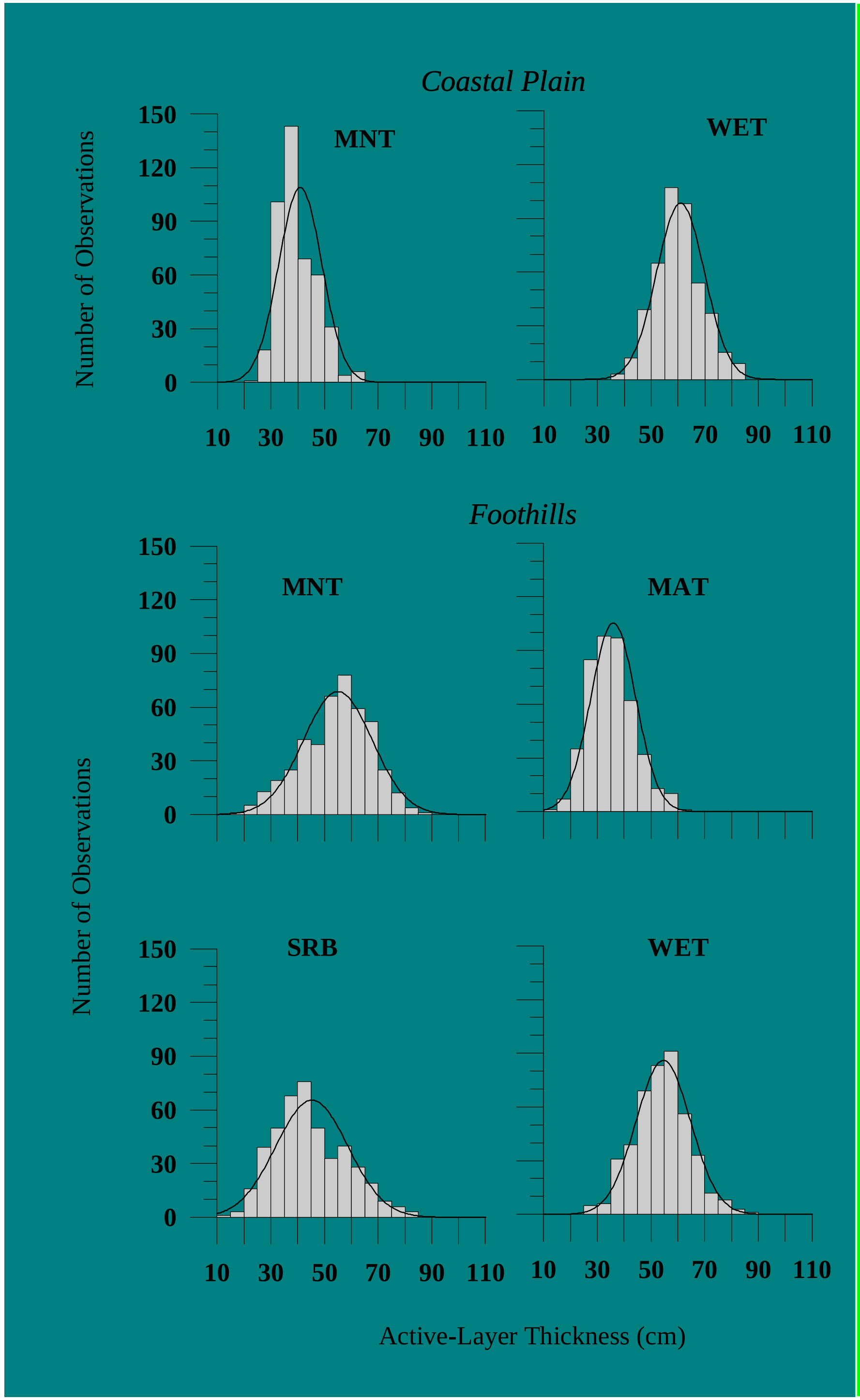
$$z = E \cdot \sqrt{DDT}$$

z = active-layer thickness
k = thermal conductivity of soil
s = unit conversion factor
n = n-factor
DDT = Degree Days of Thawing
ρ= soil density
w = soil moisture
L = latent heat of fusion



Site	Land-Cover Class	*E*
	Coastal Plain	
FL-1	Moist Nonacidic	1.87
FL-2	Wet Nonacidic	1.97
56m	Wet Tundra	2.42
	Foothills	
FL-3	Moist Nonacidic	2.29
FL-4	Moist Acidic	1.62
FL-6	Moist Acidic / Water Track	1.71
FL-7	Wet Acidic	2.08
FL-8	Moist Acidic	1.65
FL-10	Shrubs / Water Track complex	1.73





Conventional formalism:

z = E C, *(1)*

where E=[(2nl)/(rwL)]$^{1/2}$, C= DDT$^{1/2}$

Stochastic formalism:

Variables are represented as mean value *`f* and fluctuation *f¢ :*

f = `f + f¢ *(2)*

Stefan solution becomes

`z + z¢ = `E `C + E¢ `C+ `E C¢ + E¢ C¢ *(3)*

Averaging of (3) yields equation for the mean ALT:

`z = `E `C *(4)*

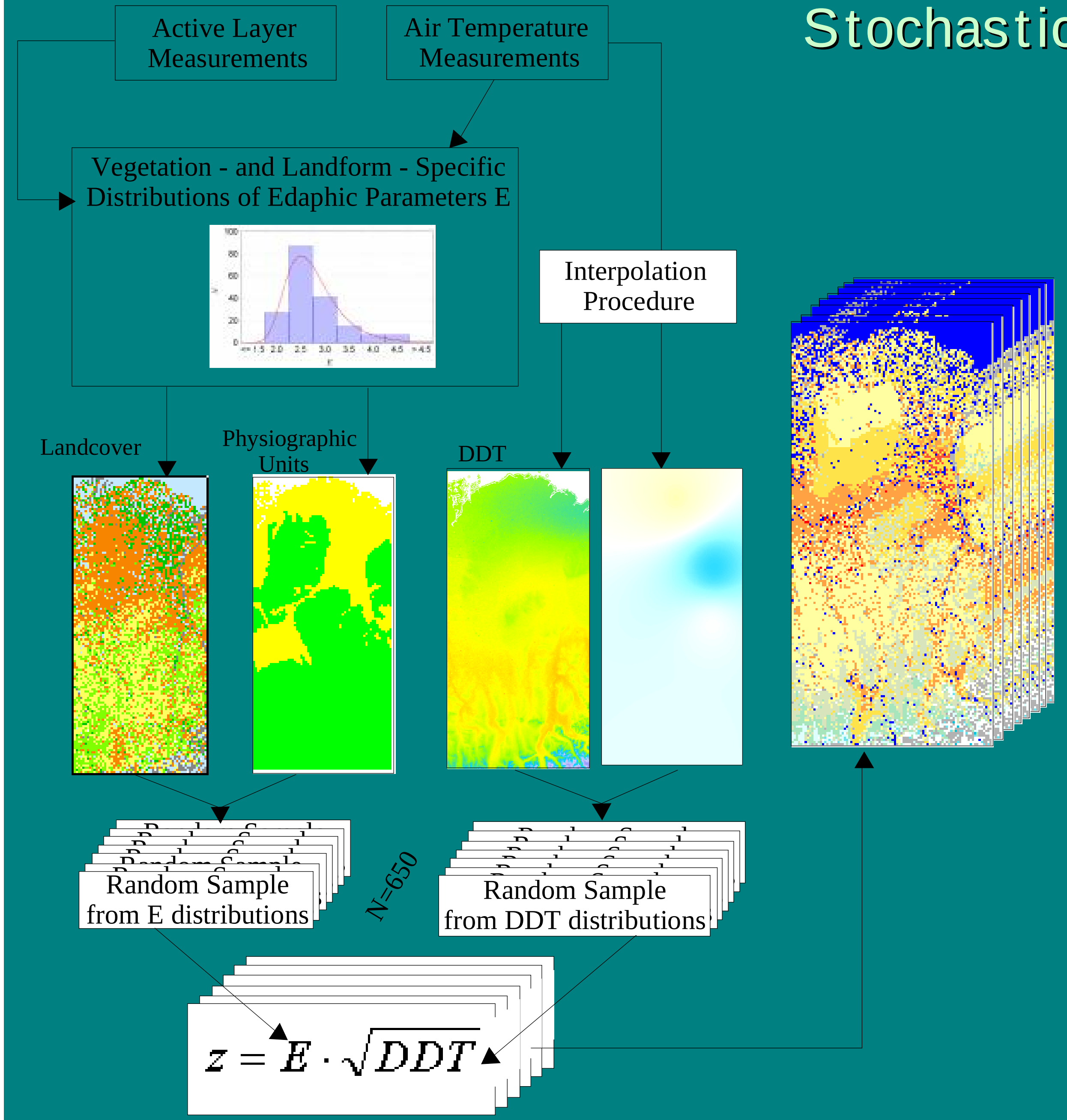
(4) – (3) yields equation for fluctuation:

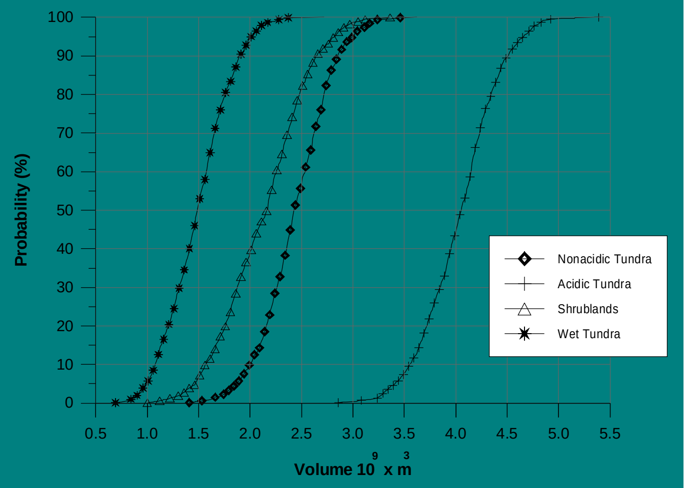
z¢ = E¢ `C+ `E C¢ + E¢ C¢ *(5)*

Square of (6) yields equation for variance:

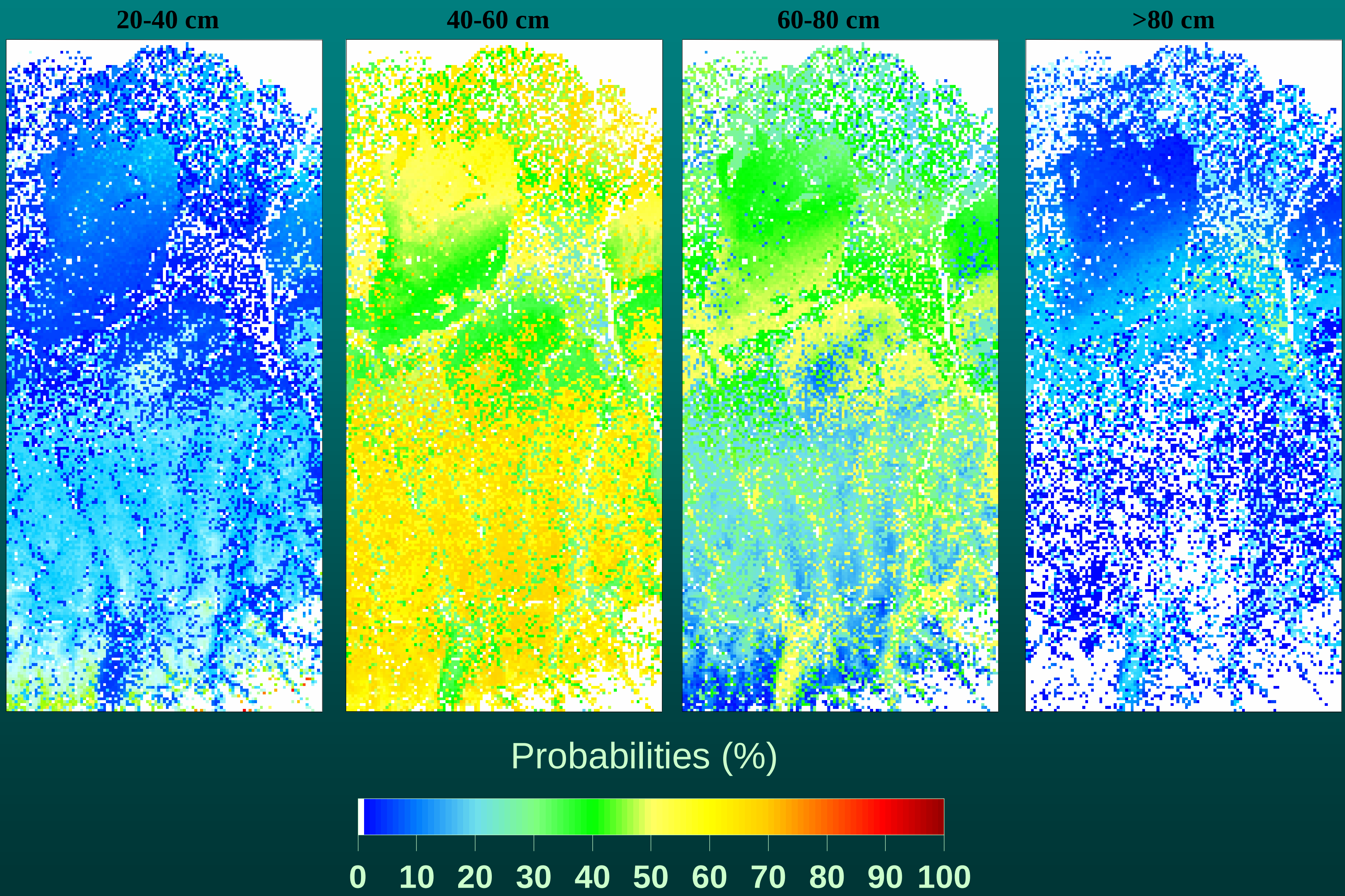
$$\overline{z'^2} = \overline{E'^2}\,\overline{C}^2 + 2\overline{E'C'}\,\overline{E}\,\overline{C} + 2\overline{E'^2C'}\,\overline{C} + \overline{E}^2\,\overline{C'^2} + 2\overline{E}\,\overline{E'C'^2} + \overline{E'^2C'^2}$$

Stochastic permafrost Model

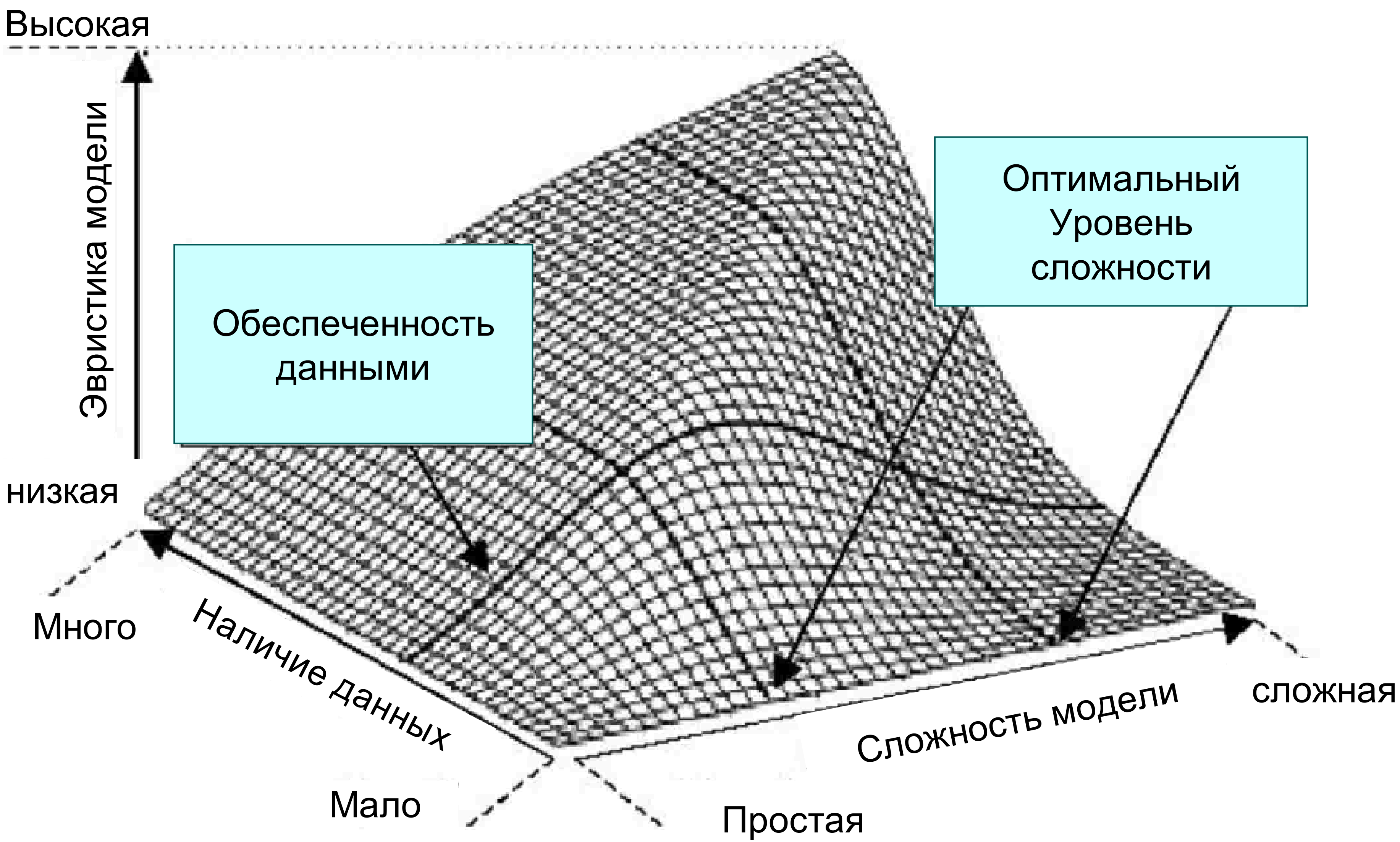




Probabilities of the active-layer thickness



Выбор оптимального уровня сложности модели в зависимости от имеющихся данных



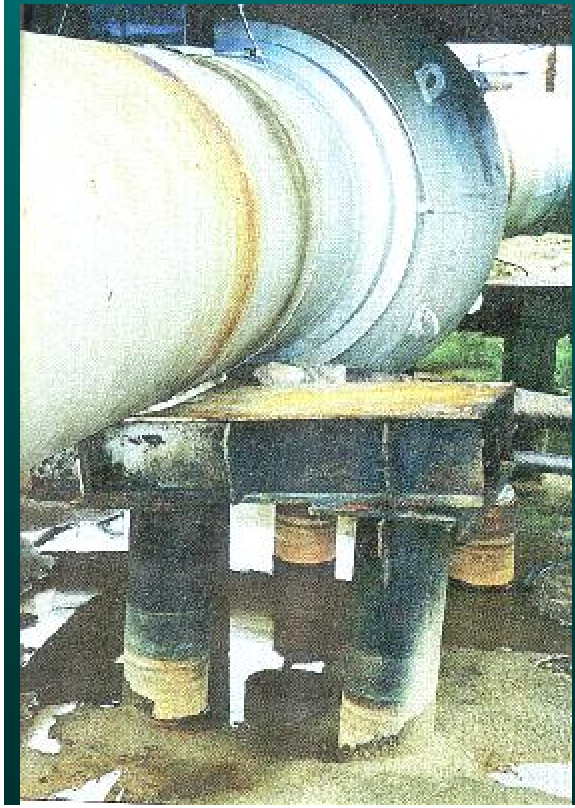
Typical permafrost terrain

Photo by N.Shiklomanov

City	Affected buildings, %
Norilsk	10%
Tiksi	22%
Dudinka	55%
Dikson	35%
Pevek, Amderma	50%
Chita	60%
Vorkuta	80%

Anisimov and Lavrov, 2004

Photo by V.Romanovsky



DT_s	Decrease of bearing capacity of foundations, % from normal	
	Under buildings	Under pipelines
0.5	**5**	**10**
1.0	**15**	**20**
1.5	**20**	**30**
2.0	**50**	**60**

Khrustalev, 2001

Permafrost hazard index, I_g

(Anisimov and Lavrov, 2004)

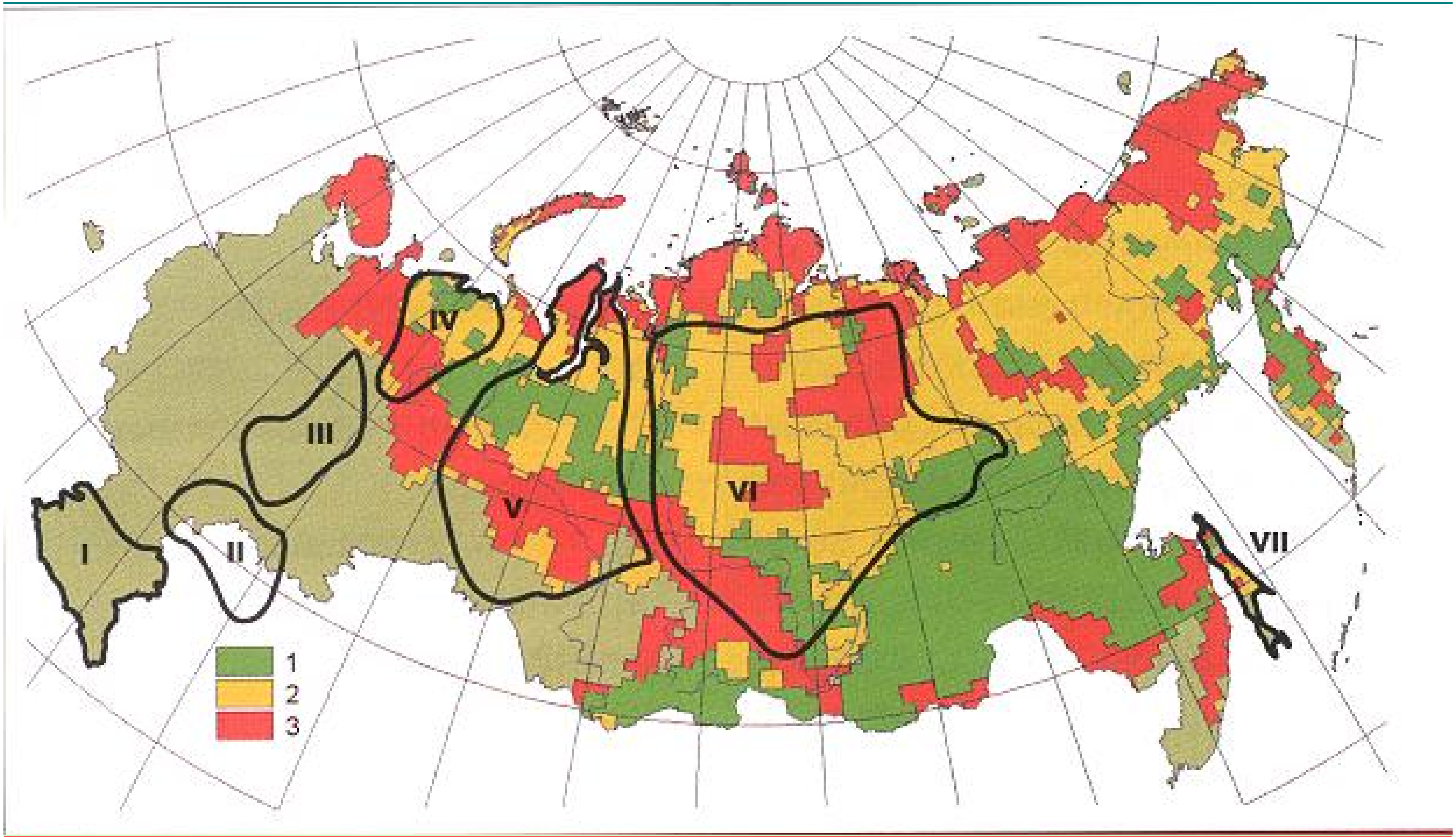
$$I_g = k \cdot (1+S) \cdot (z_2 - z_1) \cdot C_w / z_1$$

Z_i – maximum summer thaw depth under the modern (index 1) and projected for the future (index 2) climate,

C_w - volumetric ground ice content,

S - salinity of soil,

K - constant scaling factor.



Regions with low (1), moderate (2) and high (3) susceptibility to permafrost hazard, GFDL climatic projection for mid-21st century.

Numbered regions on the map designate provinces of oil and gas exploration.

(Anisimov and Lavrov, 2004)

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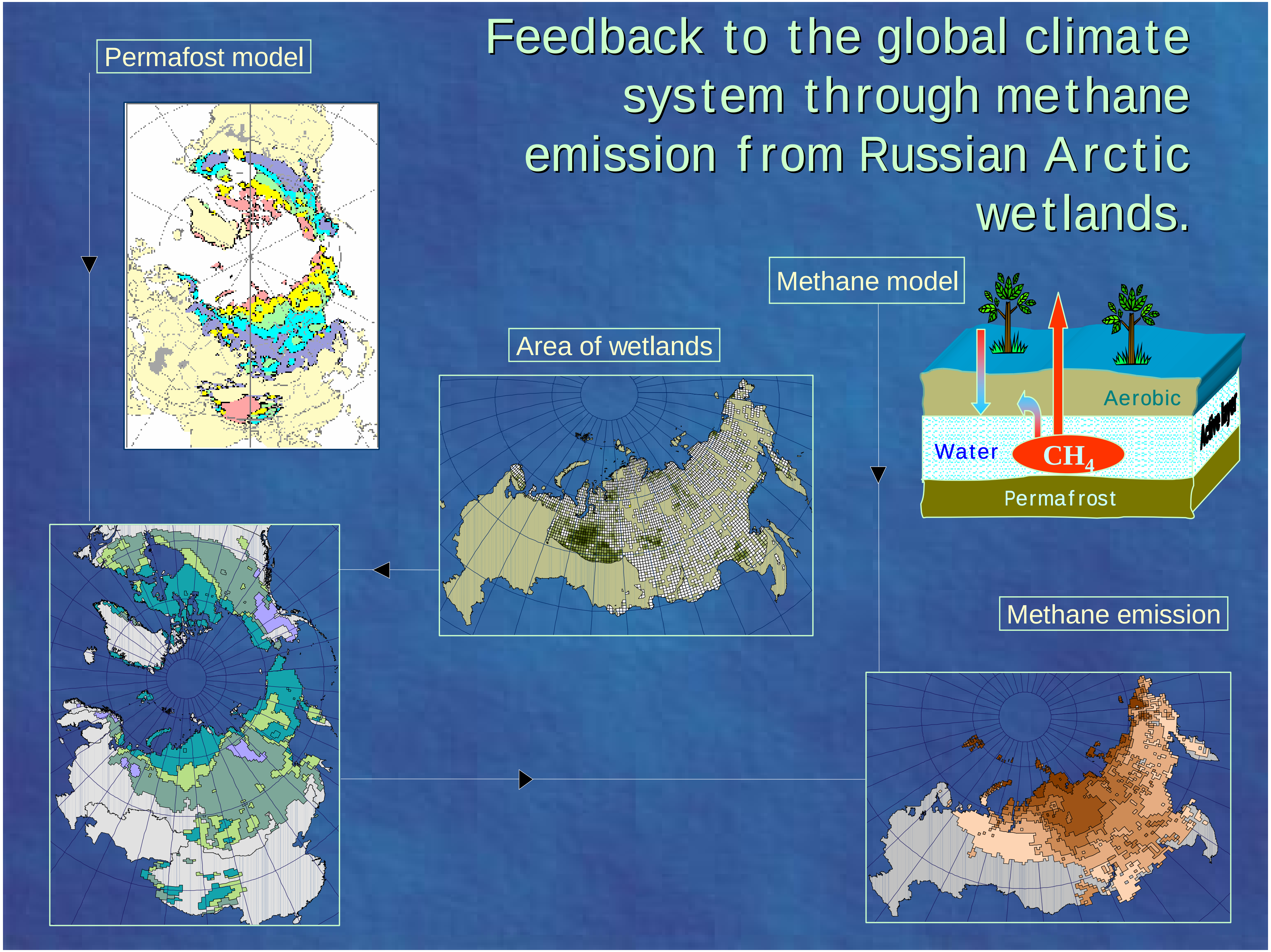
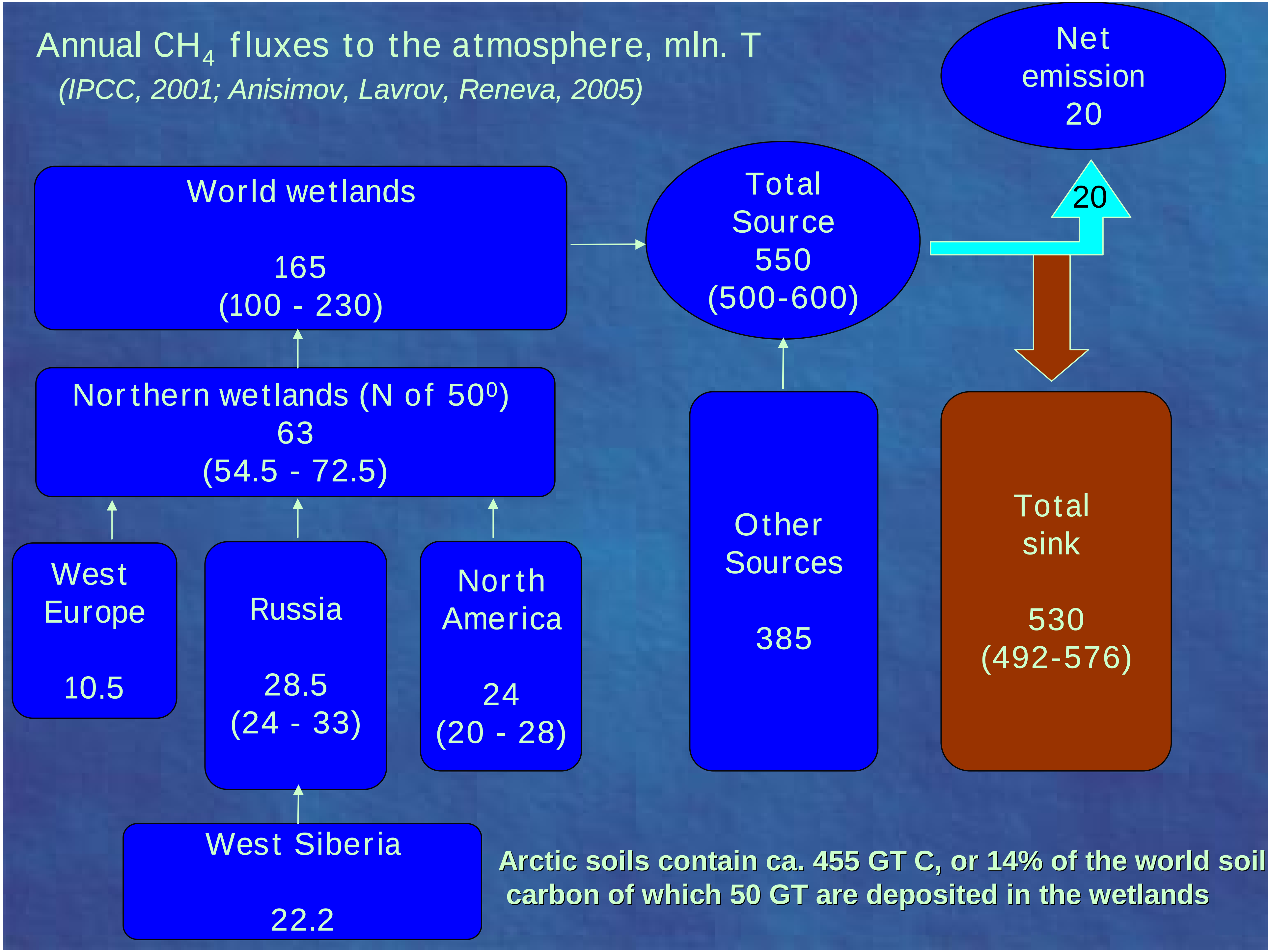
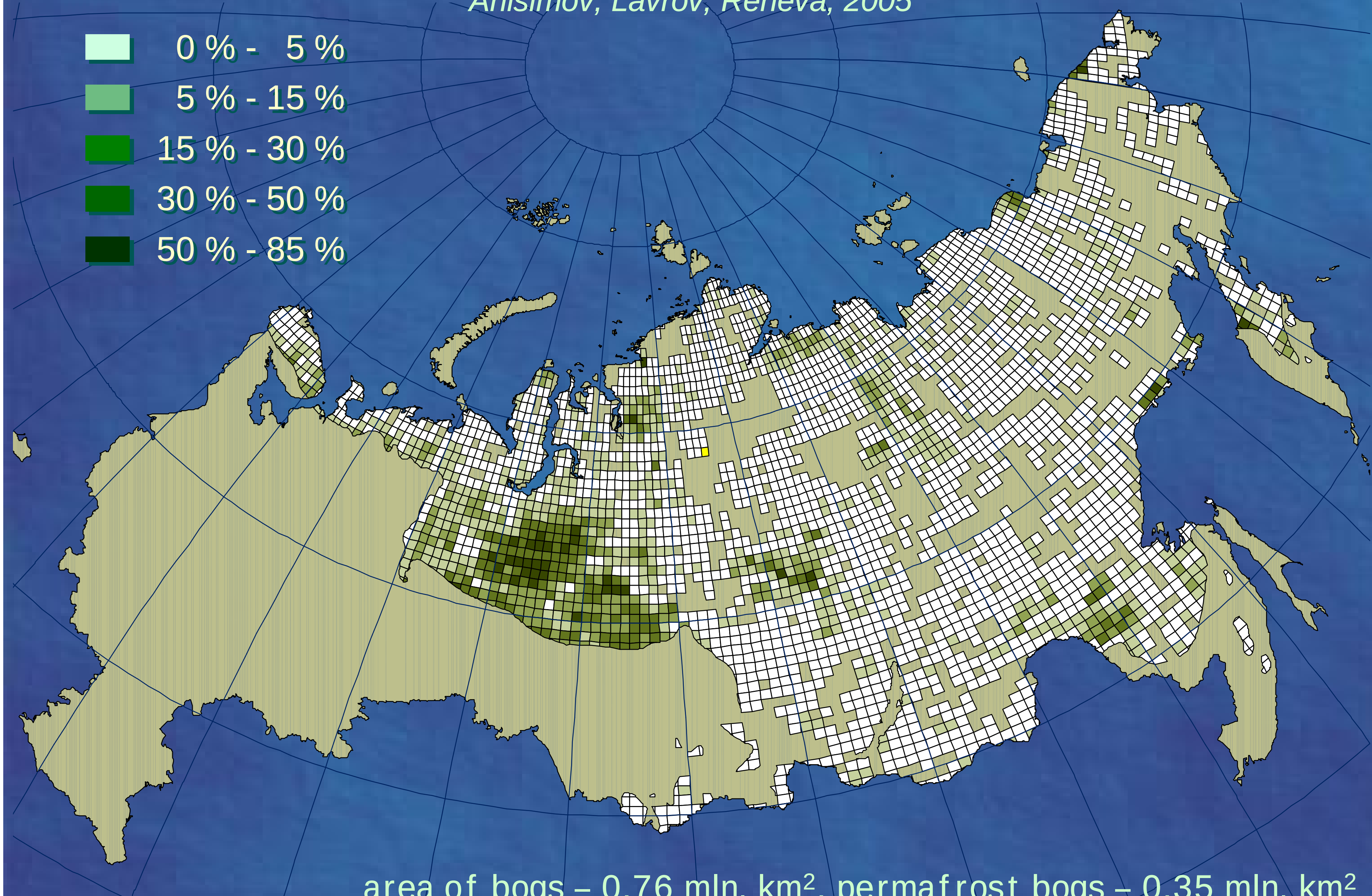


Feedback to the global climate system through methane emission from Russian Arctic wetlands.
Permafost model
Methane model
Area of wetlands
Aerobic
Water
CH_4
Permafrost
Active layer
Methane emission


Annual CH_4 fluxes to the atmosphere, mln. T
(IPCC, 2001; Anisimov, Lavrov, Reneva, 2005)
Net emission 20
World wetlands 165 (100 - 230)
Total Source 550 (500-600)
20
Northern wetlands (N of 50^0) 63 (54.5 - 72.5)
West Europe 10.5
Russia 28.5 (24 - 33)
North America 24 (20 - 28)
Other Sources 385
Total sink 530 (492-576)
West Siberia 22.2
Arctic soils contain ca. 455 GT C, or 14% of the world soil carbon of which 50 GT are deposited in the wetlands

Fraction of land occupied by wetlands in Russia

Anisimov, Lavrov, Reneva, 2005



area of bogs – 0,76 mln. km^2, permafrost bogs – 0,35 mln. km^2

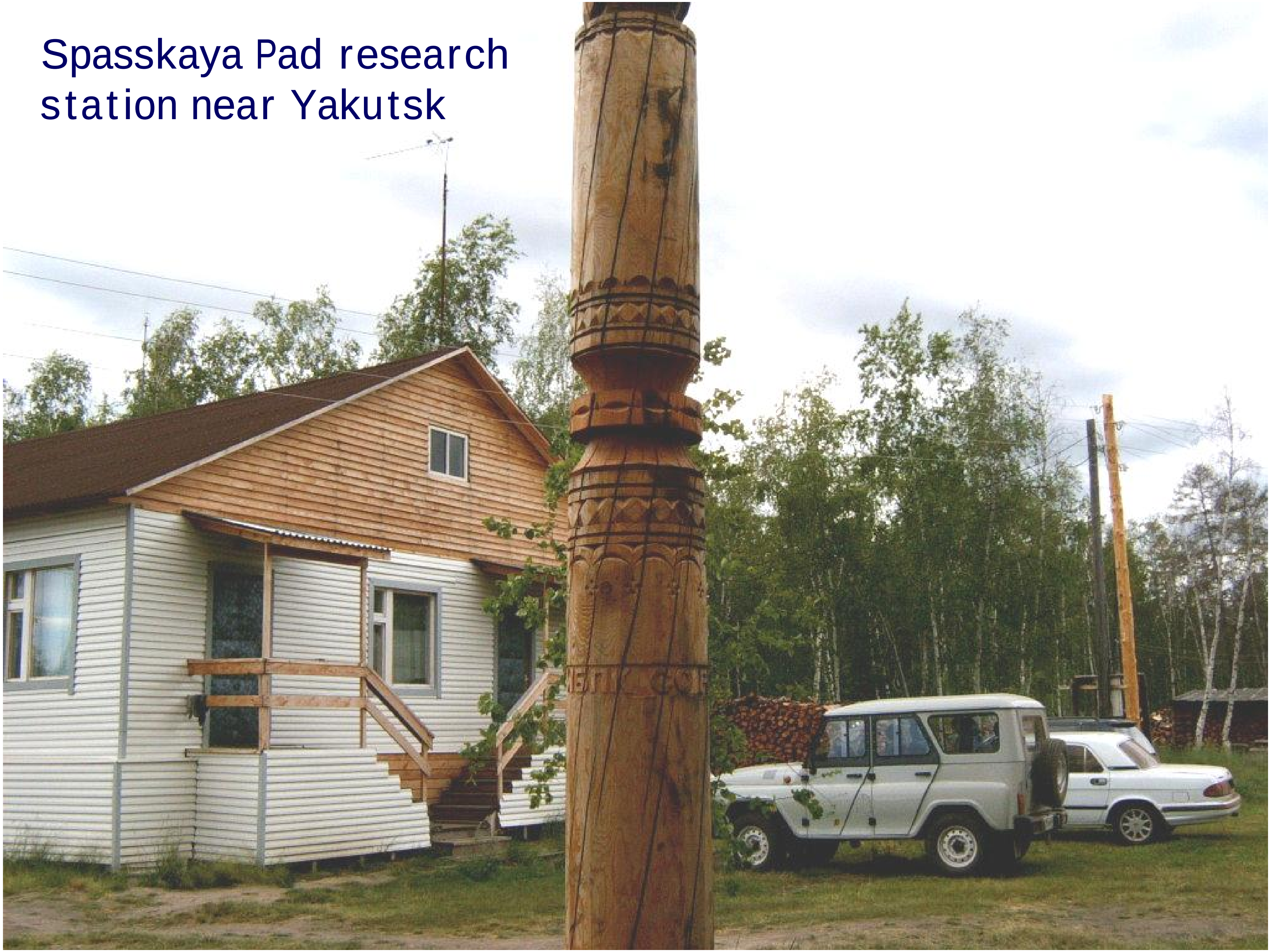
STATE HYDROLOGICAL INSTITUTE

Projected changes of the volume of seasonally thawing peat (km^3). Water content 600 мм/м / 800 мм/м.

(Anisimov, Lavrov, Reneva, 2005)

years / models	2025	2050	2080
NCAR	-	80,61 / 88,59	-
GFDL	80,88 / 90,87	137,82 / 150,40	153,94 / 173,02
ECHAM – 4	-	228,92 / 249,04	-

Spasskaya Pad research station near Yakutsk



Parameterization of methane fluxes:

Flux / thaw depth ratio:

$$J_1 / J_0 = \sqrt{H_{d1}/H_{d0}}$$

Flux / ground temperature ratio:

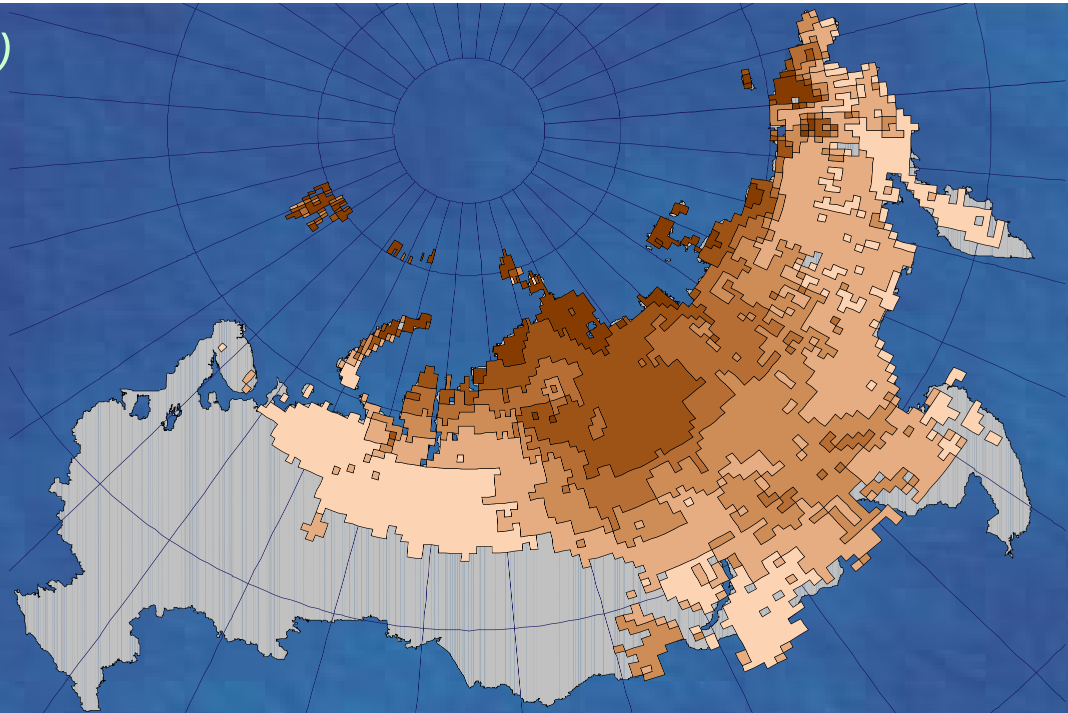
$$J_1 / J_0 = \exp 0.1(T_1 - T_0)$$

Combined equation:

$$J_1 / J_0 = \exp 0.1(T_1 - T_0) \sqrt{H_{d1}/H_{d0}}$$

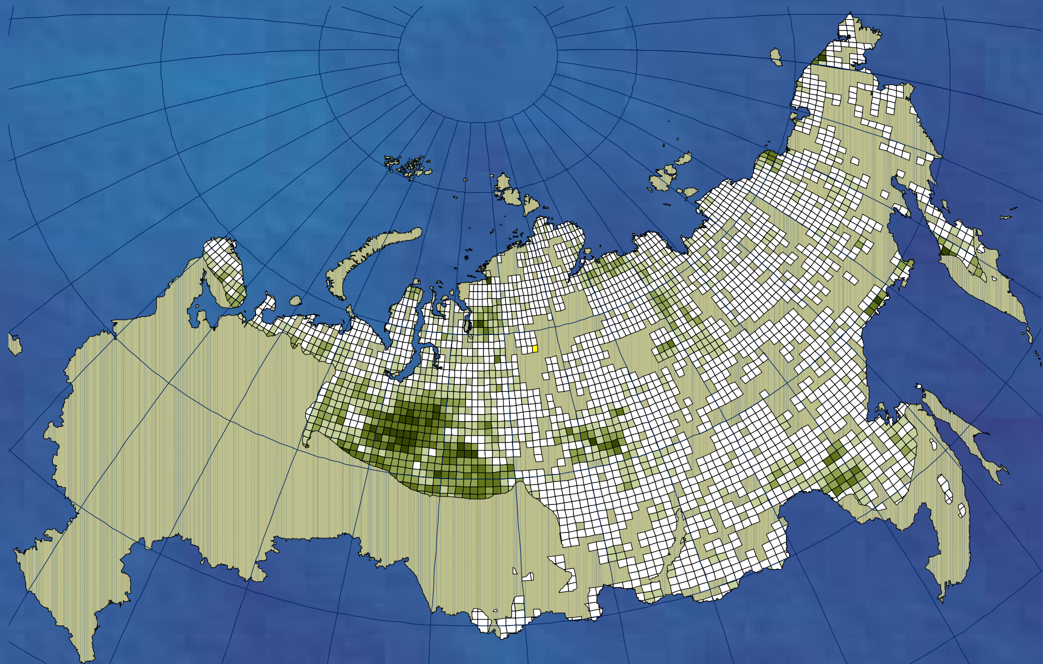
(Anisimov, Lavrov, Reneva, 2005)

Predicted changes of methane flux, GFDL scenario for 2050

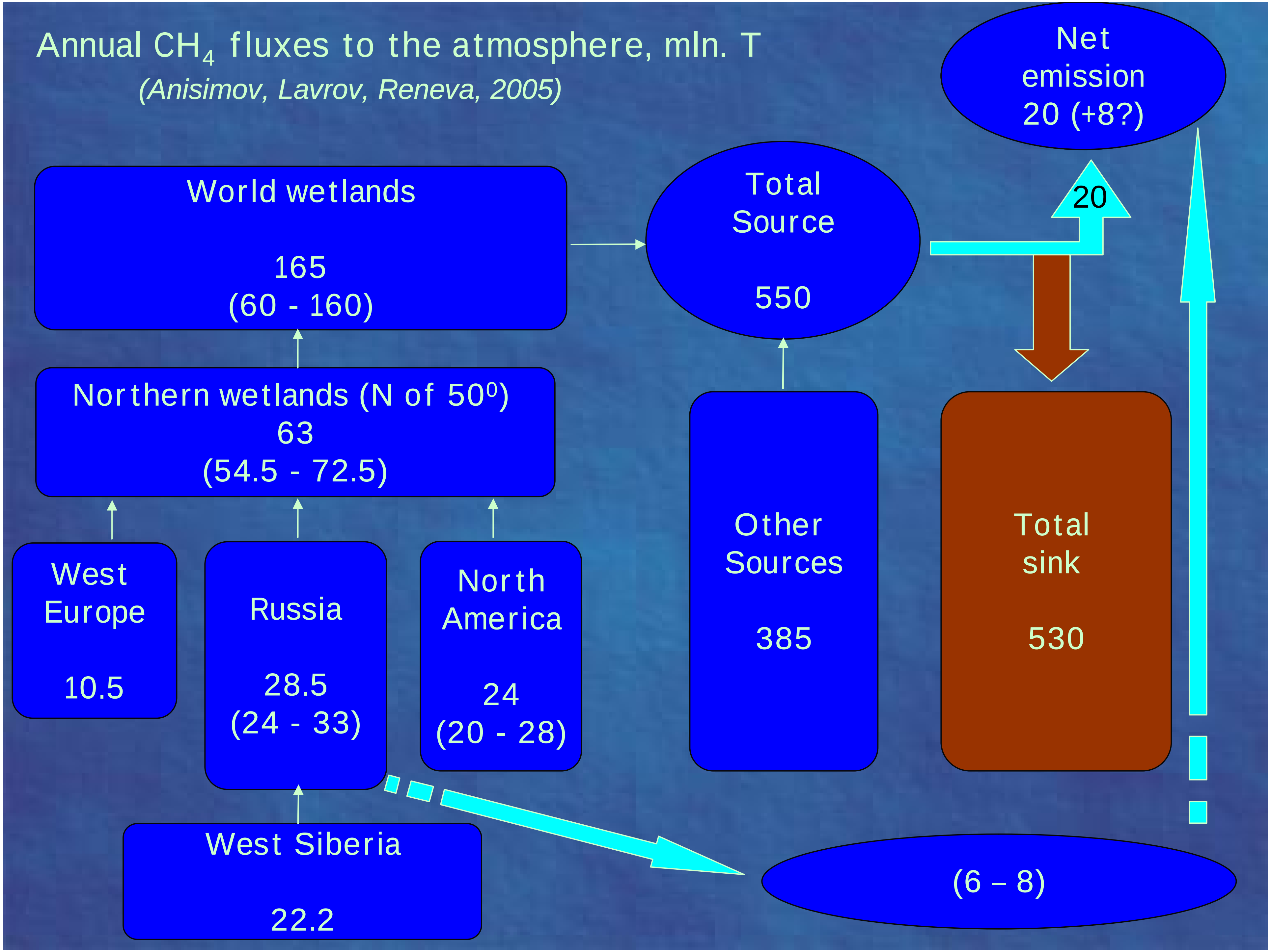


- 1 % - 20 %
- 20 % - 30 %
- 30 % - 40 %
- 40 % - 50 %
- 50 % - 80 %
- > 80 %

Fraction of permafrost occupied by frozen wetlands

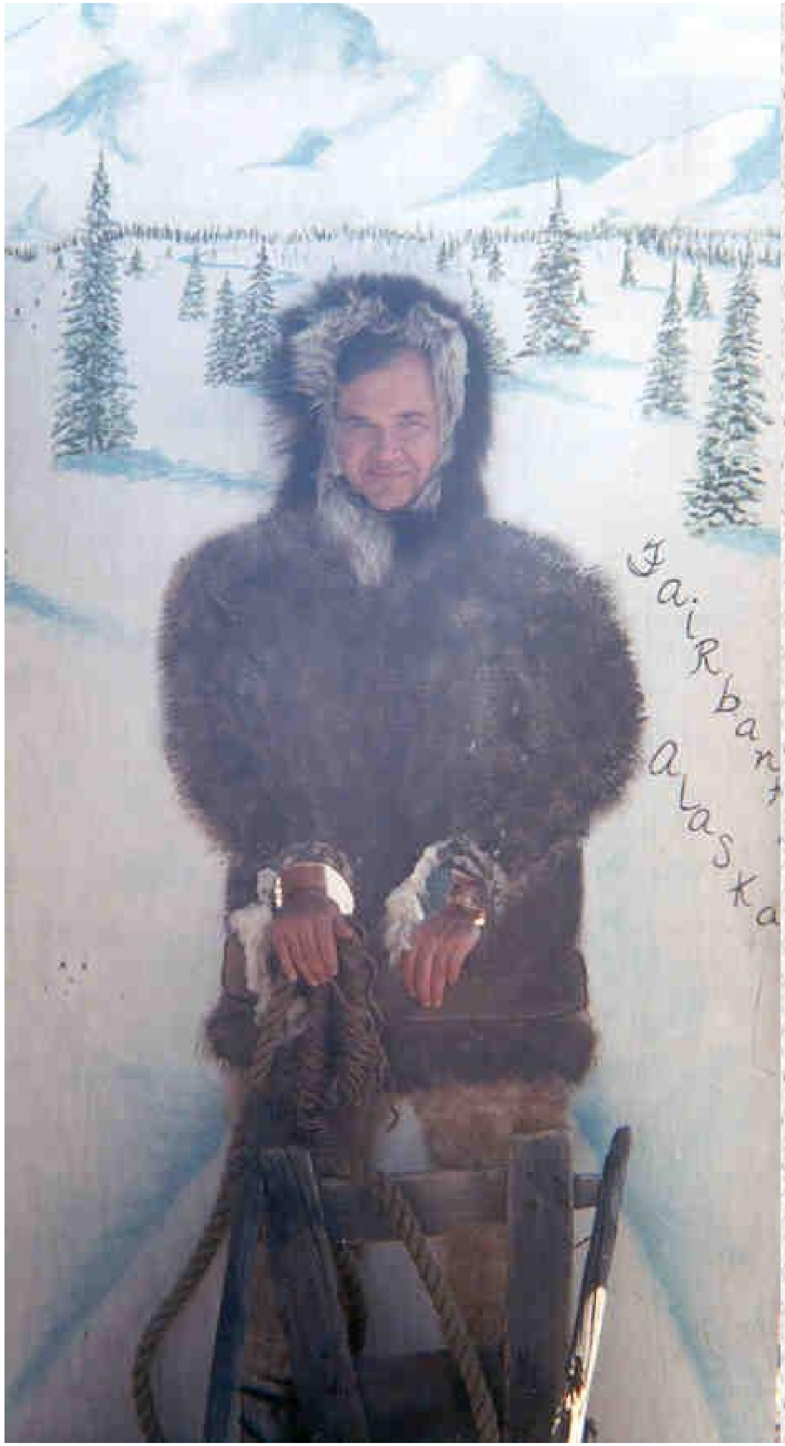


- < 5 %
- 5 % - 15 %
- 15 % - 30 %
- 30 % - 50 %
- 50 % - 85 %


Annual CH4 fluxes to the atmosphere, mln. T
(Anisimov, Lavrov, Reneva, 2005)
Net emission 20 (+8?)
World wetlands 165 (60 - 160)
Total Source 550
20
Northern wetlands (N of 50⁰) 63 (54.5 - 72.5)
West Europe 10.5
Russia 28.5 (24 - 33)
North America 24 (20 - 28)
Other Sources 385
Total sink 530
West Siberia 22.2
(6 – 8)

Projected changes of CH4 emissions from wetlands

CH4 changes	Climate change	Source
+25%	+1.5 ^{0}C	Anisimov et al., 2005
156-277mln.t./yr (+78%)	CO_2 doubling in GISS GCM (+3.4 ^{0}C)	Schindell et all., 2004
±20% change	Uniform ±1 ^{0}C temperature change	Walter et al., 2001
±8% change	±20% precipitation change	Walter et al., 2001
26% increase	global warming of 2.5 ^{0}C	Liu, 1996; Prinn et al, 1999
+19% increase	Uniform +2 ^{0}C temperature change	Cao et al., 1998
+21% increase, N60+	+2 ^{0}C temperature and +10% precipitation change	Cao et al., 1998
Decreased emission	> 4 ^{0}C temperature change	Cao et al., 1998
+38%, N60+	+10 cm thaw depth	Zhuang et al., 2004
0 to +25%, N60+	+10 cm water table rise	Walter and Heimann, 2000



Thank you !