The ARCHY code, and permafrost carbon

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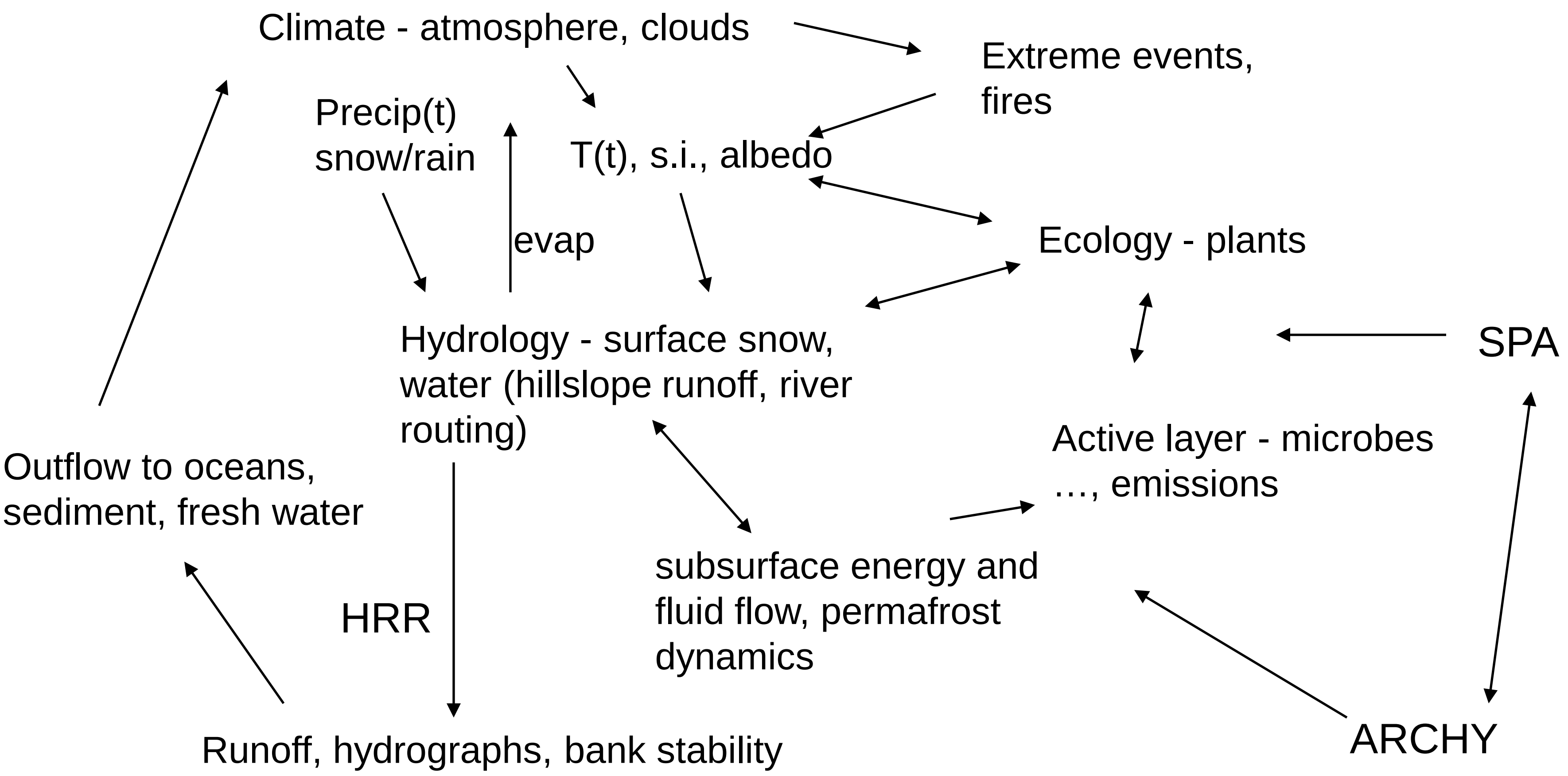
LOS ALAMOS NATIONAL LABORATORY
EARTH & ENVIRONMENTAL SCIENCES

Coupled Dynamics of Arctic Regions



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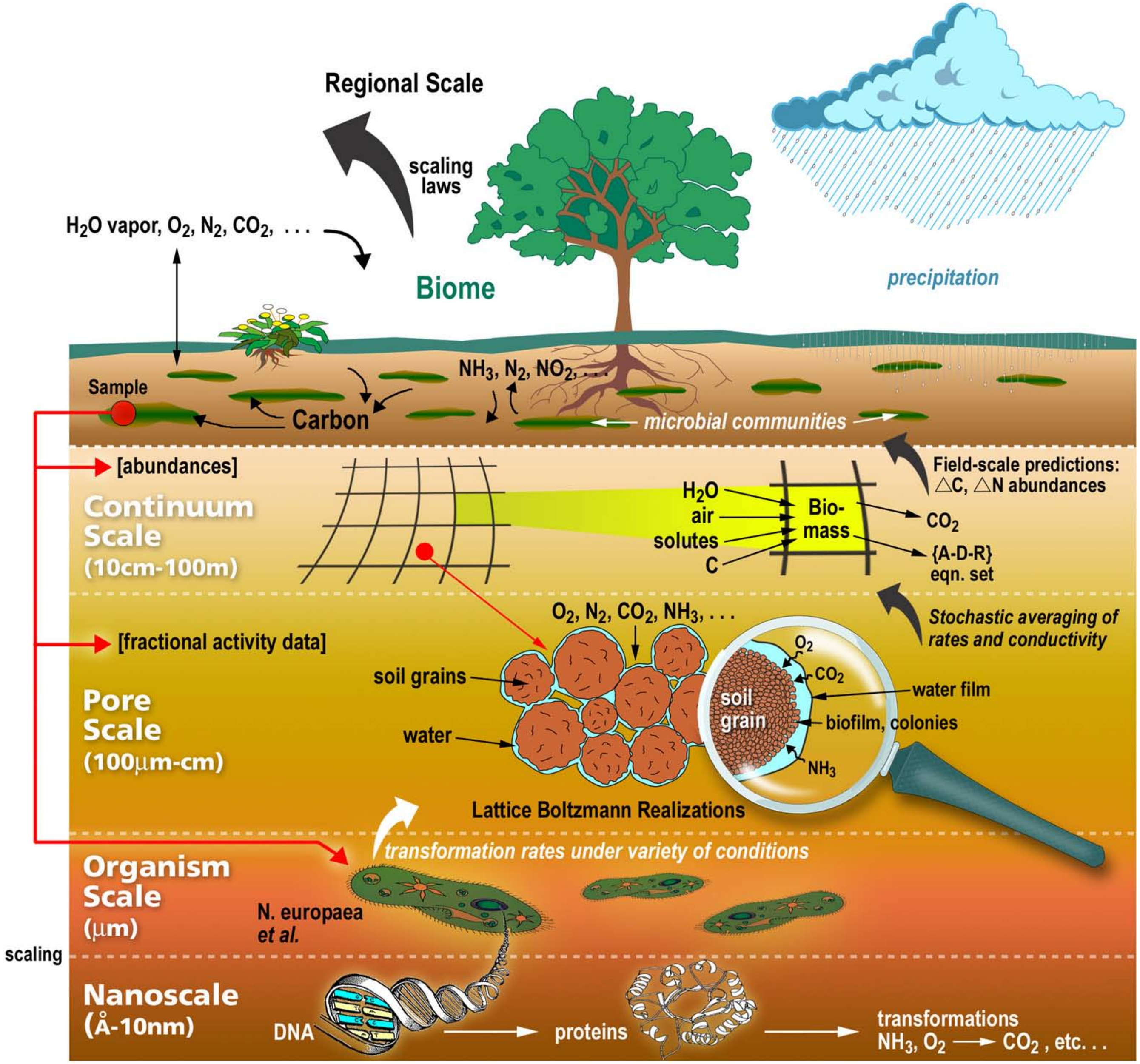

Regional Scale
scaling laws
H_2O vapor, O_2, N_2, CO_2, . . .
Biome
precipitation
Sample
Carbon
NH_3, N_2, NO_2, . . .
microbial communities
[abundances]
Continuum Scale
(10cm-100m)
H_2O
air
solutes
C
Bio-mass
CO_2
{A-D-R} eqn. set
Field-scale predictions: $\triangle$C, $\triangle$N abundances
[fractional activity data]
O_2, N_2, CO_2, NH_3, . . .
Stochastic averaging of rates and conductivity
soil grains
water
Pore Scale
(100µm-cm)
soil grain
O_2
CO_2
water film
biofilm, colonies
NH_3
Lattice Boltzmann Realizations
transformation rates under variety of conditions
Organism Scale
(µm)
N. europaea
et al.
scaling
Nanoscale
(Å-10nm)
DNA
proteins
transformations
NH_3, O_2 → CO_2 , etc. . .

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ARCHY/MAGHNUM model

1-D, 2-D, 3-D + time; Cartesian, cylindrical coordinates; integrated finite differences; MPI version this year

Two-phase flow; mass and energy conservation equations + Darcy's Law; water (single phase), water + air/vapor (two phase coupled), ice, melting/thawing, latent heat

Variable properties (H_2O eos, permeability, porosity, thermal properties, spatial and temporal variation, feedbacks)

Chemistry – one version coupled to PHREEQC; solute transport, precipitation/dissolution, feedback to porosity and permeability

Microbial kinetics module – multiple Monod, multiple species including aerobic and anaerobic; C-N cycles

Checks and tests

- Analytic solutions for some simple cases
- Diffusion with phase change (Stefan problems)
- Single phase flow – steady solutions, comparisons to other codes for transient cases
- Similarity solutions for 2-phase flow
- Comparisons to other numerical solutions (e.g., Grimm & McSween; McKenzie et al)
- Comparisons to experiments (e.g., McGraw)
- Predecessor codes (MAGHNUM, TRACRI, …) have been used and tested for a variety of applications

Numerical Modeling:

MAGHNUM:

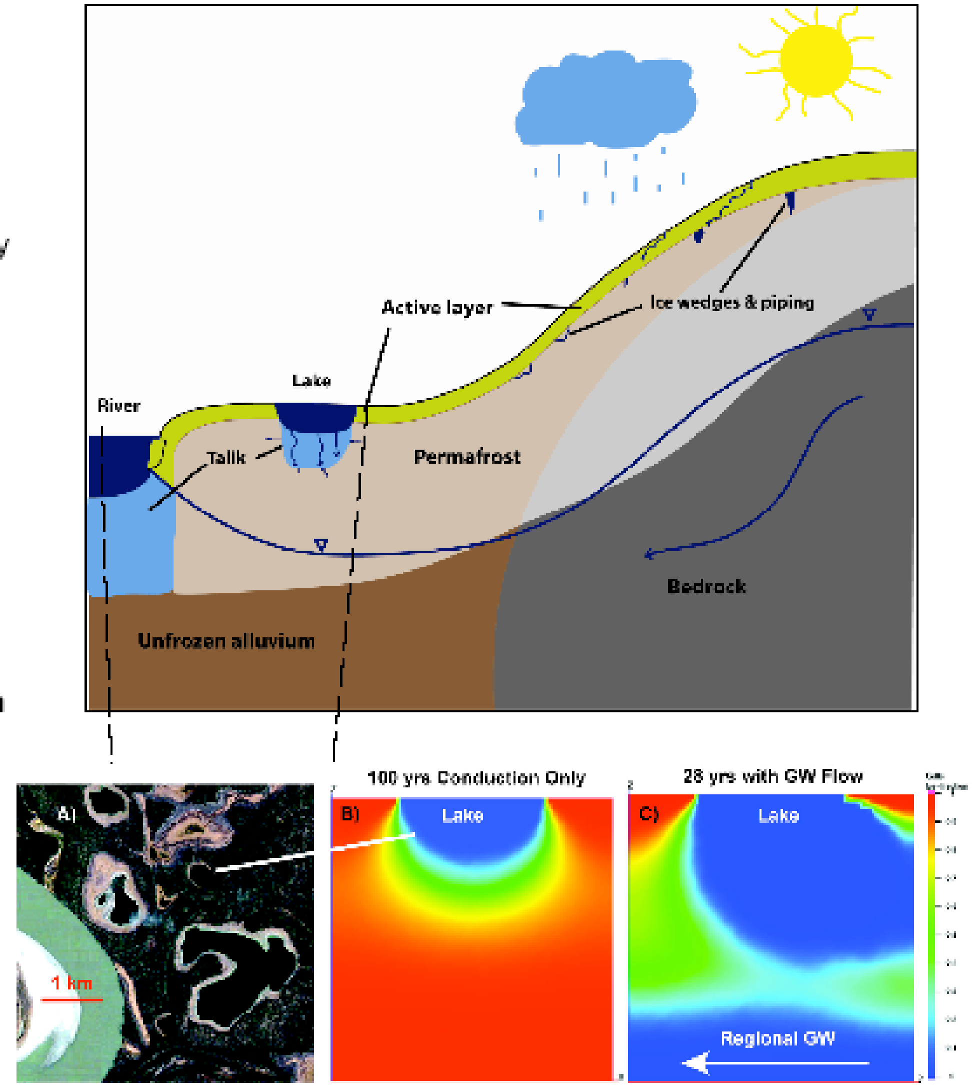
- Coupled heat, fluid and vapor transport in 3D
- Saturated and unsaturated
- Ice phase change and related thermophysics
- Dynamic changes in porosity and permeability in response to phase change
- Microbial metabolic model -CO_2, CH_4, O_2, DOC

Controls on spatial scales:

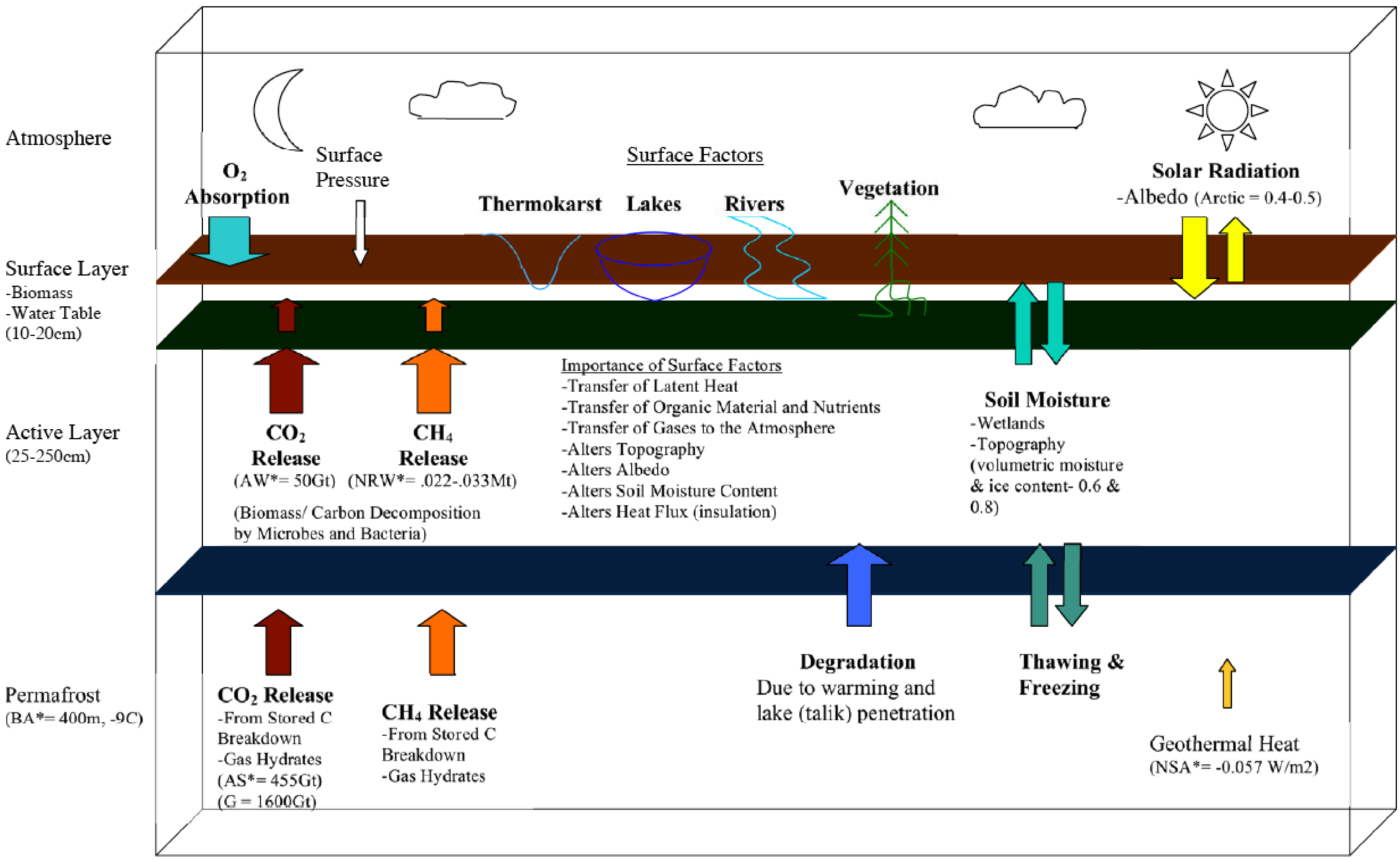
- Topography
- Subsurface heterogeneities from pore to hillslope scale
- **Heterogeneities and connectivity within the subsurface are dynamic and change in response to thermal conditions**

Controls on temporal scales:

- External: Climatic drivers
- Internal: Dynamics
  - Conduction
  - Advection
  - Phase Changes
  - Bio-Geo-Chemistry



Active Layer & Permafrost System Feedbacks and Variables



*NRW= Northern Russian Wetlands
*AW= Arctic Wetlands
*AS= Arctic Soils
*BA= Barrow, Alaska
*NSA= North Slope, Alaska
*G = Globally

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Microbial Activity

Bacterial respiration can convert large amounts organic carbon in soil to carbon dioxide and methane. Several variables drive the response of microbial activity. Emission levels are sensitive to soil composition, temperature, moisture and nutrients (such as nitrates and phosphates) and microbial community make-up.

-Methanogens: Bacteria that produce methane under anaerobic conditions from the breakdown of organic carbon.

Reaction: $CH_3COOH \text{ --> } (1\text{-}x)\ CH_4 + (1\text{-}x)\ CO_2 + 2x\ M_{an}$ where $dM_{an}/dt = d_4R_2 - \lambda_{an}M_{an}$

-Aerobes: Bacteria that utilize oxygen to metabolize organic carbon

Reaction: $CH_3COOH + (2\text{-}x)\ O_2 \text{ --> }$ where $dM_{ae}/dt = d_2R_1 - \lambda_{ae}M$

$(2\text{-}x)\ CO_2 + (2\text{-}x)\ H_2O + x\ M_{ae}$

-Methanotrophs: Bacteria that consume methane as their predominant source of carbon and energy.

Reaction: $CH_4 + (2\text{-}x)\ O_2 \text{ --> } (1\text{-}x)\ CO_2 + (2\text{-}x)\ H_2O + x\ M_t$ where $dM_t/dt = d_5R_3 - \lambda_tM_t$

Consumption Rates

Carbon: Aerobic: $R_1 = k_1(T)\ M_{ae}\ [O_2/(K_{o2} + O_2)][C/(K_C+C)]$

Anaerobic: $R_2 = k_2(T)\ M_{an}\ [I/(I + O_2)][C/(K_{IC}+C)]$

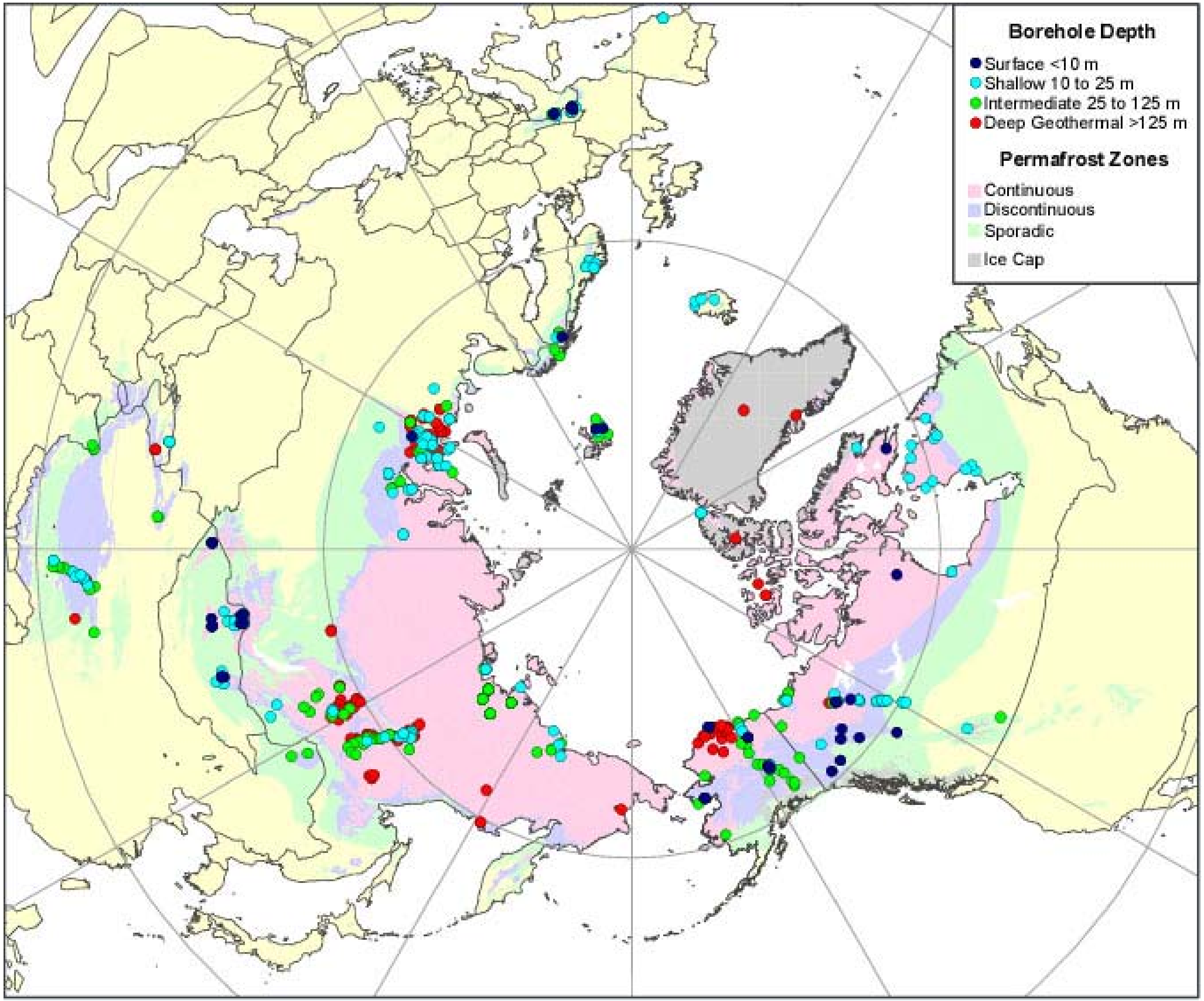
Methanotrophic: $R_3 = k_3(T)\ M_t\ [O_2/(K_{o2} + O_2)][CH_4/(K_{CH4}+CH_4)]$

CO2: $dCO_2/dt = aR_1 + bR_2 + c(b_3R_3)$

CH4: $dCH_4/dt = b_2R_2 - b_3R_3$

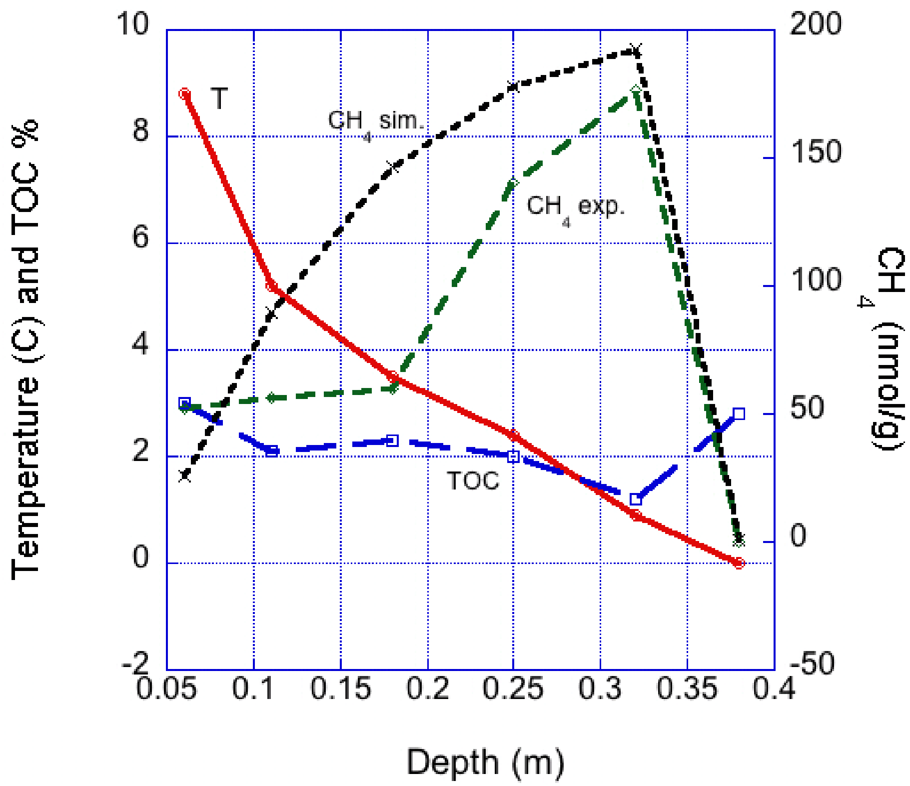
O2: $dO_2/dt = -a_2R_1 - d_3R_3$

-The various coefficients in the equations are determined from stoichiometry and experimental data.



Arctic Distribution of Permafrost and Borehole Measurements

Courtesy of : http://www.gtnp.org/location_e.html

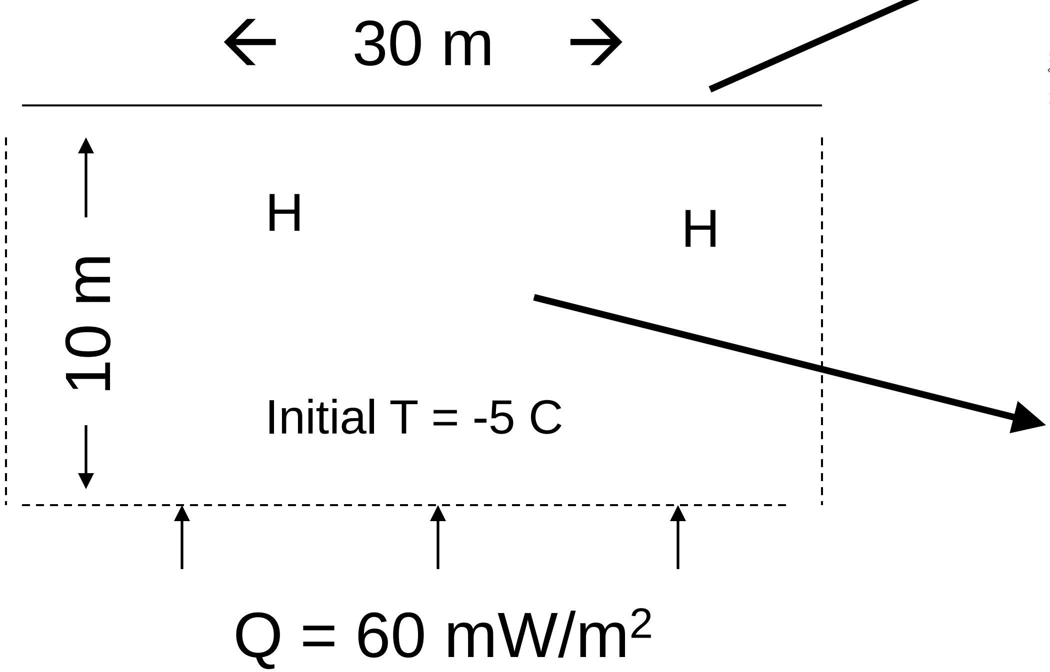


Measurements of temperature and CH_4 and TOC concentrations vs depth at a Siberian site. In the top soil, low water level leads to oxic conditions and a limited methane accumulation due to transformation of methane by methanotrophs. At greater depths, methane accumulates from anaerobic microbe activity. We are using databases of In situ data to calibrate our model.

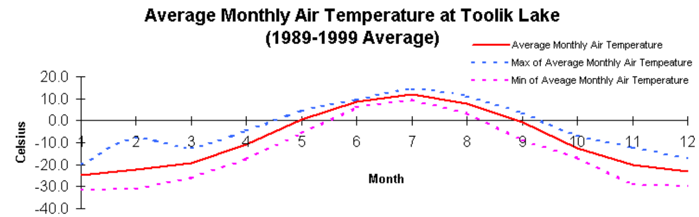
Data from: S. Liebner, K. Rublack, T. Stuehrmann, and D. Wagner, 2009. Diversity of Aerobic Methanotrophic Bacteria in a Permafrost Active Layer Soil of the Lena Delta, Siberia

Example model domain

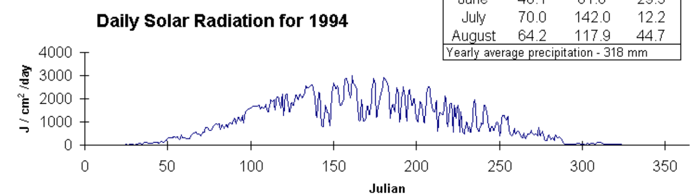
Heat transport, melting/thawing, fluid flow

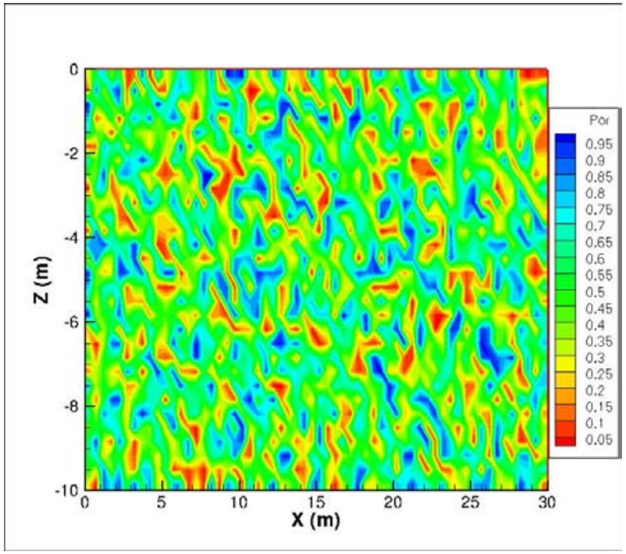


H = heater location; part of study is to see how different heater configurations affect permafrost distribution



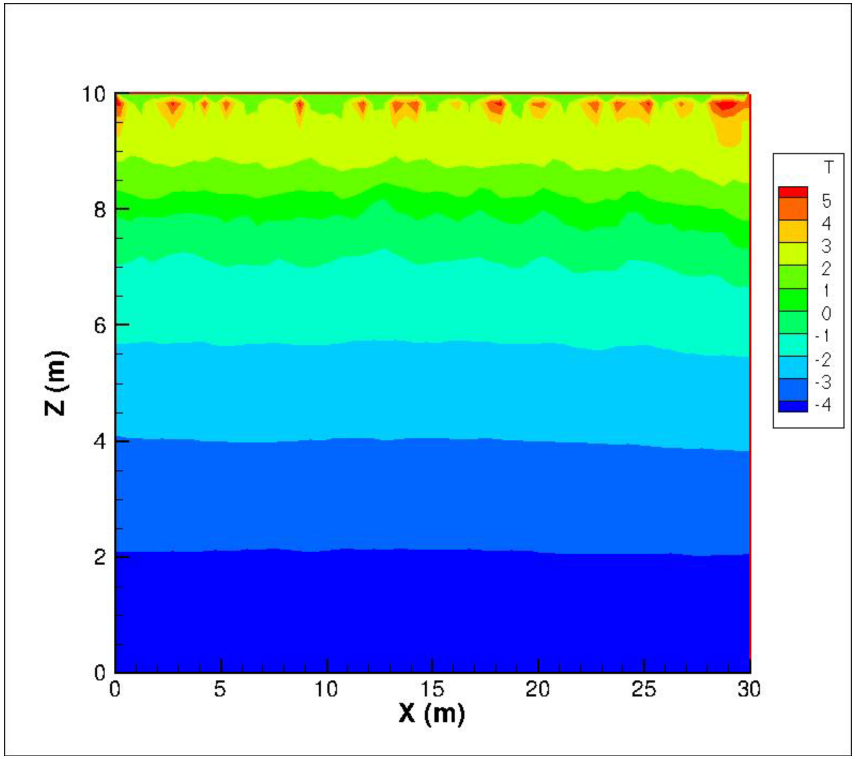
Avg. Monthly Total Rain (mm) 89-99			
Month	Average	Max	Min
June	46.1	61.0	29.5
July	70.0	142.0	12.2
August	64.2	117.9	44.7
Yearly average precipitation - 318 mm			

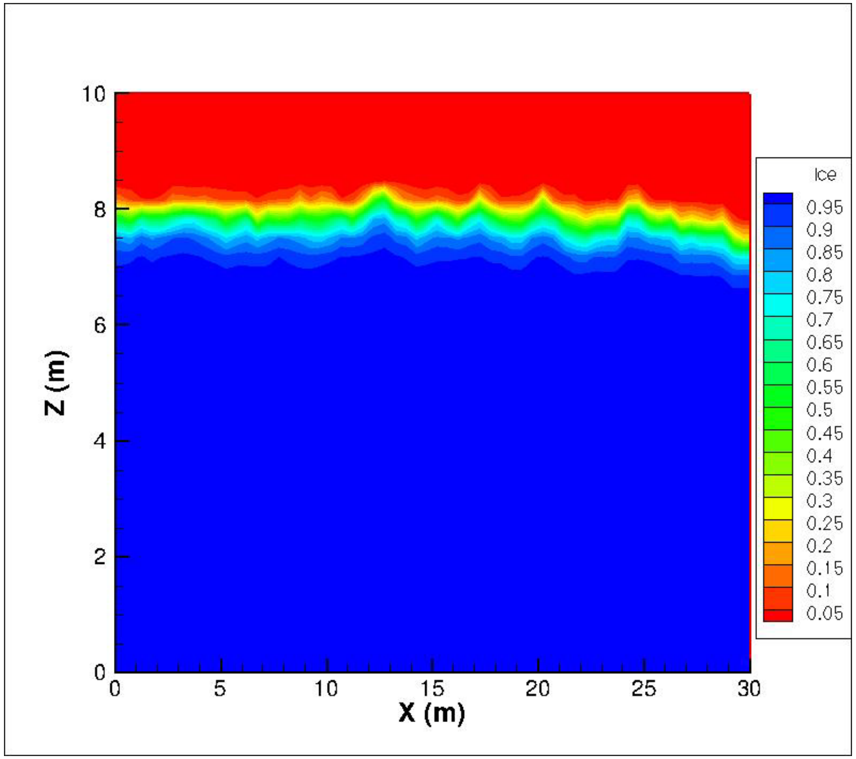




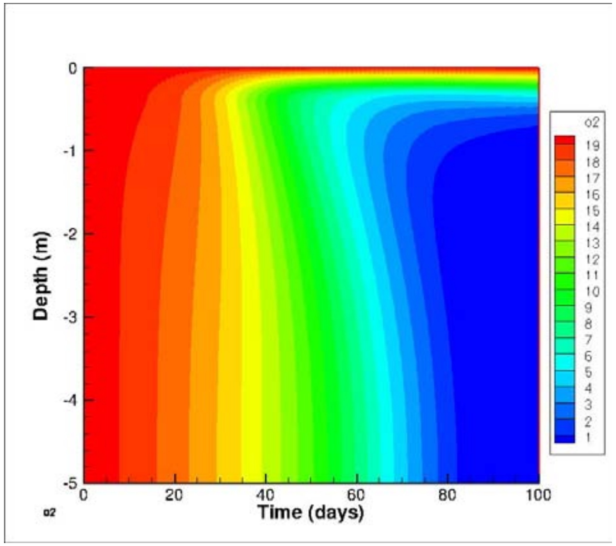
Porosity and permeability assumed randomly distributed; pores are water or ice-filled

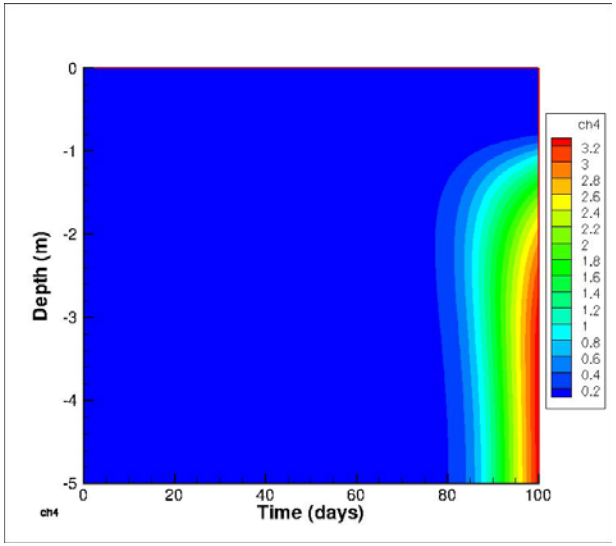
Ice (l) and Temperature (r) distributions - August

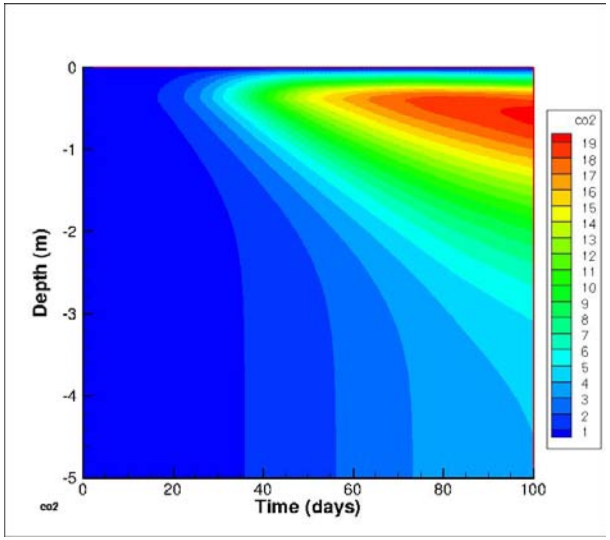




A z-t profile of sample ARCHY simulation of microbial species activity (aerobes, anaerobes, methanotrophs) in spring to summer







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Plans for Model

- Comparison to soil data (CO_2, CH_4 soil measurements, fluxes)
- Study interactions between physical and biological factors
- Couple to surface vegetation and roots model, e.g., SPA
- Sensitivity analysis – ranking of importance
- Prediction of responses to climate changes