Modeling permafrost dynamics in Alaska by CLM 3 and comparing with observations

D. Nicolsky[1], V. Alexeev[2], S. Marchenko[1], V. Romanovsky[1]

1. Geophysical Institute, University of Alaska Fairbanks
2. International Arctic Research Center, University of Alaska Fairbanks

Open issues with CLM3

Increased thickness of the soil layers

Typical 200-300 year temperature variability on the ground surface extends down to 100-150 meters. We run a version of the CLM3 with the total simulated soil thickness of 80 meters by adding a certain number of soil layers.

Mineral soil horizon		Thermal conductivity	
		Frozen	Thawed
Highly enriched with organic matter	[0.0 0.2]	0.9	0.5
Silt enriched with organic matter	[0.2 1.5]	1.4	0.8
Silt, loess	[1.5 3.0]	1.7	1.0

Modification of the numerical solution of the heat equation

The temperature dynamics near 0C is described by a heat equation with phase change. In the CLM3, the heat conduction and the phase change processes are simulated consequently, which may result in a slower rate of soil freezing and thawing than observed in nature. We propose the following modifications. During evaluation of the heat capacity of the soil layers, we suggest to compute the so-called apparent heat capacity:

$$C_{app} = C_s + \frac{\partial \theta_w}{\partial T}$$

and use it in the original code of CLM3 instead of the heat capacity . Since the apparent heat capacity is a rapidly changing function of the temperature near 0C, we suggest to iterate the solution in the original code.

Unfrozen water content

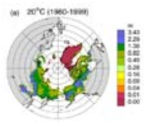
Even though in many cases the presence of unfrozen water content can be neglected, its existence is important to simulate the temperature dynamics near 0C and to provide certain feedback processes to the dynamic vegetation model. The unfrozen water content

$$\theta_w = n \begin{cases} 1, & T > T_p \\ \left(\frac{T}{T_p}\right)^b, & T < T_p \end{cases}$$

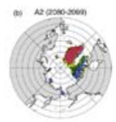
depends on the soil texture, i.e. on sand and clay percentage via the coefficients . We suggest to parameterize it based on these quantities. b, T_p

Organic Cover and Organic Layer

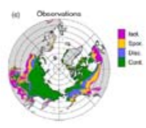
The CLM3 simulates an organic cover by running the dynamic vegetation model. However, influence of the organic cover on thermal properties of the soil is absent, since the thermal conductivity and heat capacity of each soil layer are directly parameterized by its sand and clay content. The organic layer (a typical depth up to 0.2-0.3 meter) in the permafrost rich regions plays a dominant role by resisting to or allowing heat penetration to the underlying frozen ground during summer and winter, respectively. Therefore, the organic layer is crucial for accurate modeling of the long-term permafrost evolution, and its thermal properties can be parameterized by the plant functional types.



Simulated present day permafrost distribution

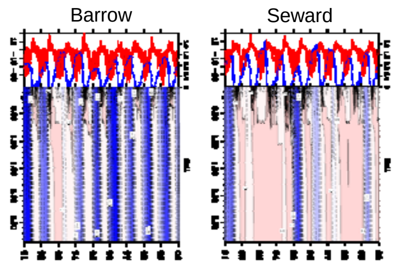


Projected permafrost distribution by CLM3



Observed present day permafrost distribution

Simulated soil temperature by CLM 3



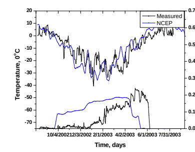
The active layer is too deep

Red curve is the air temperature at the lowest atmosphere level. **Blue curve is the snow depth.**

The CLM simulations are performed in the offline mode. Upper boundary conditions are provided by the output from the global CCSM model.

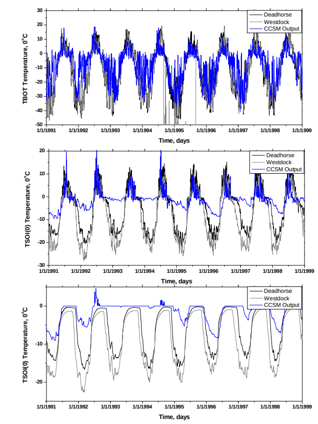
Due to an inadequately small simulated soil thickness, the current temperature dynamics is fully resolved by several preceding years. For example, the quasi-stationary regime is obtained after only 10 full years of the simulation time.

The small simulated soil thickness, large values of the thermal conductivity and snow depths result in thawing and freezing of the entire simulated ground.



The early snow falls insulated the ground during early winter cold temperatures and results in warm bias at Barrow.

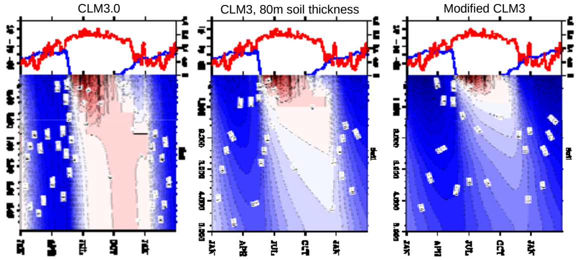
Simulated and measured temperatures, Deadhorse



Strong warm bias with the CCSM forcing

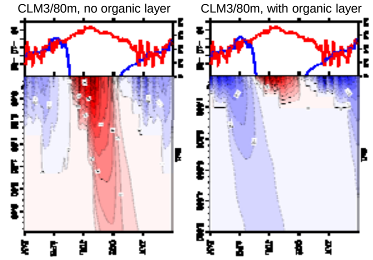
Simulated soil temperature by different versions of CLM 3.0 (perpetual NCEP 98 forcing)

Barrow



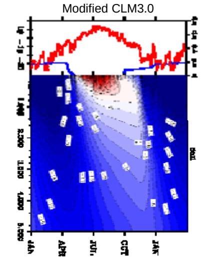
An increased soil thickness results in a non-zero heat flux at 2.8 meter depth and decreased thickness of the active layer.

Seward peninsula

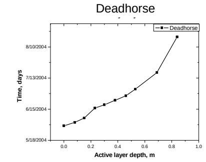


A simulation of the organically enriched mineral soil leads in certain case to preserving of the permafrost over extensive time periods. Removal of the "organic" layer usually results in an increase of the active layer thickness and further degradation of the underlying permafrost.

Deadhorse

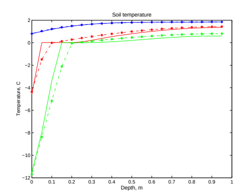


Measured active layer dynamics at Deadhorse



The comparison of the active layer dynamics for Deadhorse show good results with the modified CLM 3.

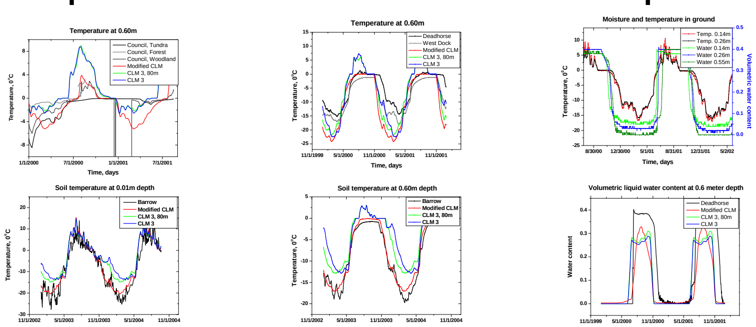
Comparison of numerical schemes



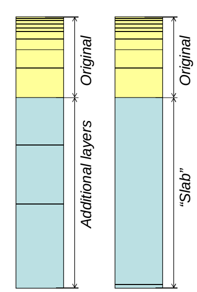
Blue = the 1st time step, **Red** = the 3rd time step, **Green** = the 5th time step.

The dashed lines are temperature profiles computed by CLM3 without iterating the heat equation. The solid lines are temperatures computed by modified numerical scheme in CLM3 with iterations.

Comparison of measured and simulated temperature

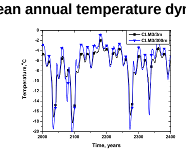


Sensitivity analysis with respect to soil layer geometry

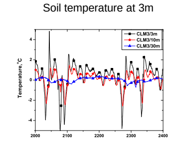


Additional layers:
"Slab" configurations: 30,100 and 300m

Mean annual temperature dynamics

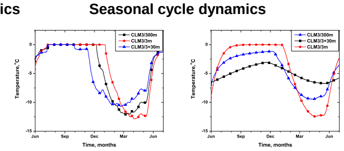


Soil temperature at 3m



Soil temperature "error" at 3m

Seasonal cycle dynamics



Soil temperature at 1m

Soil temperature at 3m

We run CLM3 for 8000 years. The last 6000 years were used for comparison. We define the "exact" solution as the temperature dynamics computed for 300m total soil thickness.

Conclusions

1. **The unaccounted deep soil layers in the CLM 3.0 represent a significant heat reservoir which is important for long-term climate simulations.**
2. **The thermal properties of the organically enriched mineral soil layer plays an important role for correct simulation of the temperature regime both in winter and summer.**
3. **Proper treatment of the unfrozen liquid water at negative temperatures is extremely important for accurate resolution of the permafrost dynamics near 0C.**
4. **Simplifications of numerical algorithms in CLM3 result in unrealistic temperature regimes near freezing.**
5. **Both NCEP and CCSM forcings have significant biases in precipitation and low atmospheric level temperature. This has a certain negative impact on the quality of the simulated results.**

ACKNOWLEDGEMENTS: This research was funded by ARCSS Program and by the Polar Earth Science Program, Office of Polar Programs, National Science Foundation (OPP-0120736, OPP-9732126, OPP-9870635, IARC-NSF CA: Project 3.1 Permafrost Research), and by the State of Alaska.