Permafrost Modeling Toolbox

Irina Overeem, Mark Piper, Kang Wang

with help of Elchin Jafarov, Scott Stewart, Kevin Schaefer

COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

National Snow and Ice Data Center

Objectives

- Learn about the development goals and status of implementation of the Permafrost Toolbox.
- Gain ability in running simulations in data-model and visualize results of permafrost occurrence for Alaska.
- Learn about possibilities for more advanced modeling
- Contribute to the discussion of future development of the modeling system.

Outline of Clinic

- Lecture (30 minutes)
- Demonstration of permafrost models in WMT
- (15 min)

- Hands-on exercise with permafrost toolbox
- (60 minutes) with wrap-up discussion

- Discussion on advanced model development
- and what developments are planned (15 minutes)

Why

- The state of Arctic permafrost is an essential climate indicator and carbon emissions from thawing permafrost will amplify anthropogenic warming.

- Observations can quantify the current state of permafrost, but we need models to make predictions of future permafrost conditions.

Our team

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Mark Piper, CU Boulder
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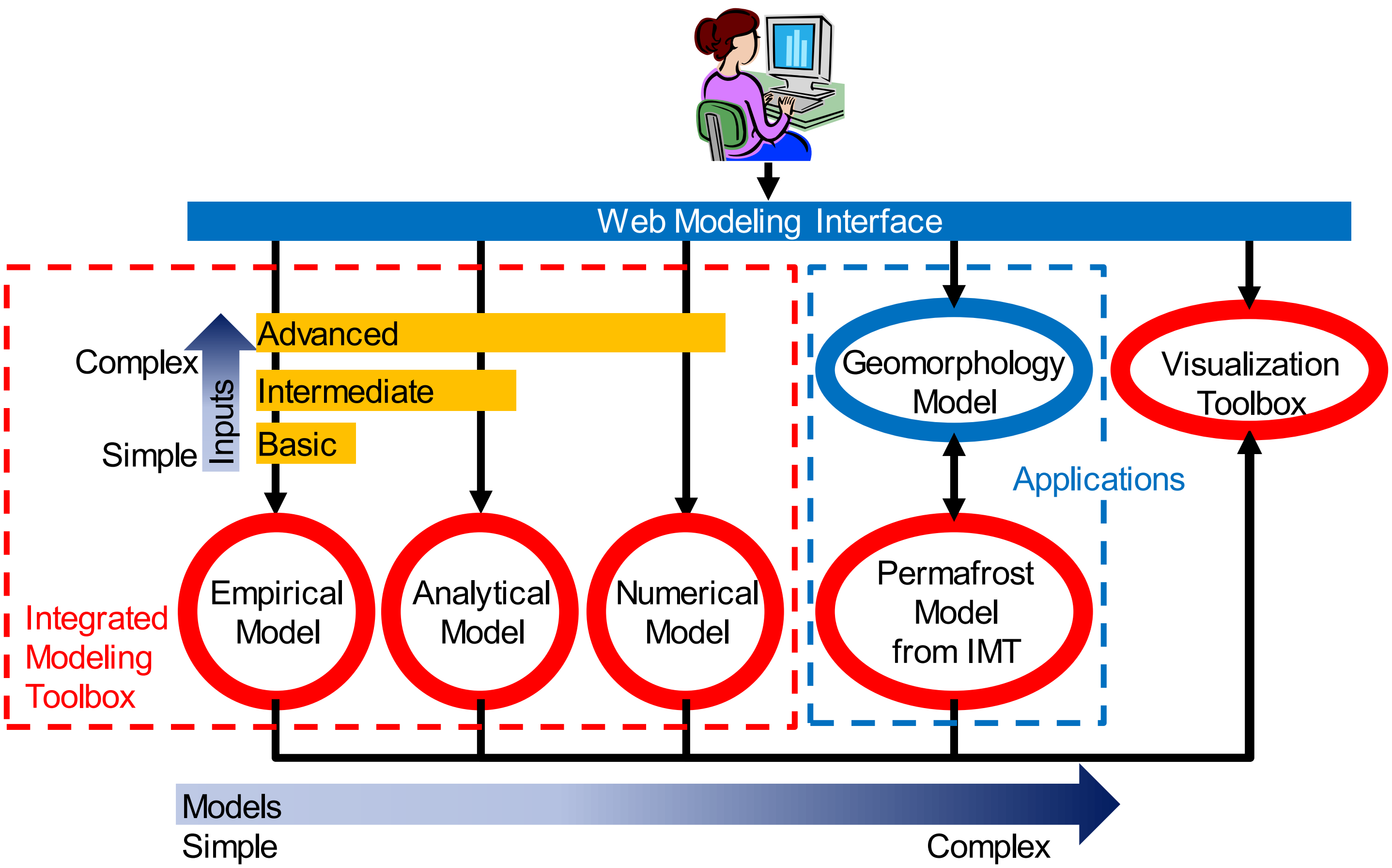
Gary Clow, USGS

Goal

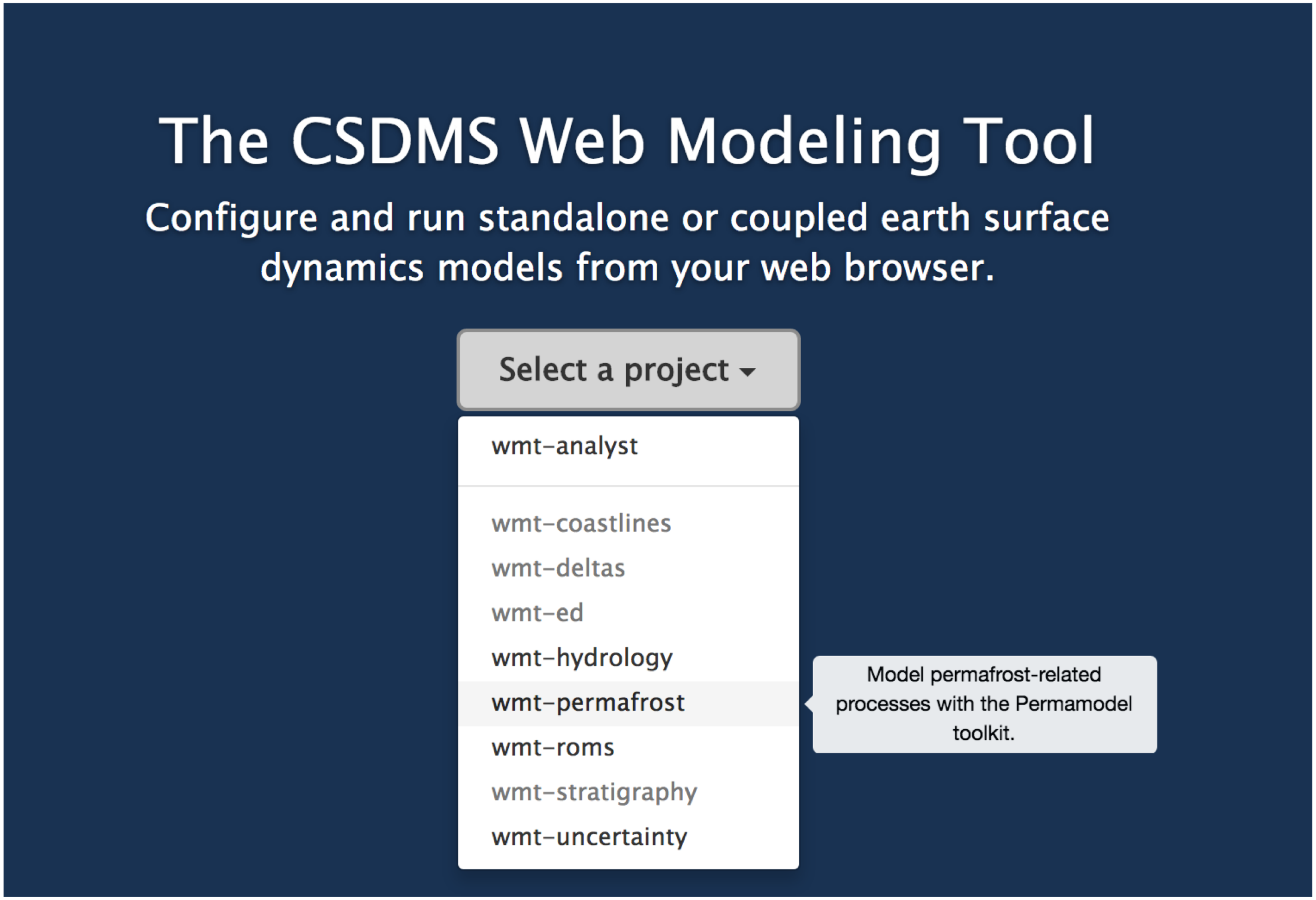
Permafrost Modeling toolbox develops easy-to-access and comprehensive cyberinfrastructure to promote permafrost modeling

Vision for Permafrost Modeling Toolbox



- Models ranging in complexity
- Allow input data to easily be ingested
- Web interface for ease of use
- Ultimate goal: coupled modeling across domains

Web Modeling Tool

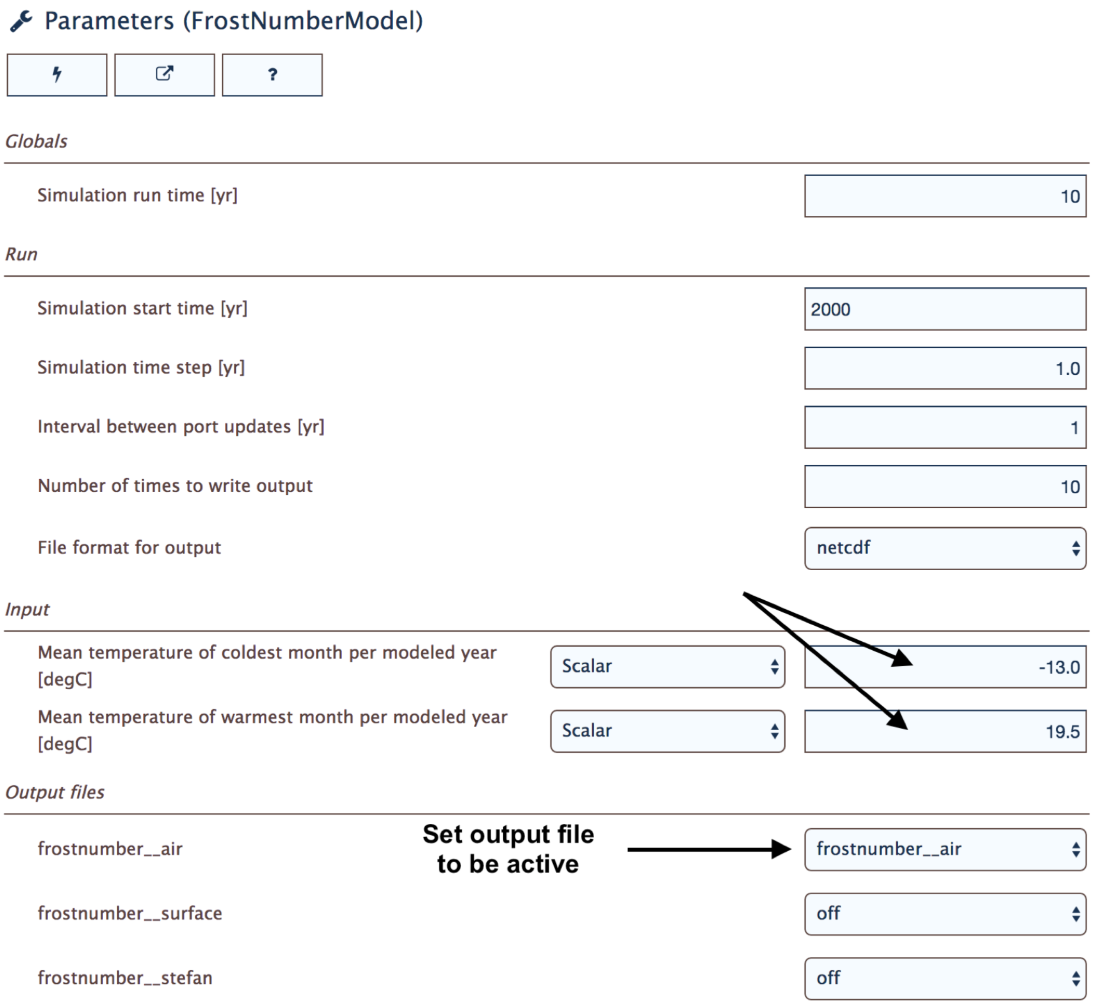


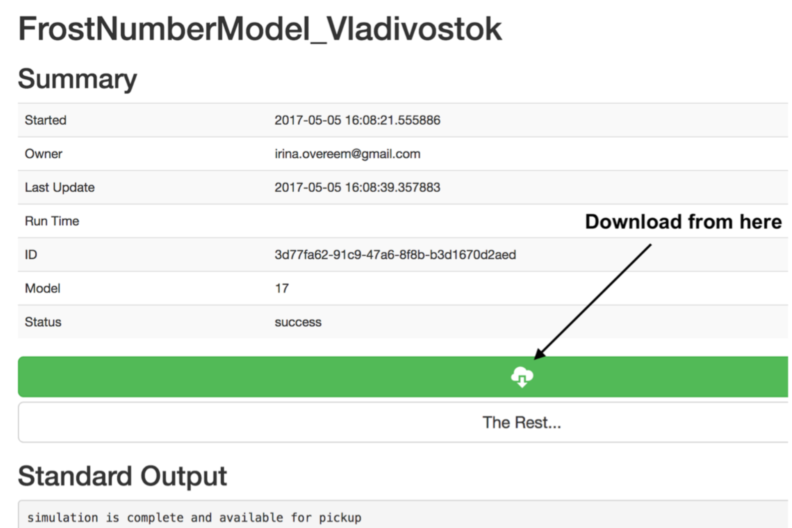
https://csdms.colorado.edu/wmt/

Develop Models as ‘Components’

- Models receive a ‘Basic Model Interface’
- Specify with precision which parameters components do need, which parameters do they generate (Standard Names).
- Components generate netCDF output

Web Modeling Tool





Web Modeling Tool allows new users to get familiar with main parameters of components in permafrost modeling toolbox, run simple simulations, download output.

Physical Models

- Air Frost Number model – 1D
- Air Frost number model –GEO

- Kudryavtsev model – 1D
- Kudryavtsev model – GEO

- GIPL model – daily time-series, continuous depth
- (UAF Geophysical Institute Permafrost Lab model)

- Continuum volume model (G. Clow, USGS)

Increasing complexity

‘Air’ Frost Number

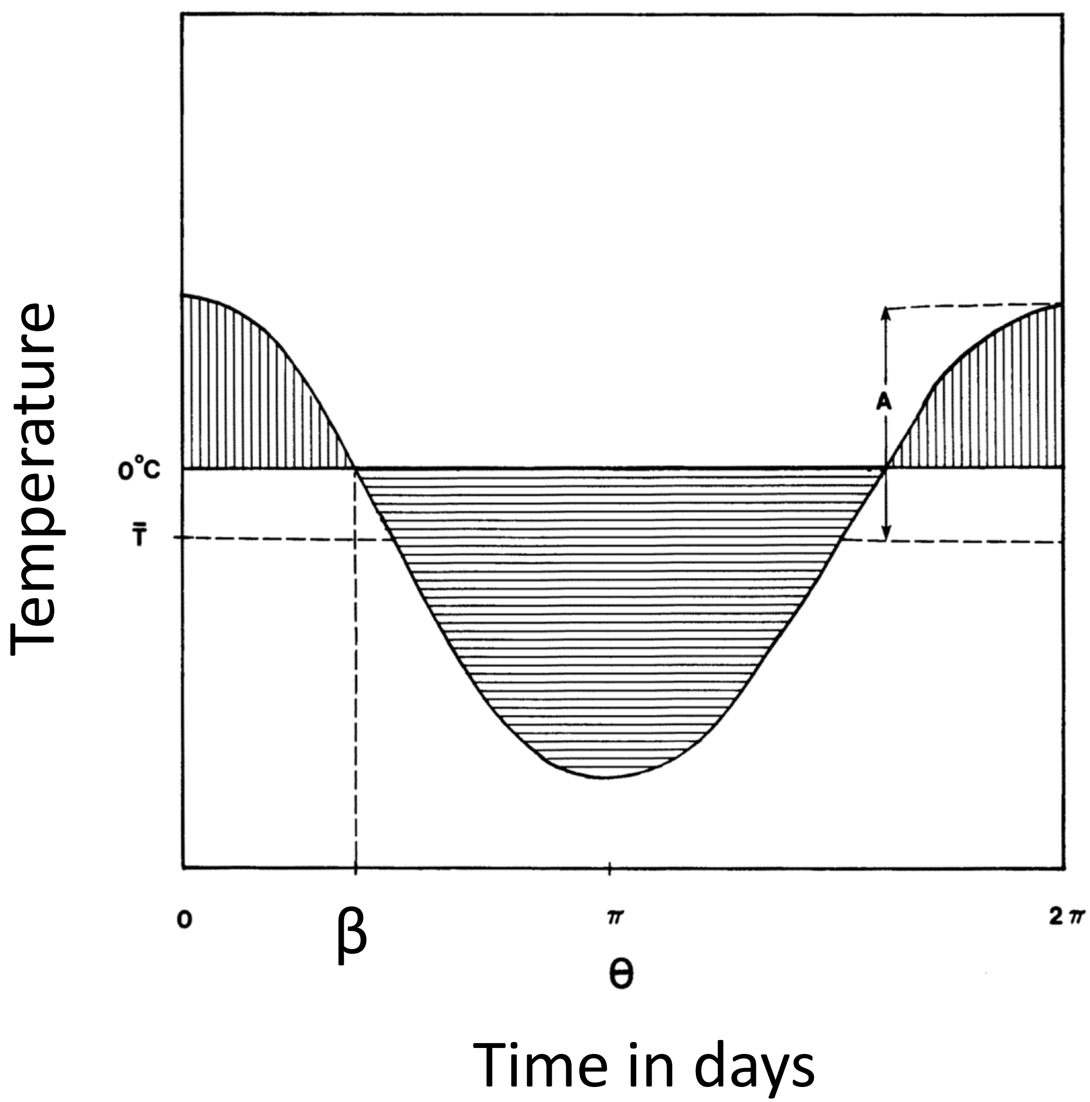
$$F = \frac{DDF^{1/2}}{DDF^{1/2} + DDT^{1/2}}$$

F = Frost Number (-)

DDF = freezing day index (°C days)
DDT = thawing day index (°C days)

(From: Nelson and Outcalt, 1987, AAAR.)

Cosine Approximation of Annual Temperature Distribution



A= amplitude in °C

How much time in a year are temperatures above or below freezing?

(From: Nelson and Outcalt, 1987, AAAR)

Calculate DDT and DDF

$$MAAT = (T_h + T_c)/2$$

$$A = (T_h - T_c)/2$$

$$\beta = \cos^{-1}(-MAAT/A)$$

$$T_s = MAAT + A((\sin\beta)/\beta)$$

$$T_w = MAAT - A((\sin\beta)/(\pi - \beta))$$

$$L_s = 365(\beta/\pi)$$

$$L_w = 365 - L_s$$

Symbol	Parameter	unit
MAAT	Mean annual temperature	°C
A	Yearly temperature amplitude	°C
beta	Frost angle	-
Ts	Mean summer temperature	°C
Tw	Mean winter temperature	°C
Ls	Length of summer	days
Lw	Length of winter	days

$$DDT = T_s L_s$$

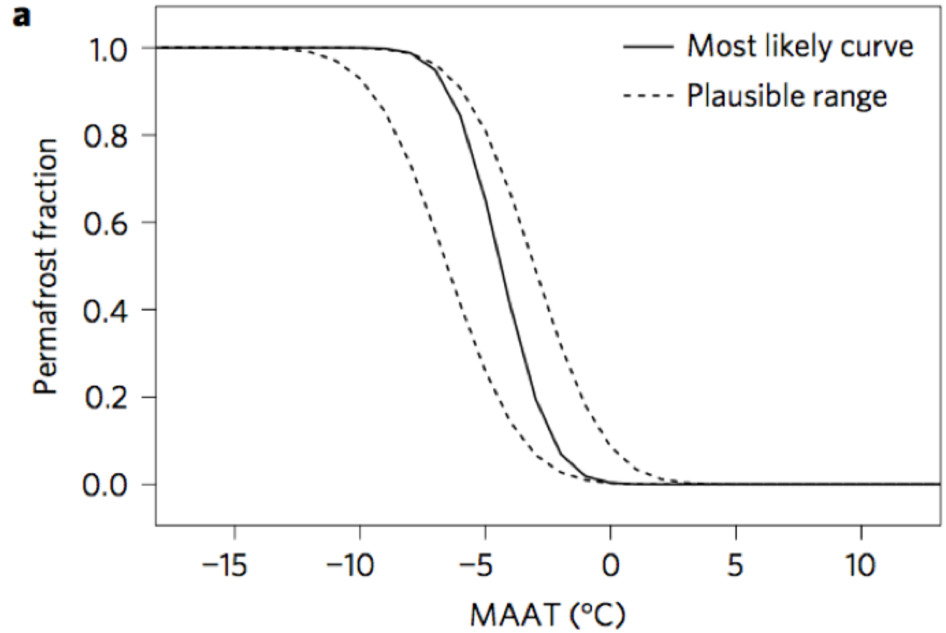
$$DDF = T_w L_w$$

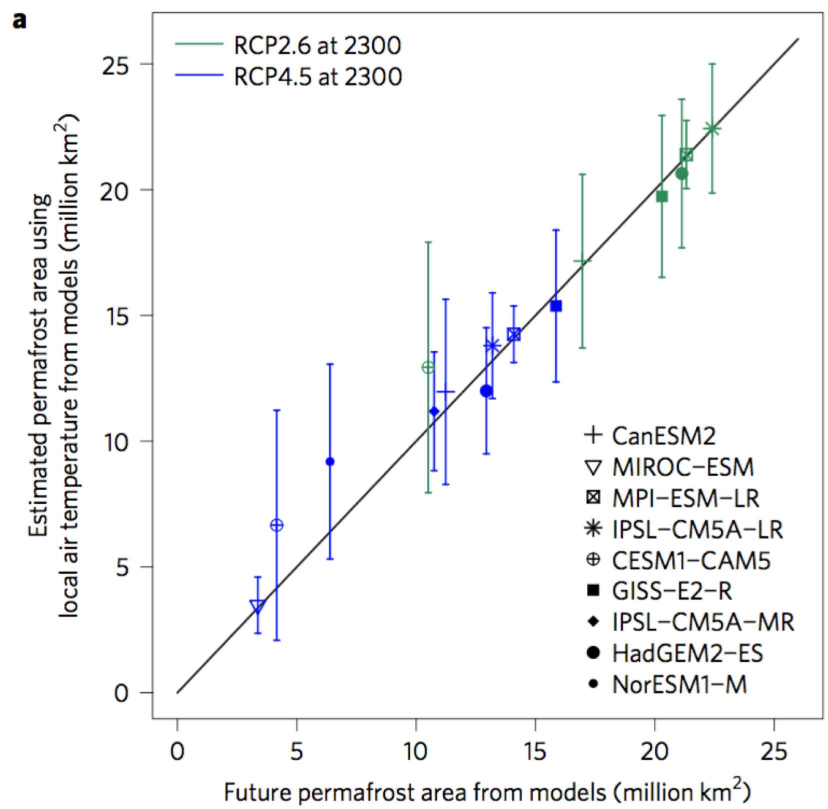
Defining the Permafrost Limit

- ‘Air Frost Number’ predicts that permafrost is theoretically possible:

- When the mean annual temperature is < 0°C
- When the freezing and thawing indices are equal; thus when Frost Number >= 0.5

What is the use of such a simple model?

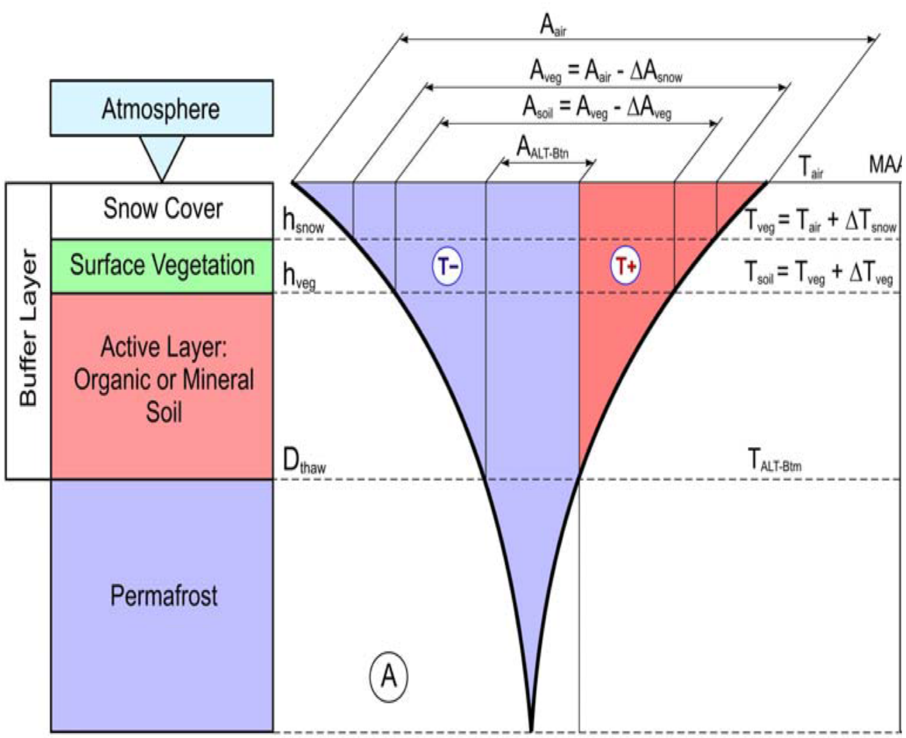




(From: Chadburn et al., 2017, Nature Climate Change)

Kudryavstev Model

- The Ku model is an semi-empirical model developed in 1970s.
- It essentially is an thermal equilibrium model.
- Calculates annual soil temperature, active layer thickness
- Includes layers of snow and vegetation.



(Anisimov et al., 1997)

Depth to freezing or thawing (Z)

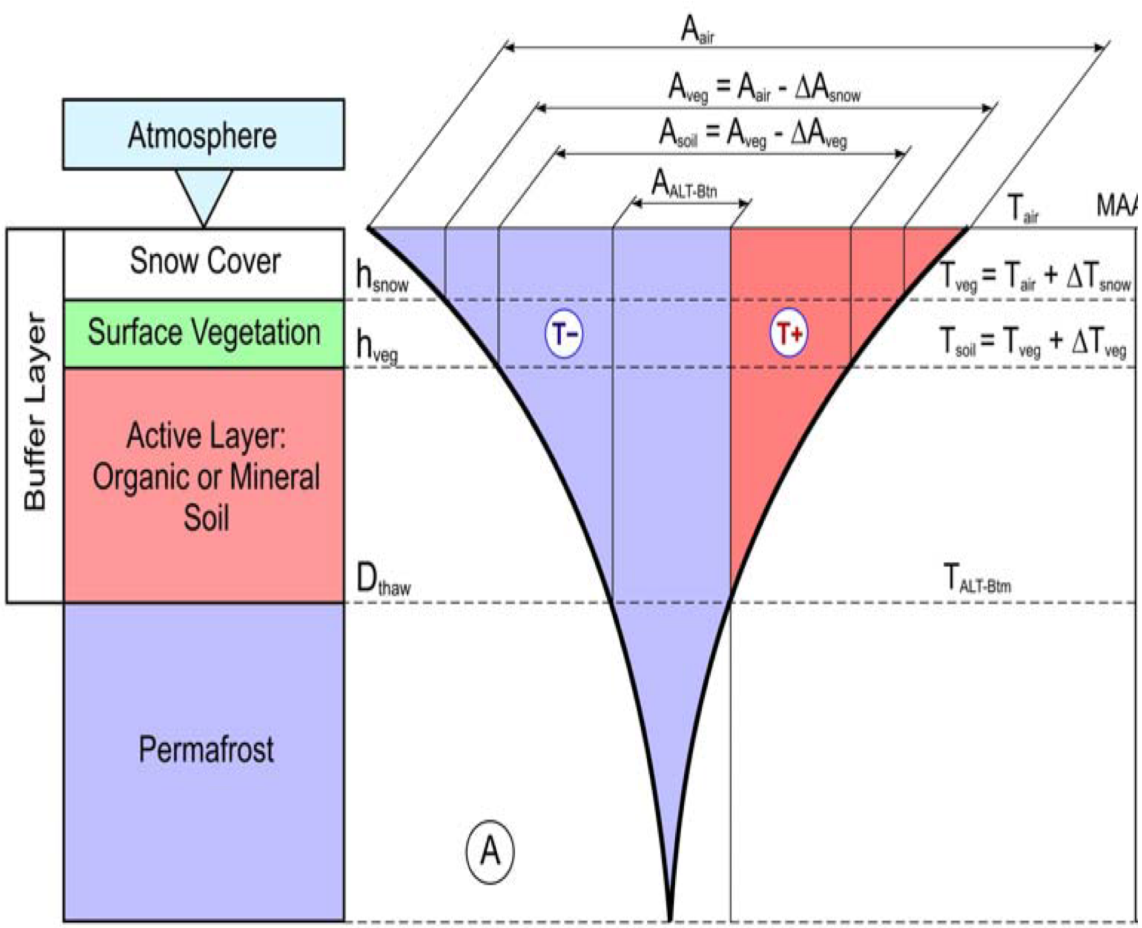
$$Z = \frac{2\left(A_s - \bar{T}_z\right)\cdot\left(\frac{\lambda\cdot P\cdot C}{\pi}\right)^{1/2} + \frac{\left(2A_z\cdot C\cdot Z_c + Q_L\cdot Z\right)\cdot Q_L\left(\frac{\lambda\cdot P}{\pi\cdot C}\right)^{1/2}}{2A_z\cdot C\cdot Z_c + Q_L\cdot Z + \left(2A_z\cdot C + Q_L\right)\cdot\left(\frac{\lambda\cdot P}{\pi\cdot C}\right)^{1/2}}}{2A_zC + Q_L}$$

$$A_z = \frac{A_s - \bar{T}_z}{\ln\left(\frac{A_s Q_L/2C}{\bar{T}_z + Q_L/2C}\right)} - \frac{Q_L}{2C}$$

$$Z_c = \frac{2\left(A_s - \bar{T}_z\right)\cdot\left(\frac{\lambda\cdot P\cdot C}{\pi}\right)^{1/2}}{2A_z\cdot C + Q_L}$$

A_s = annual amplitude of surface temperature
T_z = mean annual temperature at depth of seasonal thawing
λ = thermal conductivity $W\ m^{-1}\ C^{-1}$
C = volumetric heat capacity $J\ m^{-3}\ C^{-1}$
Ql = volumetric latent heat of fusion $J\ m^{-3}$

Consider temperature at each layer interface separately



$$\bar{T}_s = \bar{T}_a + \Delta T_{sn} + \Delta T_{veg}$$

$$A_s = A_a - \Delta A_{sn} - \Delta A_{veg}$$

Temperature and annual amplitude at the soil surface (s) depends on the thermal effects of snow and vegetation.

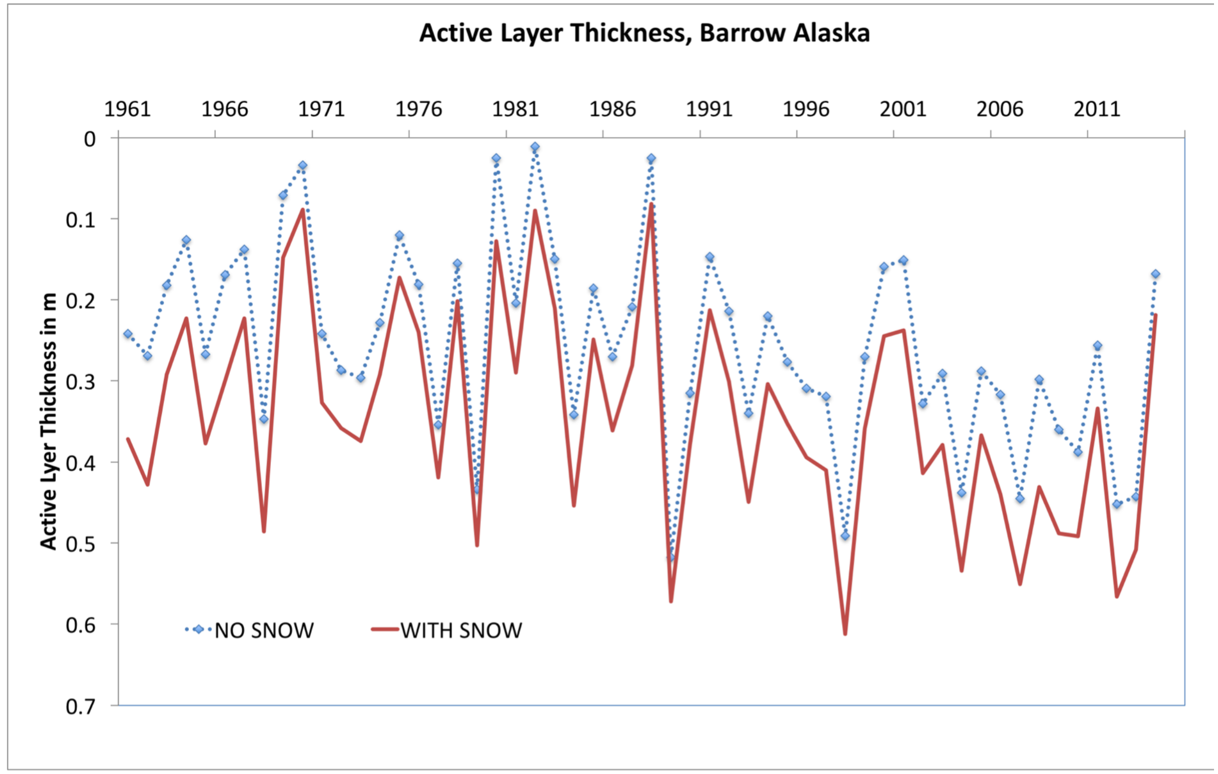
(Anisimov et al., 1997)

Snow thermal effect

$$\Delta T_{\mathrm{sn}} = A_{\mathrm{a}}\left\{1 -- \exp\left[-Z_{\mathrm{sn}}\left(\frac{\pi \cdot C_{\mathrm{sn}}\, \rho_{\mathrm{sn}}}{P \cdot \lambda_{\mathrm{sn}}}\right)^{1/2}\right]\right\}$$

Z_{sn} = snow cover thickness in m
λ_{sn} = snow thermal conductivity W m^{-1} C^{-1}
C_{sn} = snow volumetric heat capacity J m^{-3} C^{-1}
ρ_{sn} = density of snow in kg m^{-3}

What is the use of such a medium complexity model?



Discussion within federal agency with request to support in-situ snow monitoring on the Alaskan North Slope?

If we'd would not have data on seasonal snow thickness, our predictions of permafrost active layer thickness would be impacted. Ku model can quickly demonstrate this bias for a given location.

Datasets

- User-specified at single location
- Time-series (Barrow and Fairbanks)
- Reanalysis grids (CRU-AKtemp)
- Climate model output for future (CMIP5)

- Soil properties, snow depths
- Other climate variables CRU-NCEP, e.g. prec
- Other climate datasets (e.g. CALM stations)

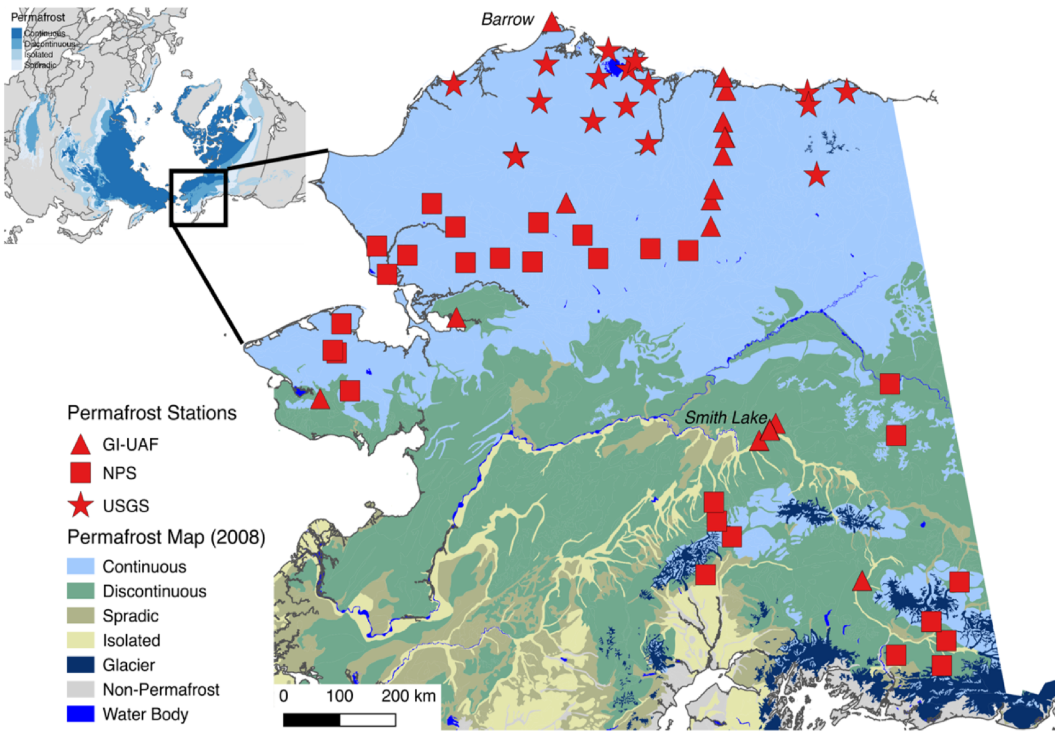
Increasing complexity

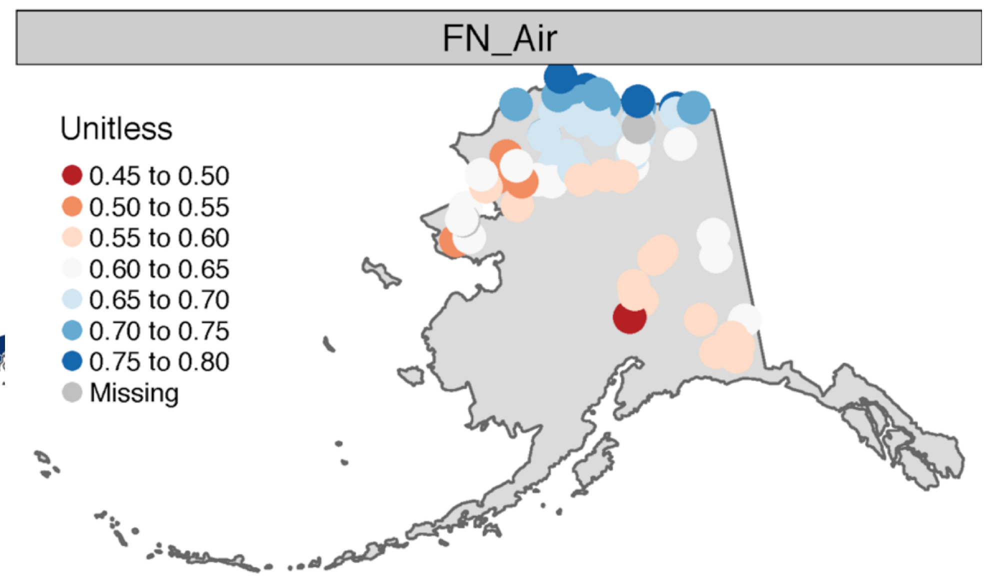
Time series of climate data

- Focus on Barrow and Fairbanks, Alaska
- 1961-2015 observed meteorological data
- Alaska data of USGS, UAF and NPS permafrost stations 1991-2015

- CRU-NCEP SNAP reanalysis dataset with spatial coverage of climate characteristics over Alaska

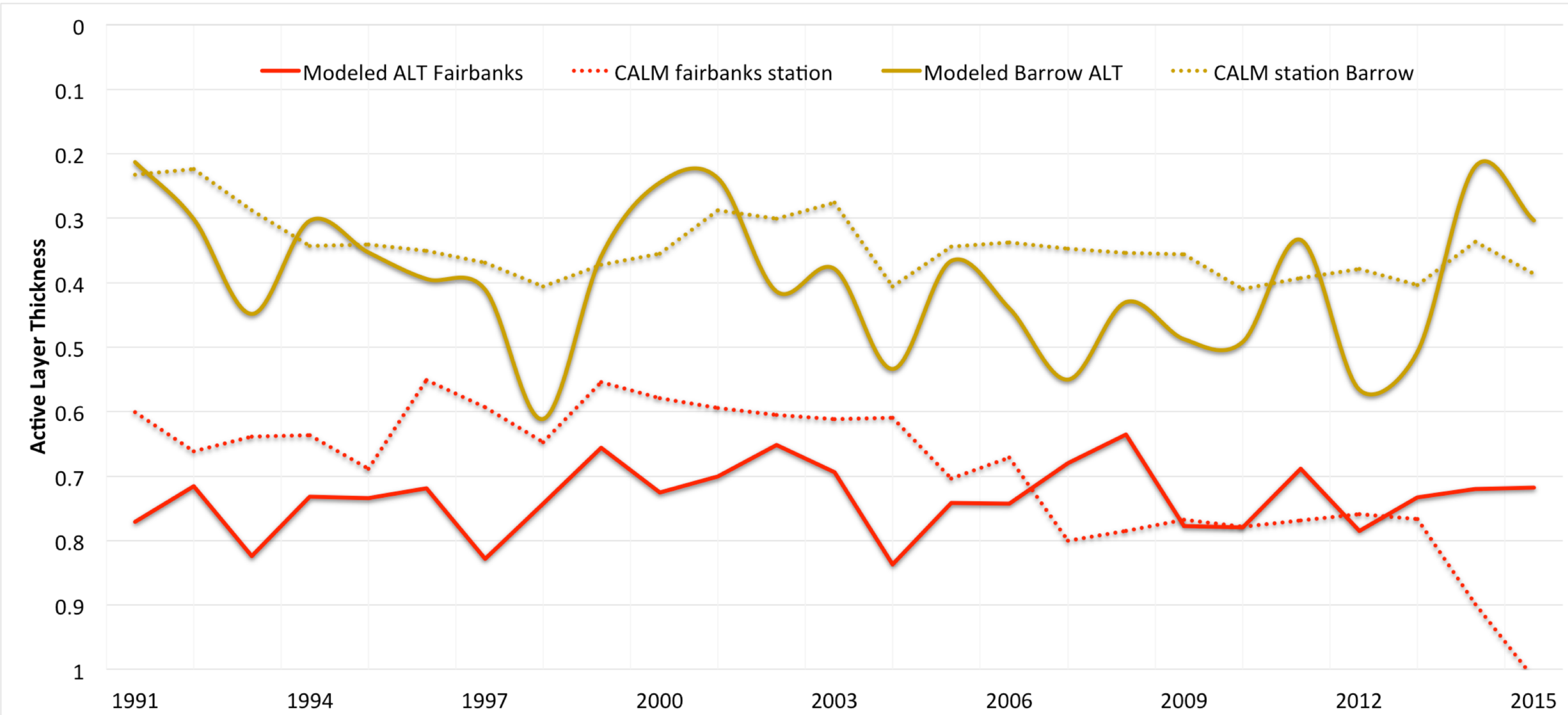
Benchmark against in-situ permafrost data



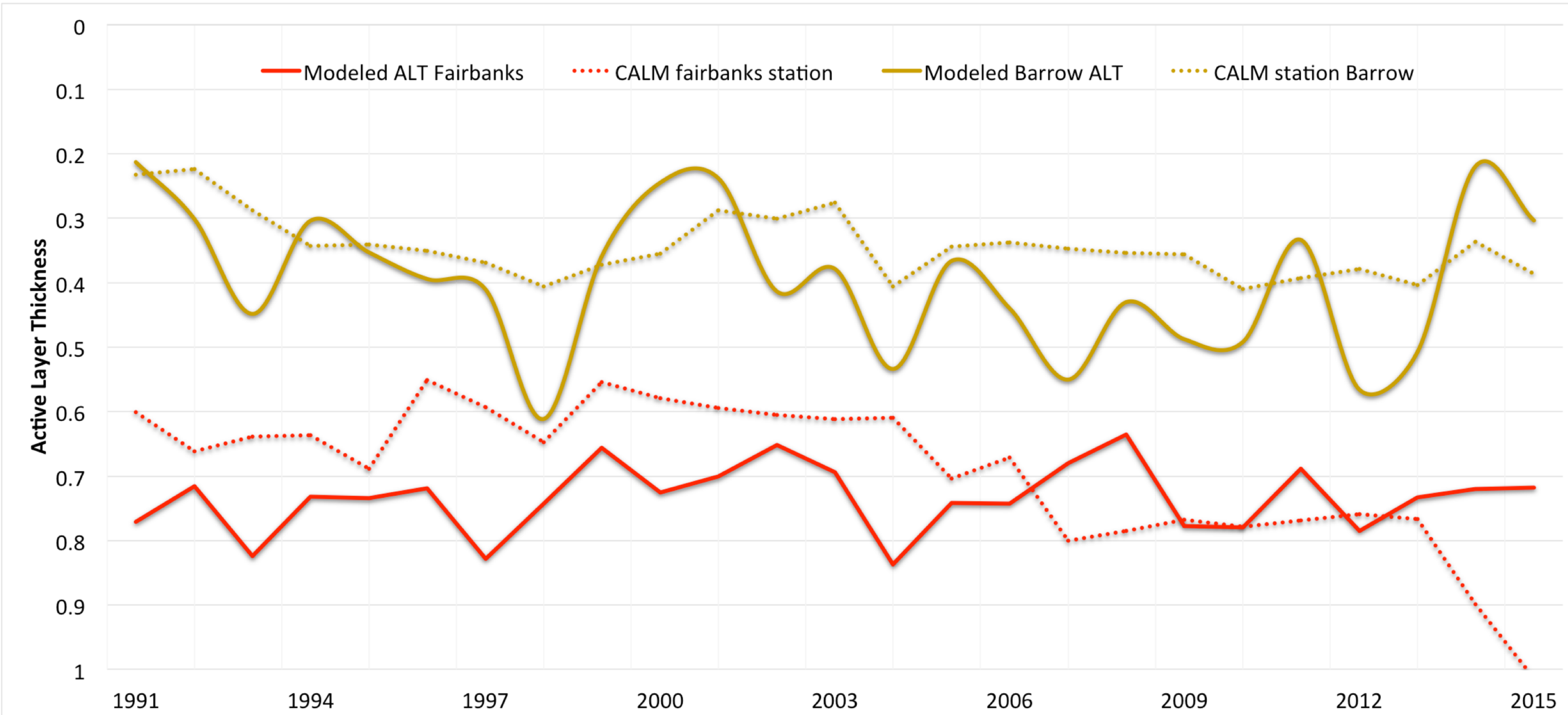


Wang et al., in review,
Earth System Science Data

Data-Model Comparison

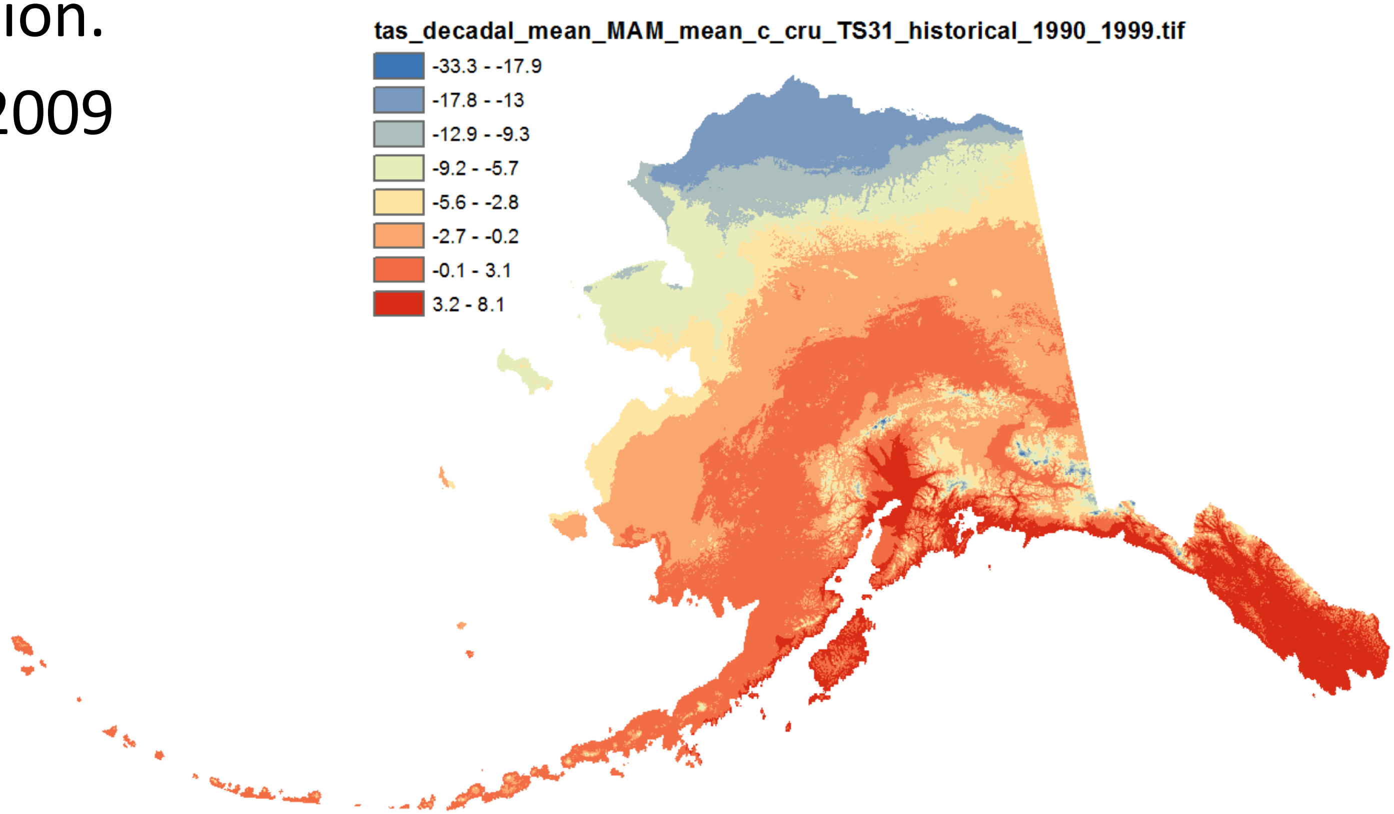


Data-Model Comparison



Climate Reanalysis Data

- Original data source was CRU-TS3 monthly climate data at 771 * 771 m resolution.
- It covers 1900-2009



http://ckan.snap.uaf.edu/dataset/historical-monthly-and-derived-temperature-products-771m-cru-ts

CRU_AKtemp

What is specific for this dataset within the permafrost modeling tool:

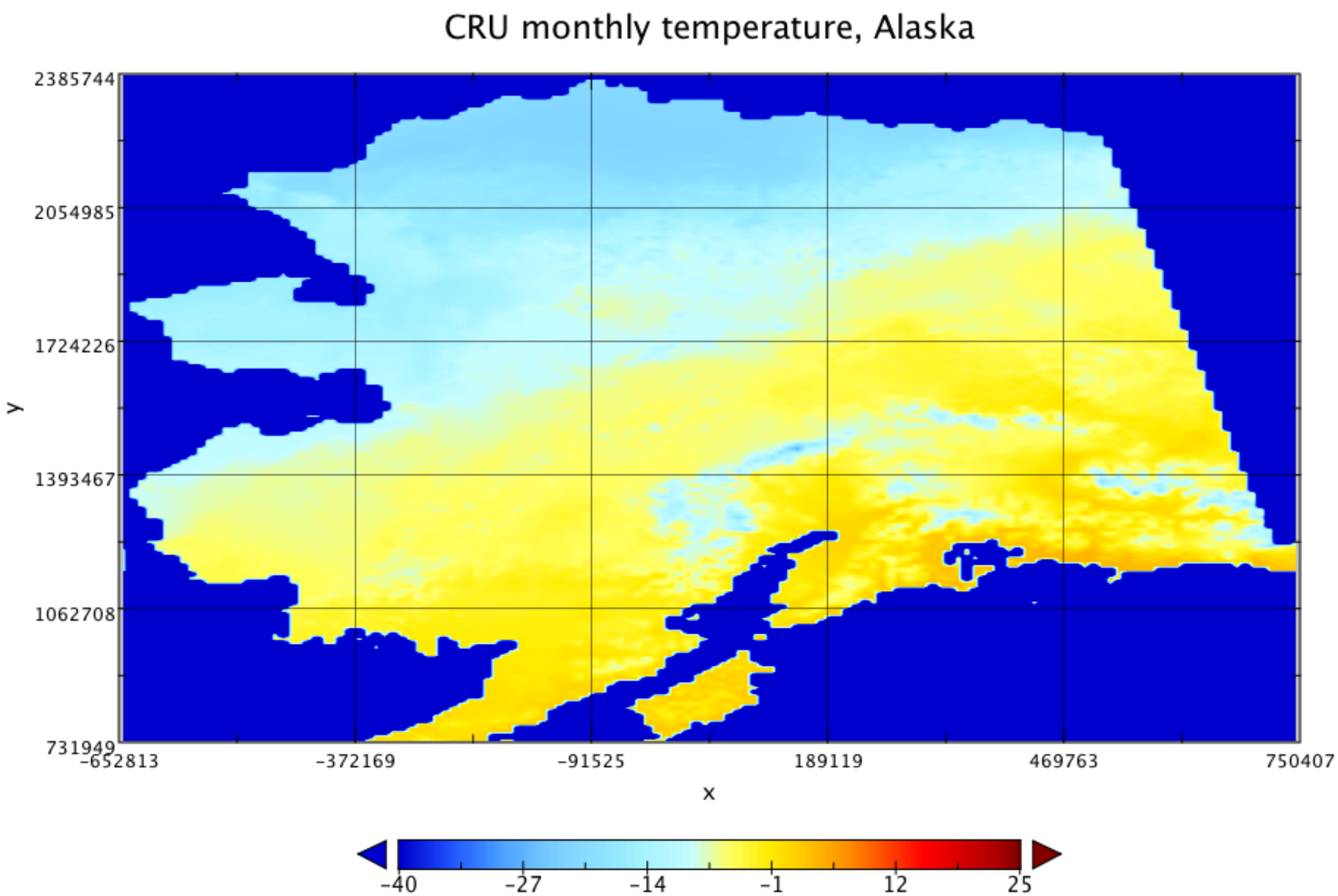
- Data component, has an CSDM basic interface and can be coupled to models that need temperature data.
- Python 2.7 package that provides access to NetCDF file constructed from the original GeoTiffs.

- Geographical extent of this dataset reduced to Alaska.

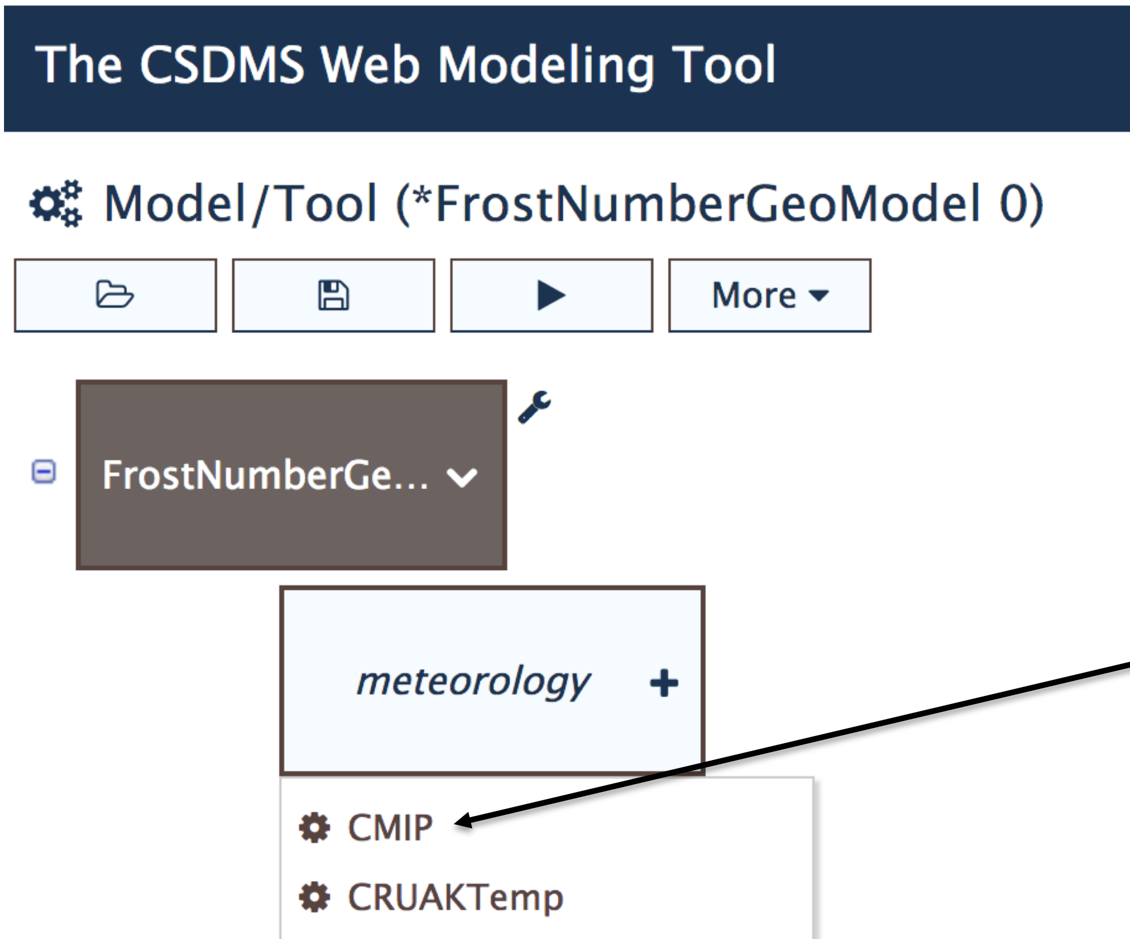
- Spatial resolution has been reduced by a factor of 13 in each direction, resulting in an effective pixel resolution of about 10km.

- The data are monthly average temperatures for each month from January 1901 through December 2009.

CRU_Aktemp example



Predicting Permafrost?

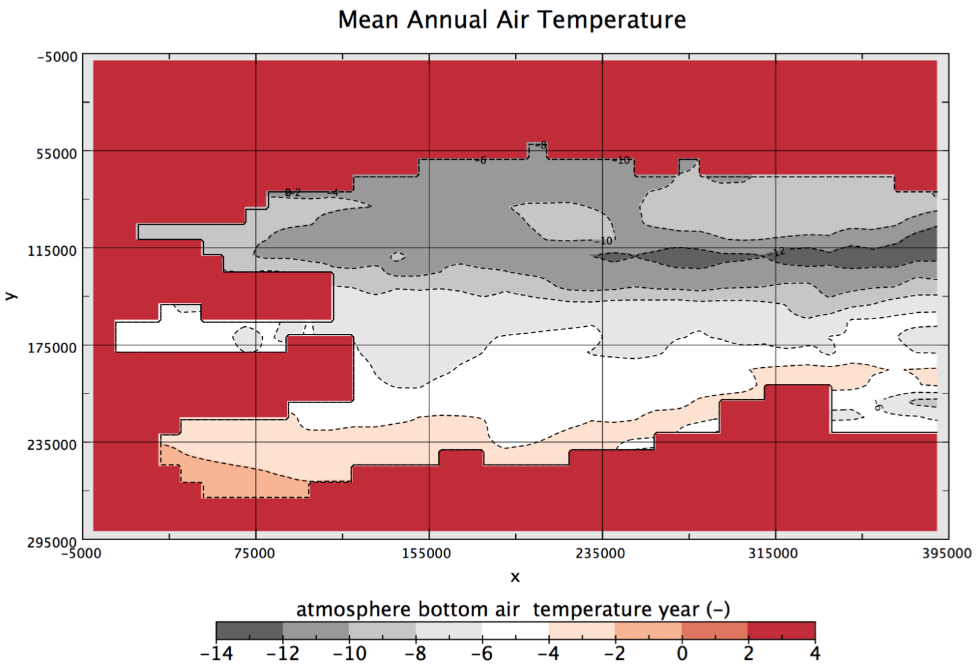


Climate Model Intercomparison Project (CMIP) data set: output of the atmosphere ocean global climate models

Duration: 1902-2100

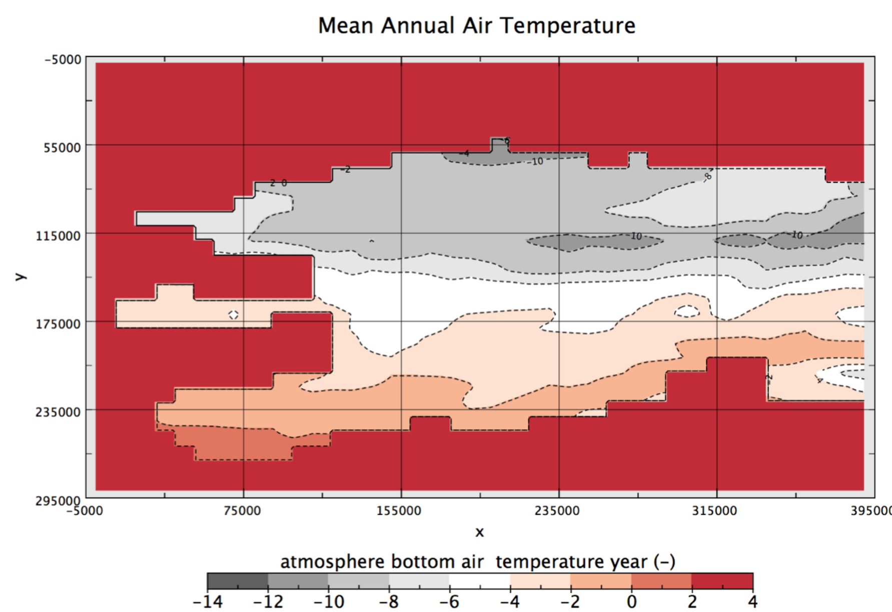
https://github.com/permamodel/cmip

CMIP5 provides mean annual air temperature to Frost and Ku models

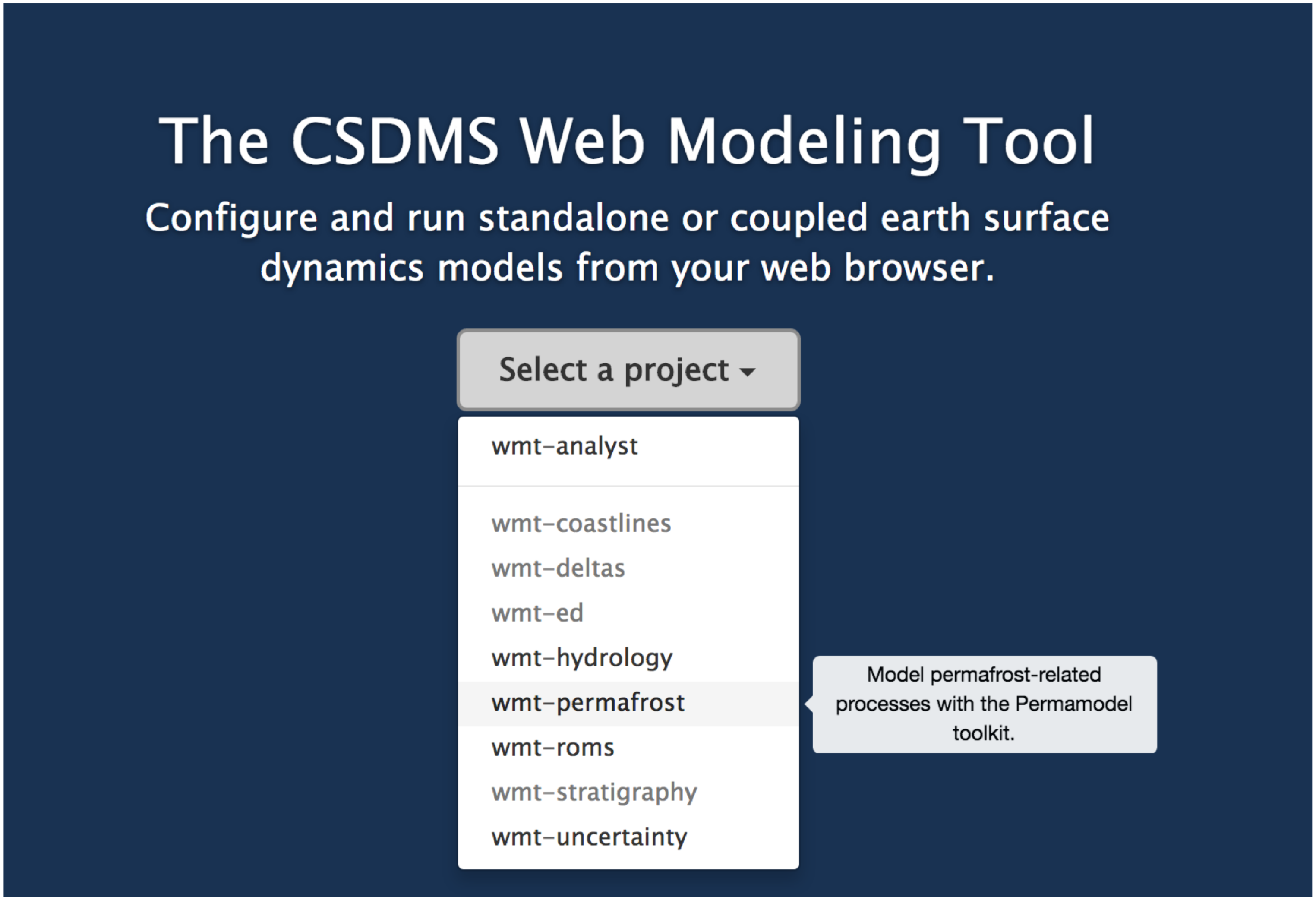


1955

2095

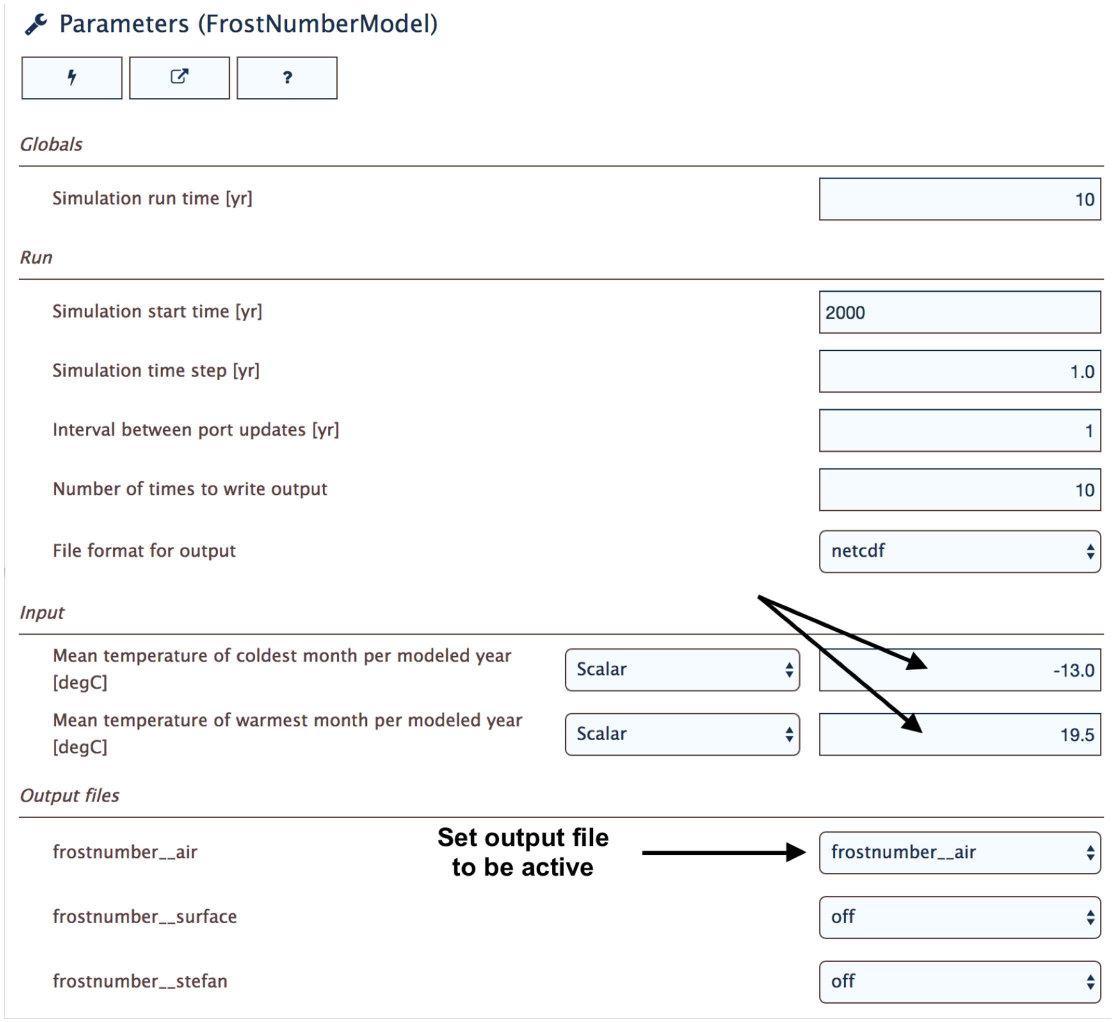


Demonstration

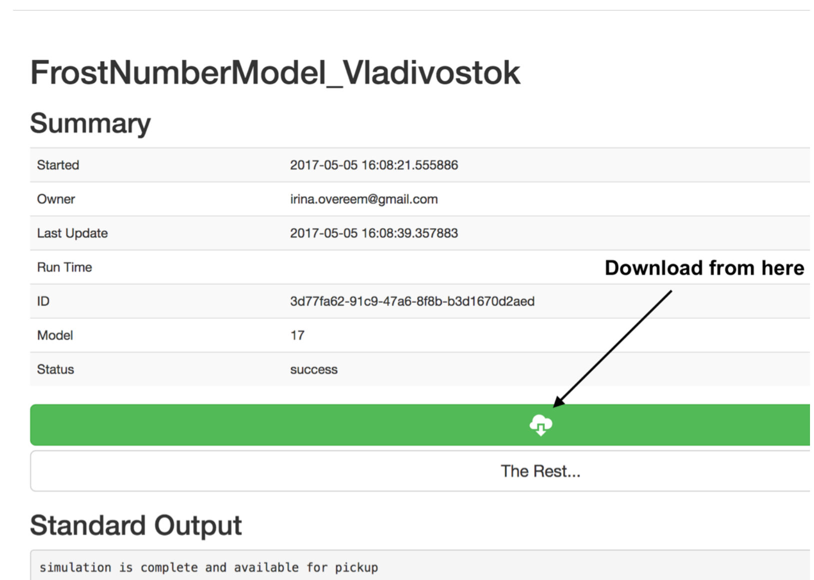


https://csdms.colorado.edu/wmt/

Demonstration

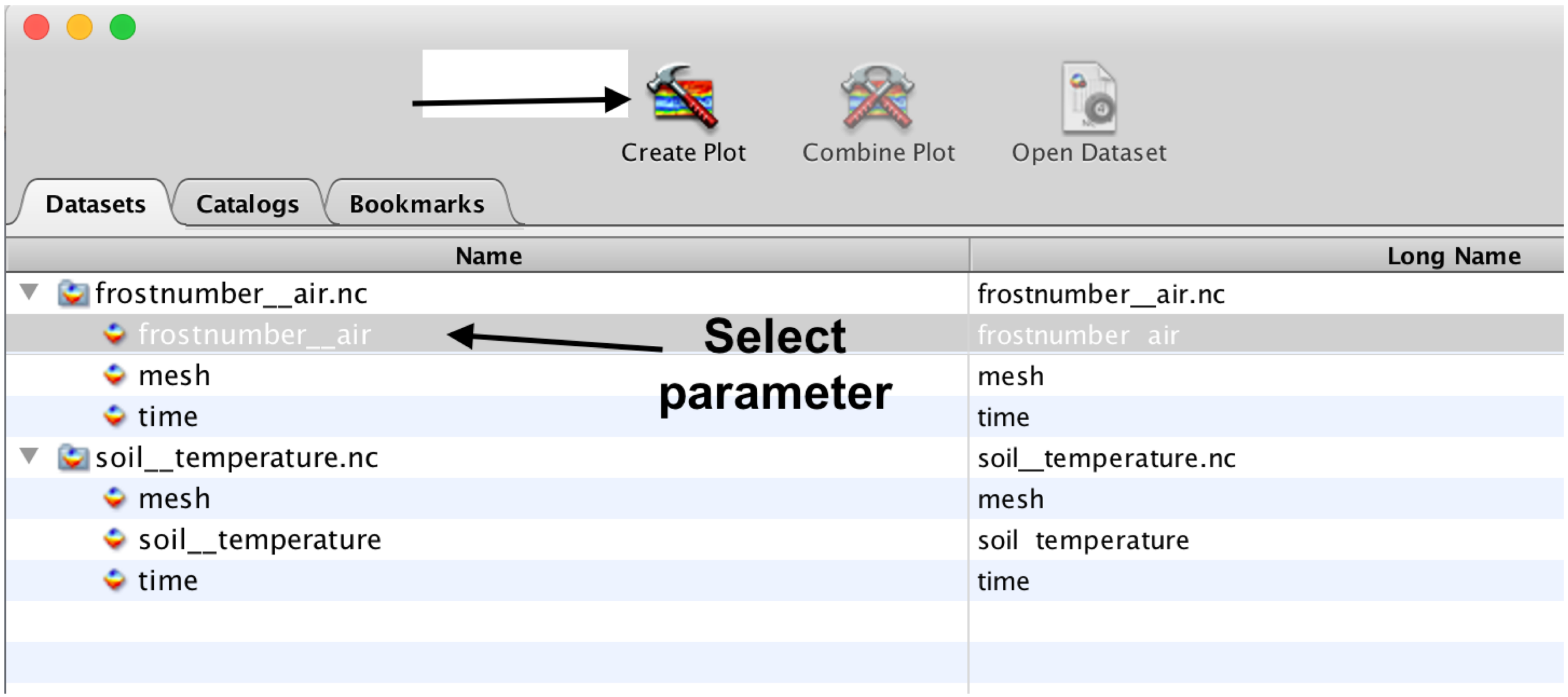


Set up parameters



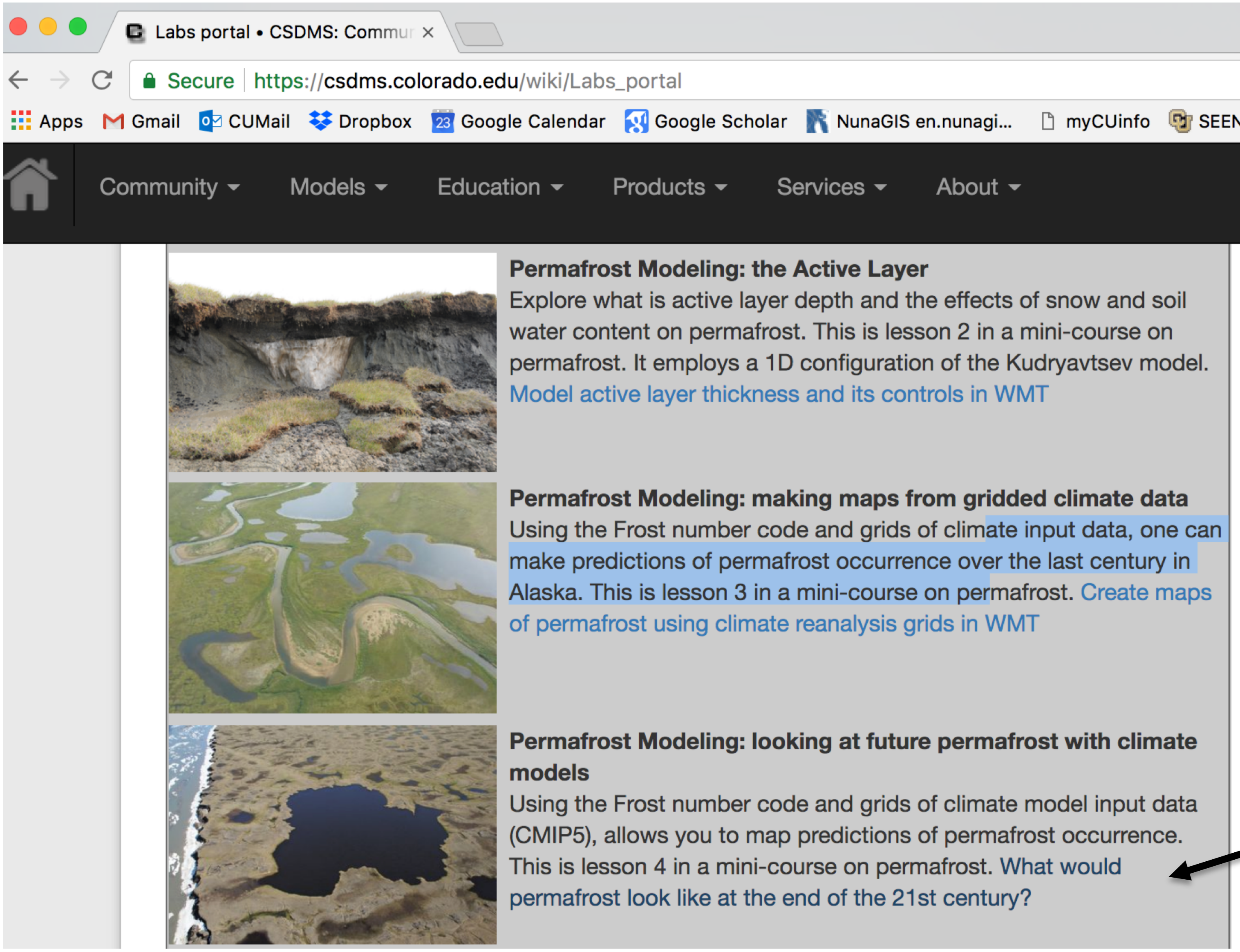
Retrieve Output

Visualize Output with Panoply



https://www.giss.nasa.gov/tools/panoply/

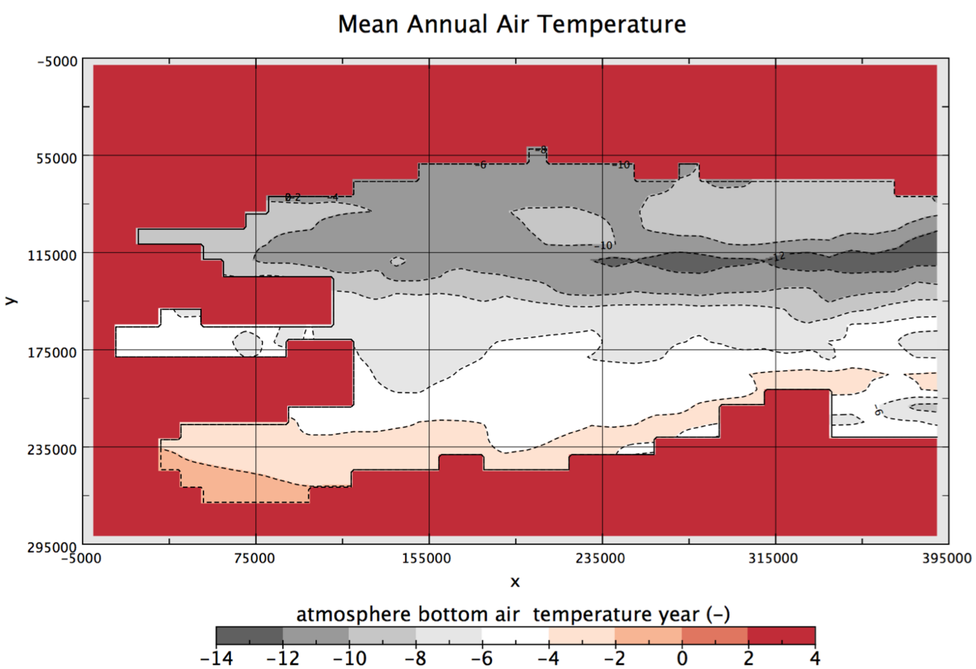
Hands-on



EXAMPLE TODAY

http://csdms.colorado.edu/wiki/Labs_portal

CMIP5 provides mean annual air temperature to Frost and Ku models



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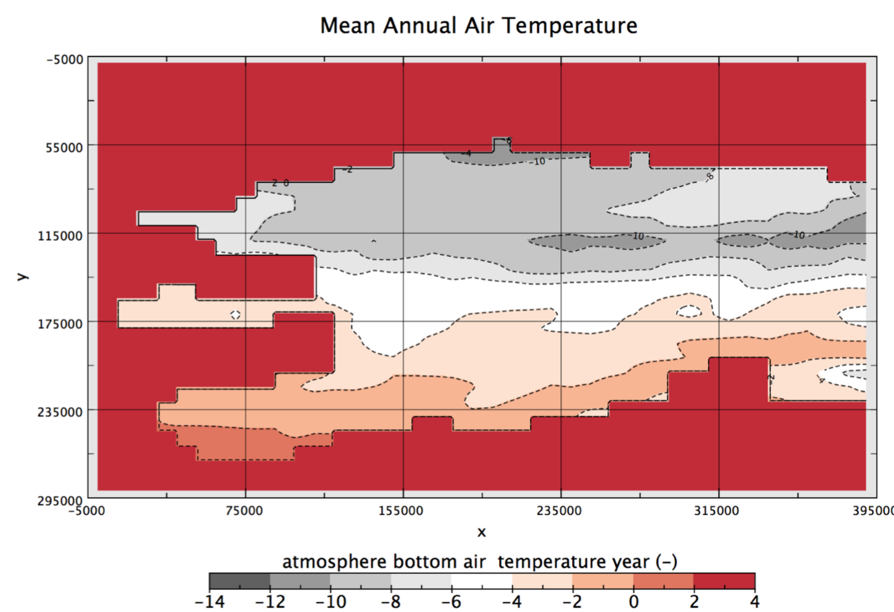
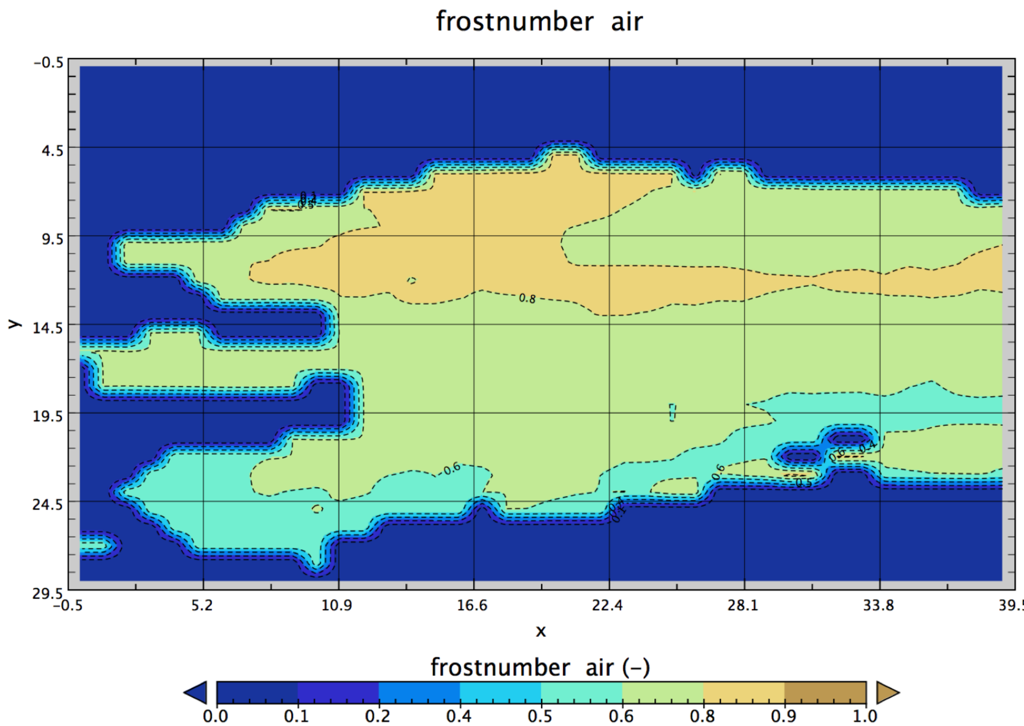


Predictions of Permafrost



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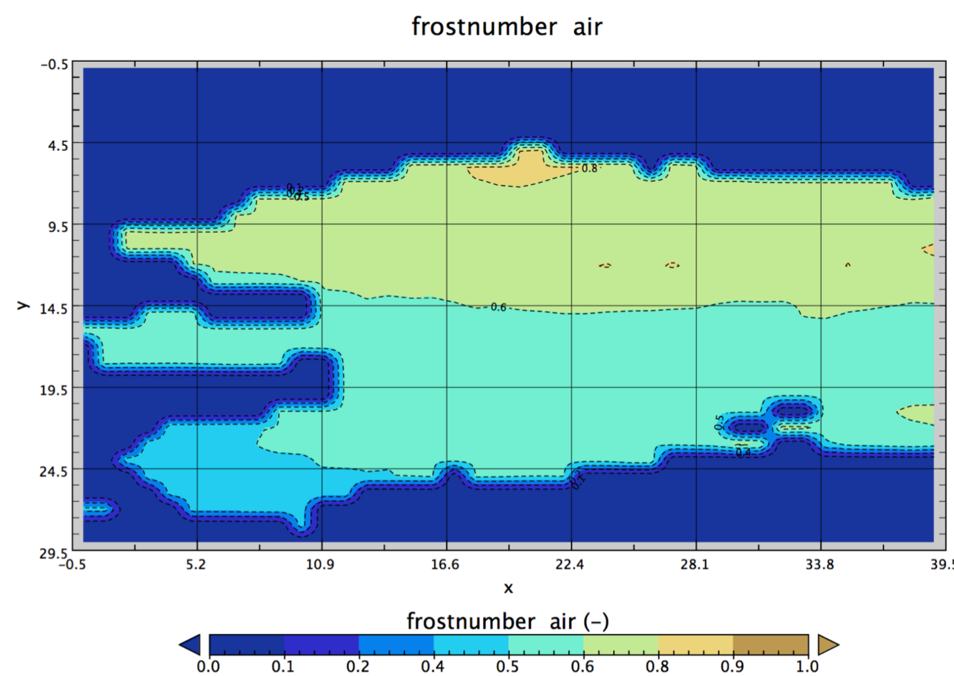
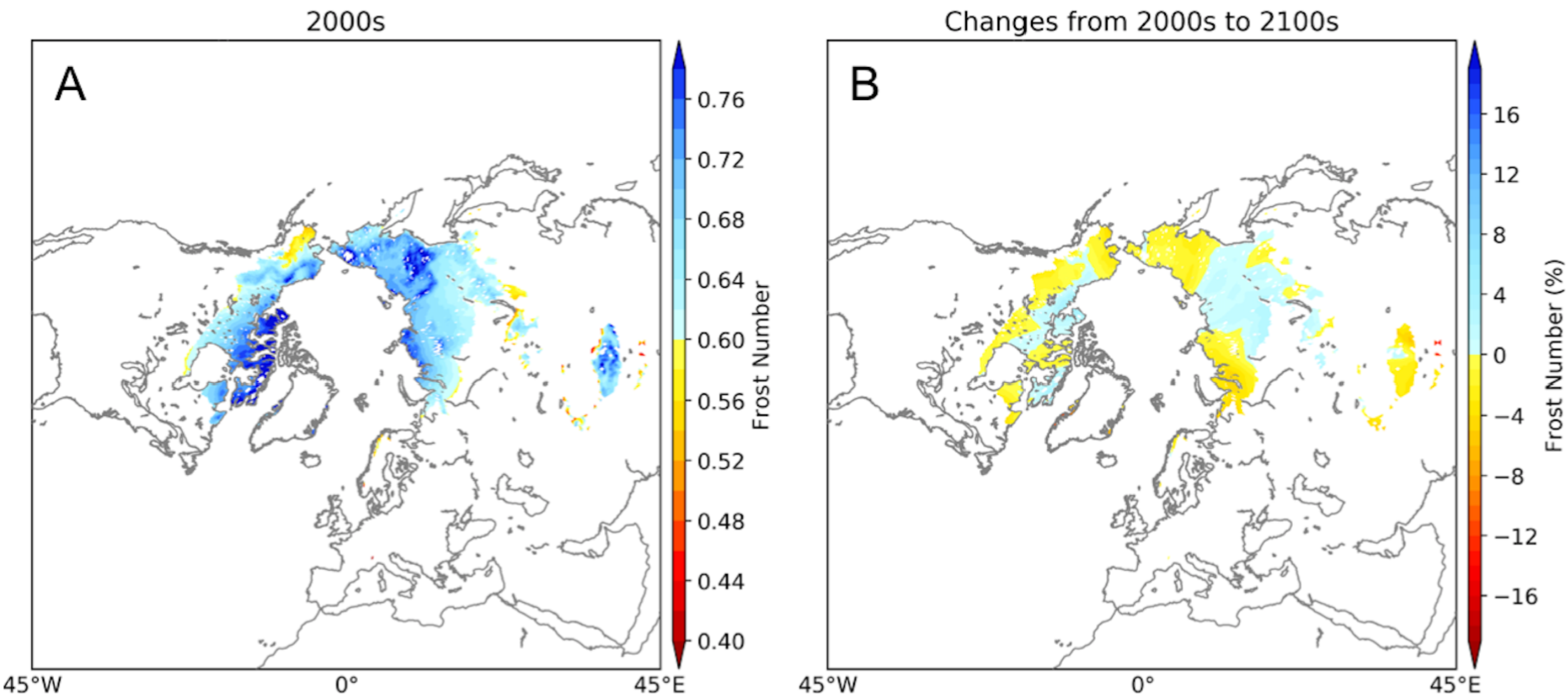


Implications for Permafrost Carbon Feedback



the loss of permafrost area is most pronounced at the southern edges of the permafrost region. In total, regions with Frost Number > 0.67, which we use here as a threshold for occurrence, declines about 6.68 million km^2 by the end of the twenty-first century.

More advanced modeling: CVPM

Continuous Volume Permafrost Model

By Gary Clow

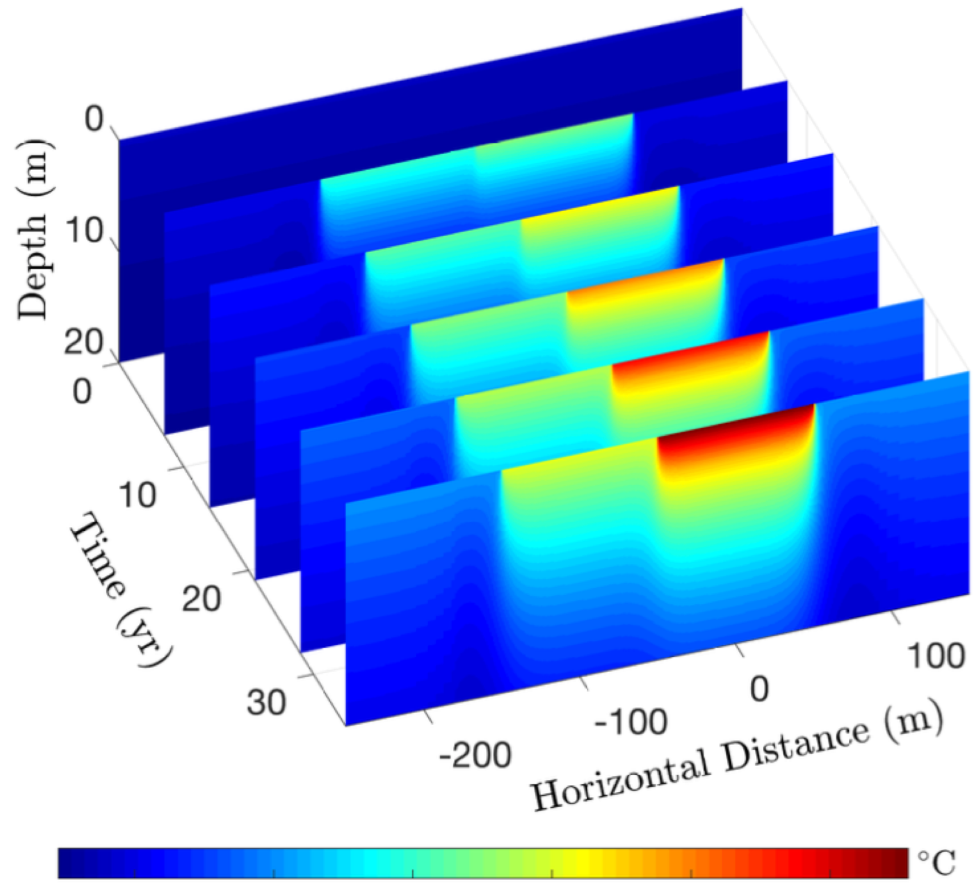


Figure 17. Simulated permafrost temperatures over a 35 yr period following the creation of a 200 m wide lake on a silty claystone unit. Depth is measured relative to the bottom of the deeper portion of the lake.

https://github.com/csdms-contrib/CVPM

More advanced modeling (2)

- Overview of GIPL developments
- Scott Stewart main CSDMS component developer, original code from Elchin Jafarov
- Discussion of development Basic Modeling Interface for GIPL

What's next: Collaborate

- https://github.com/permamodel

- You can download codes
- You can use codes and report issues
- We need to fix issues that relate to switch to Blanca

- You can become part of the team and contribute datasets or code

- Coupled model challenge for summer 2018

What’s next: cyberinfrastructure development

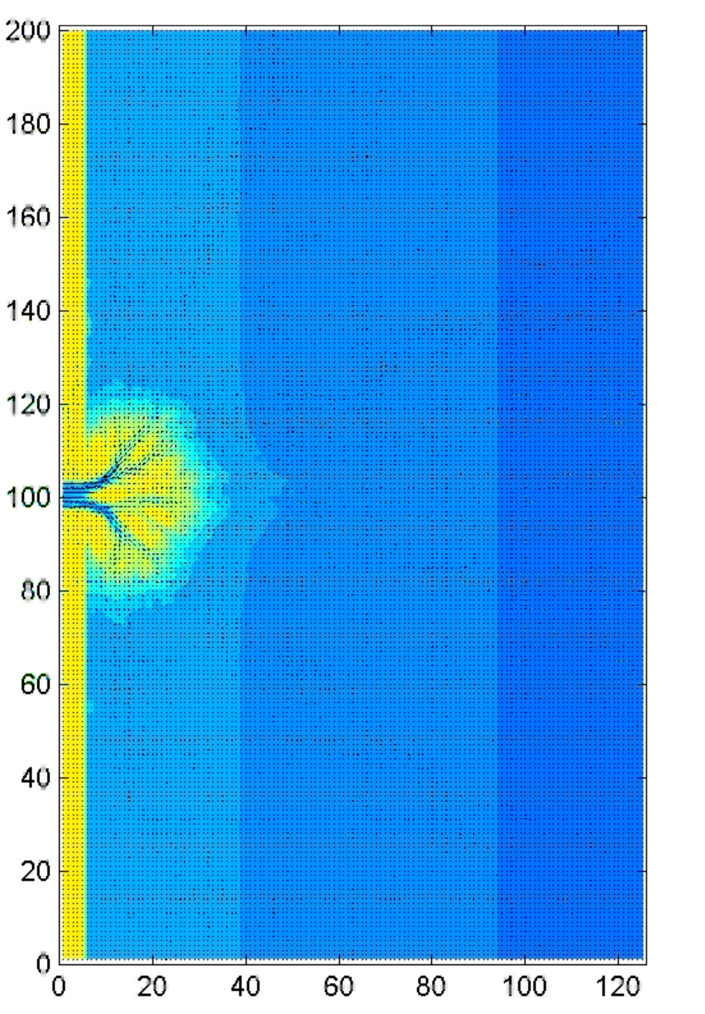
- What major questions could we tackle with this tool?

- Collaboration 1, Los Alamos HighLat project
- Permafrost Delta Modeling

- Collaboration 2, Alfred Wegener Institute, Germany
- Permafrost Evolution in Coastal Estuaries

- Discussion
- What other models can be brought in and would be useful?
- What data could be brought in and useful?

PyDeltaRCM with permafrost



Reduced Complexity Model for delta evolution, originally developed by Man Liang at Univ. of MN.

PyDelta RCM, python version of this model with Basic Model Interface by Mariela Perignon and Irina Overeem (CU)

Now linkage to permafrost dynamics: Ku model: soil water linked to drainage network, active layer depth linked to erodibility.

References

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- Sazonova, T.S., Romanovsky, V.E., 2003. A model for regional-scale estimation of temporal and spatial variability of active layer thickness and mean nnaual ground emperatures. Permafrost and periglacial processes 14, 125-139. DOI: 10.1002/ppp.449

Papers in Review

- Wang, K., Jafarov, E., Schaefer, K., Overeem, I., Romanovsky, V., Clow, G., Urban, F., Piper, M., Schwalm, C., Zhang, T., Kholodov, A., Sousanes, P., Loso, M., Swanson, D., Hill, K., (in review). A synthesis dataset of permafrost-affected soil thermal conditions for Alaska, USA, *Earth System Science Data*. *https://www.earth-syst-sci-data-discuss.net/essd-2018-54/*

- Clow, G., (in review). CVPM 1.1: a flexible heat-transfer modeling system for permafrost, *Geoscientific Model Development.*

- Overeem, I., Jafarov, E., Wang, K., Schaefer, K., Stewart, S., Clow, G., Piper, M., Elshorbany, Y., (in review). A modeling toolbox for permafrost landscapes. *EOS*.