

# Permafrost in CCSM4 and ongoing high-latitude CLM development activities



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**Andrew Slater<sup>2</sup>**  
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Boulder, CO**

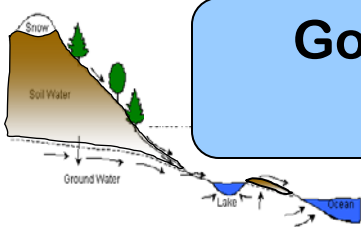
**<sup>2</sup>NSIDC, Boulder, CO**



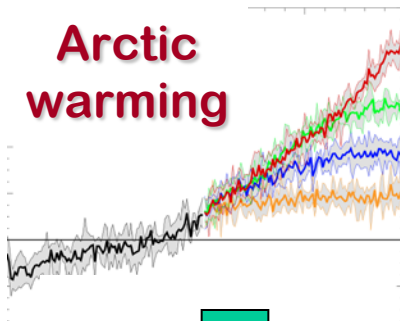
NCAR is sponsored by the National Science Foundation



# Goal: Represent Arctic terrestrial feedback processes in a global Earth System Model



Arctic warming



Carbon sequester

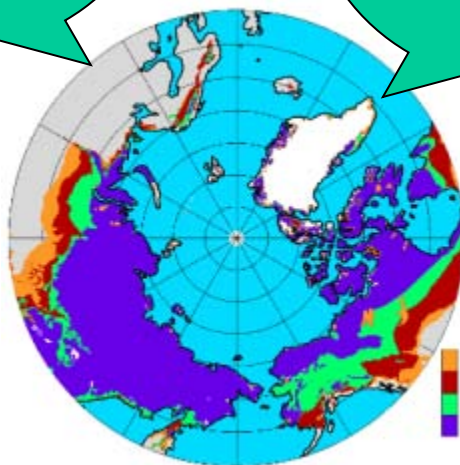
Shrub growth



Enhanced [nitrogen]

Microbial activity increases

Permafrost warms and thaws



Global warming

CH<sub>4</sub> efflux

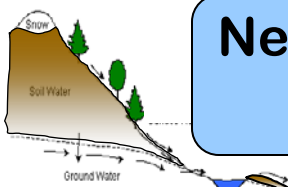
Expanded wetlands

Lakes drain, soil dries

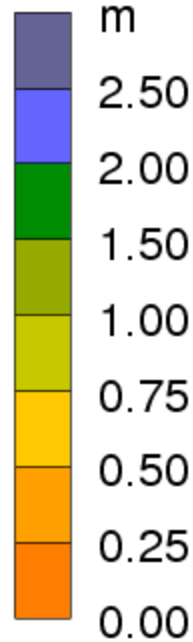
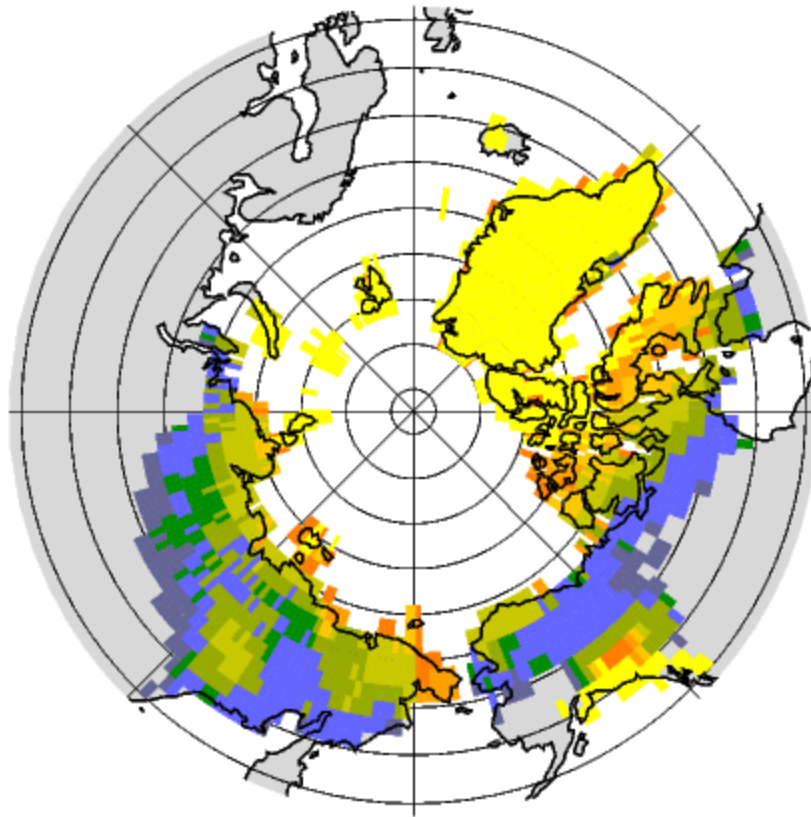
CO<sub>2</sub> efflux

Arctic runoff increases

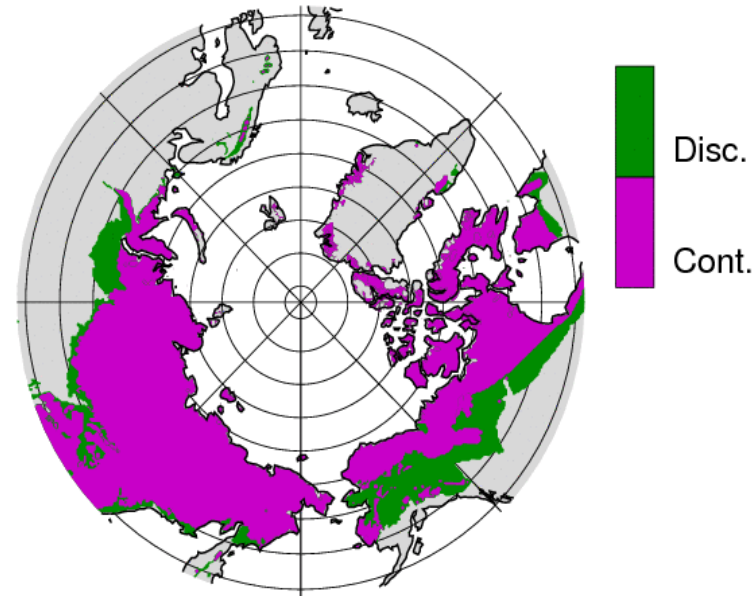
# Near-surface permafrost extent and active layer thickness (ALT) in CCSM3 (1980-99)

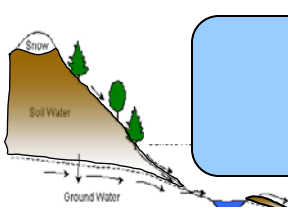


## CCSM3 (10.7)



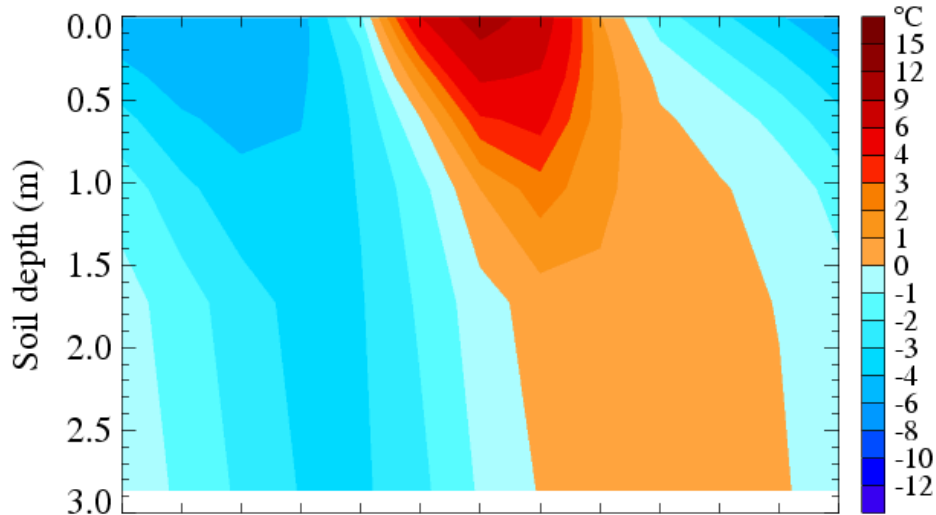
## IPA Observed Extent Estimate (11.1-14.9 million km<sup>2</sup>)



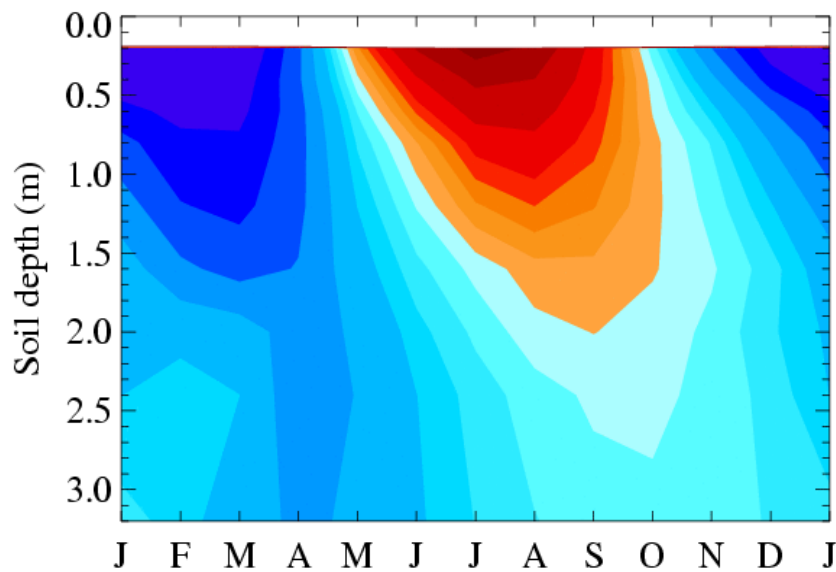


# Soil temperature (Siberia) and ALT in CCSM3 compared to observations

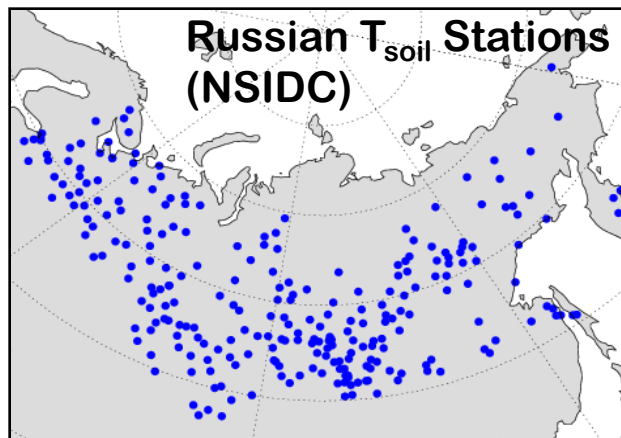
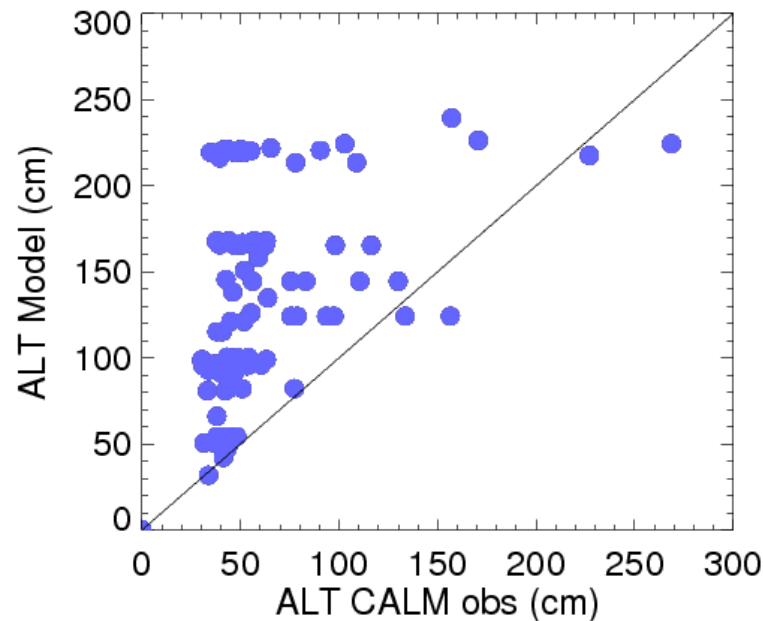
CCSM3

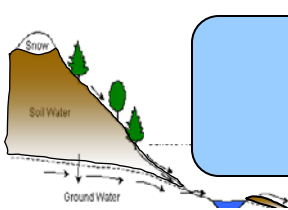


Observations



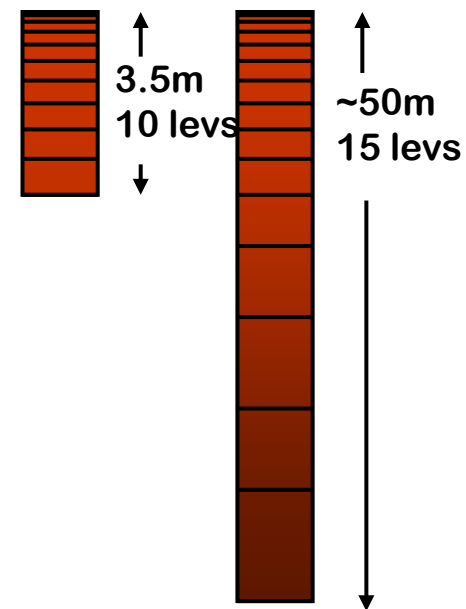
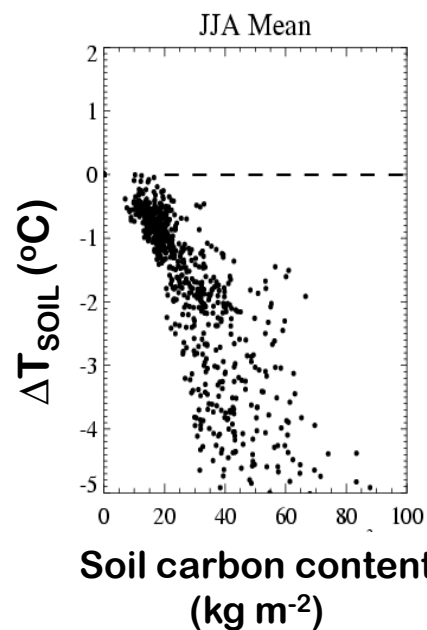
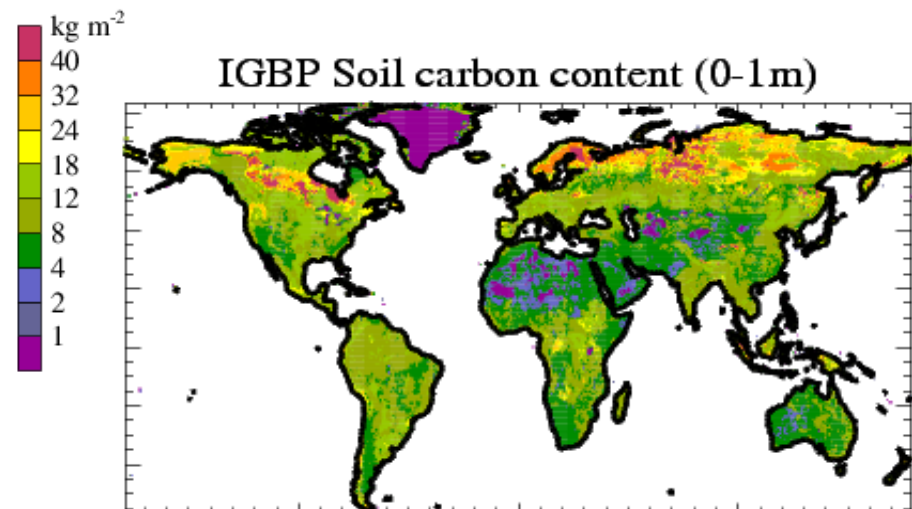
CCSM3



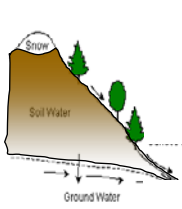


# Improvements in the Community Land Model (CLM3 → CLM4)

- **Explicit treatment of thermal and hydraulic properties of soil organic matter** (Nicolsky et al. 2007, Lawrence and Slater, 2008)
- **Extended ground column from 3.5 to ~50m depth** (Alexeev et al. 2007, Lawrence et al., 2008)
- **Many other changes to snow model and soil hydrology model**

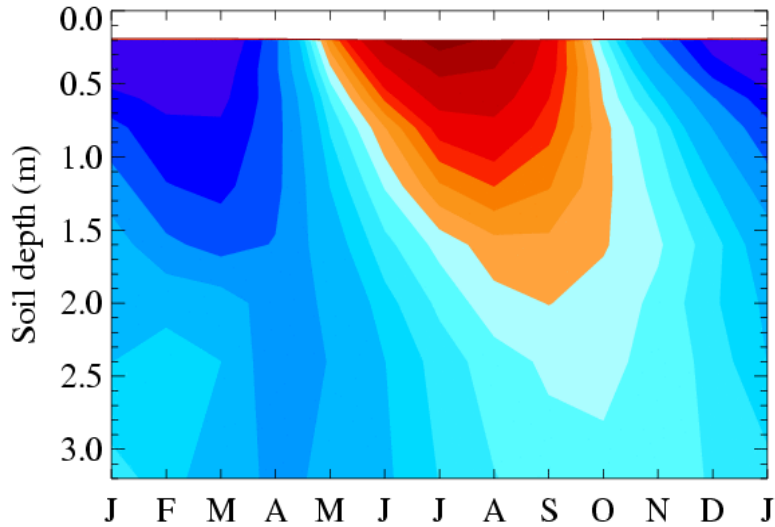




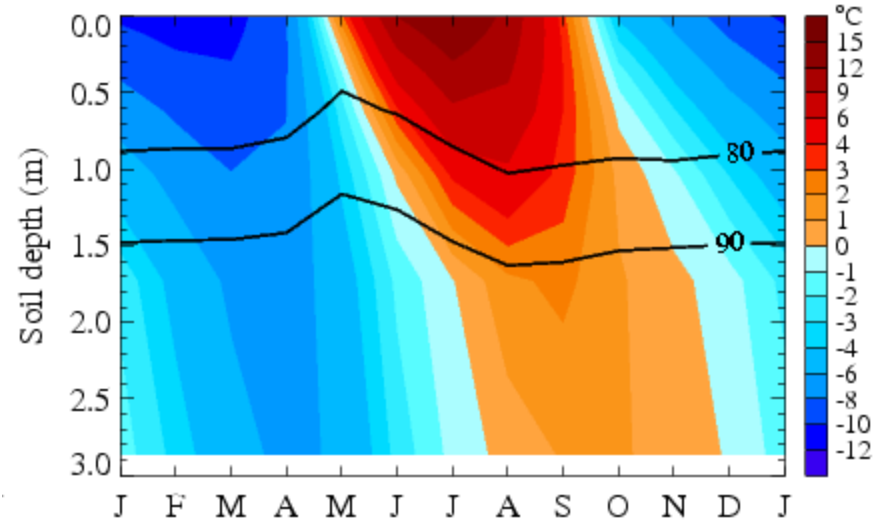


# Soil temperature: Annual cycle-depth

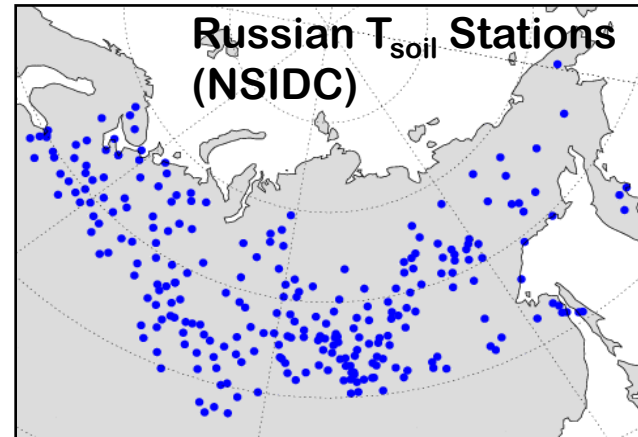
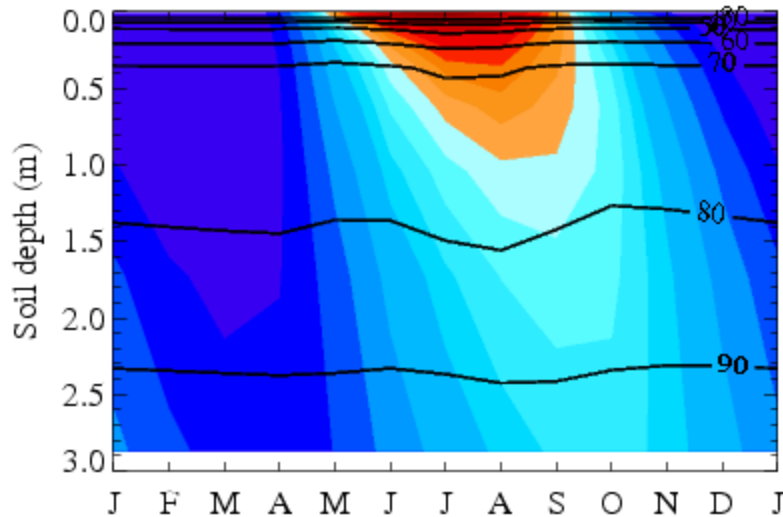
Observations

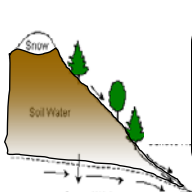


CLM3.5



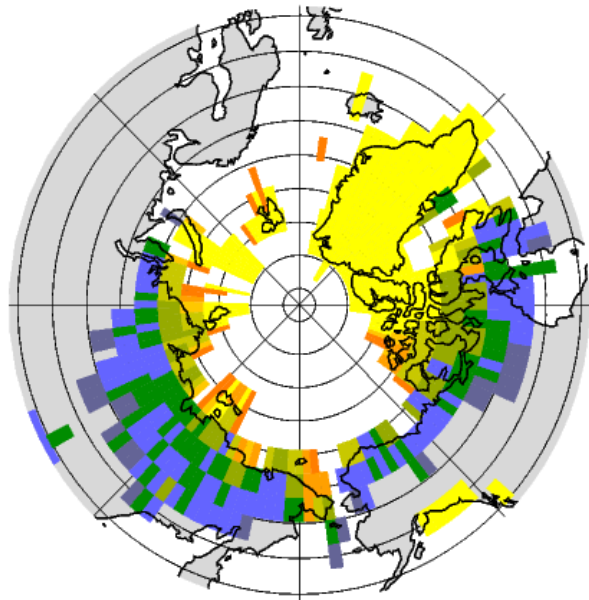
CLM4SP



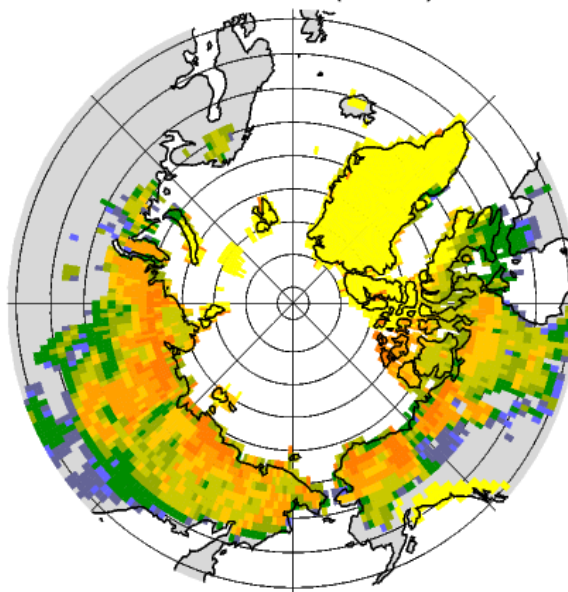


# Near-surface permafrost extent and ALT in offline CLM (1980-99)

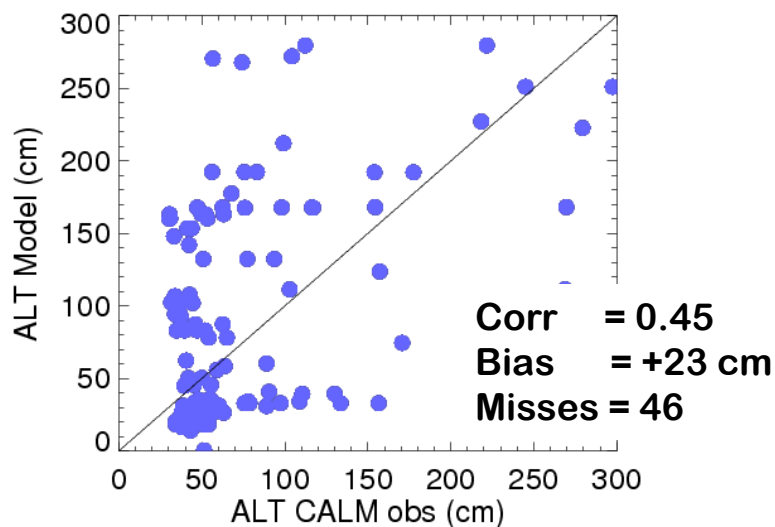
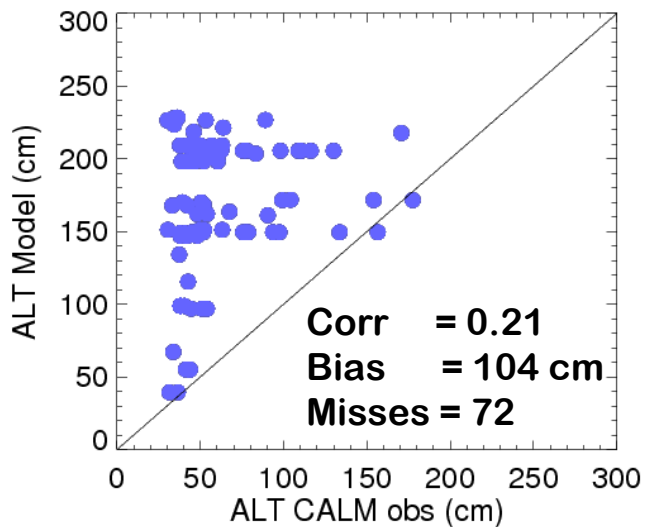
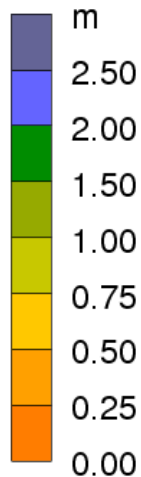
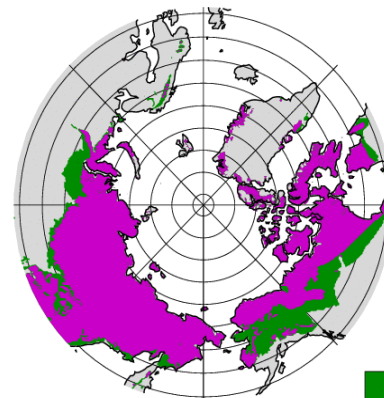
CLM3 (10.4)



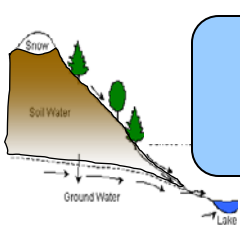
CLM4SP (14.4)



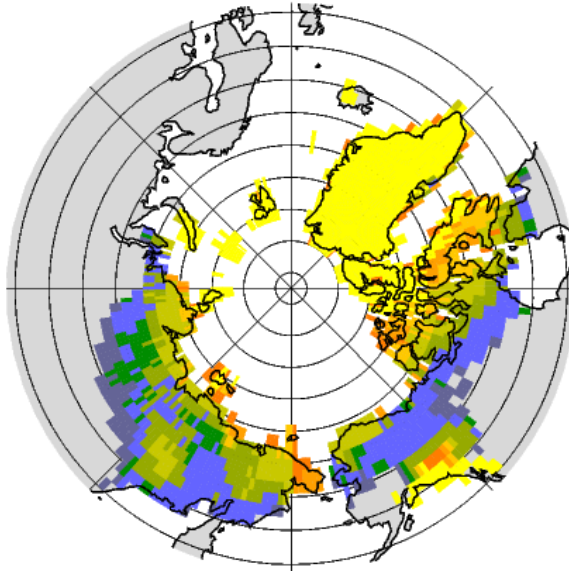
IPA (11.1-14.9)



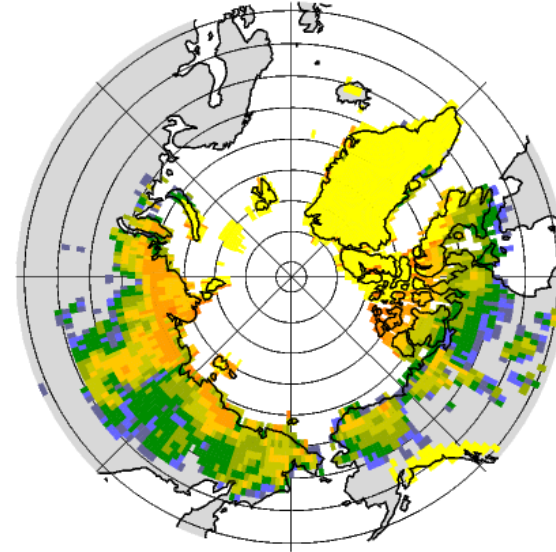
# Near-surface permafrost extent and ALT in CCSM (1980-99)



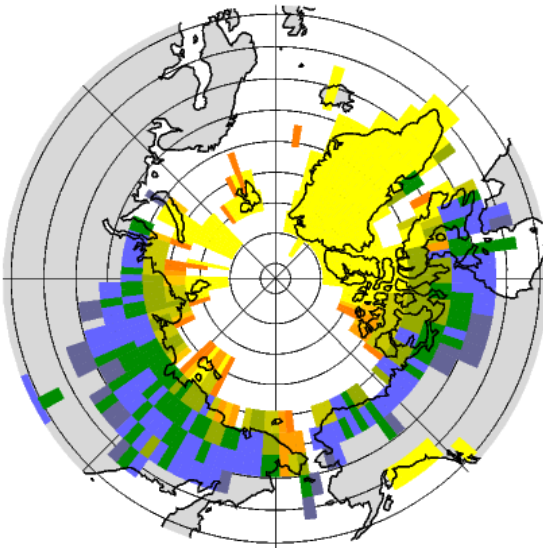
CCSM3 (10.7)



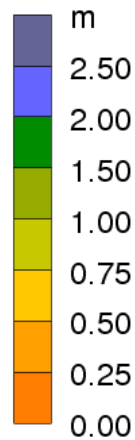
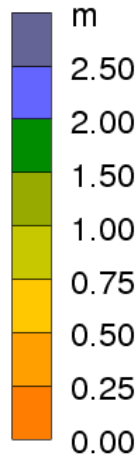
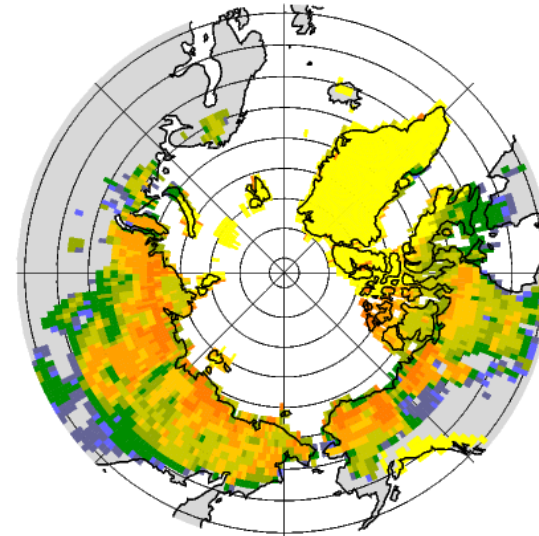
CCSM4 (11.4)



CLM3 (10.4)

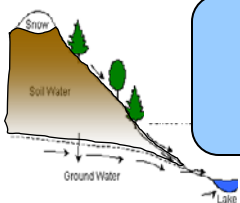


CLM4SP (14.4)

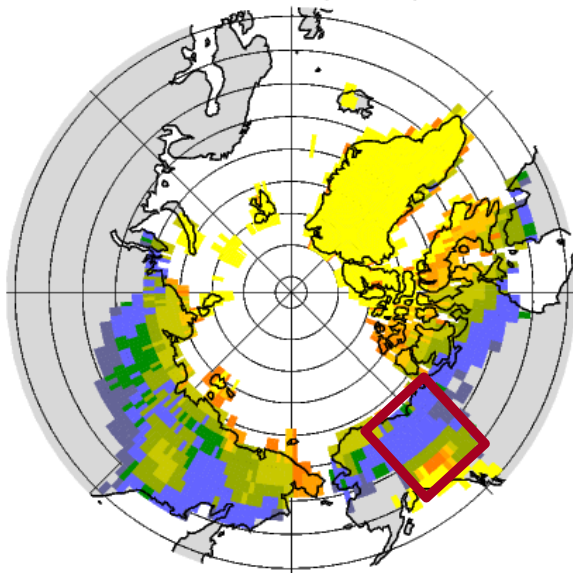




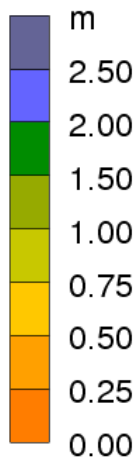
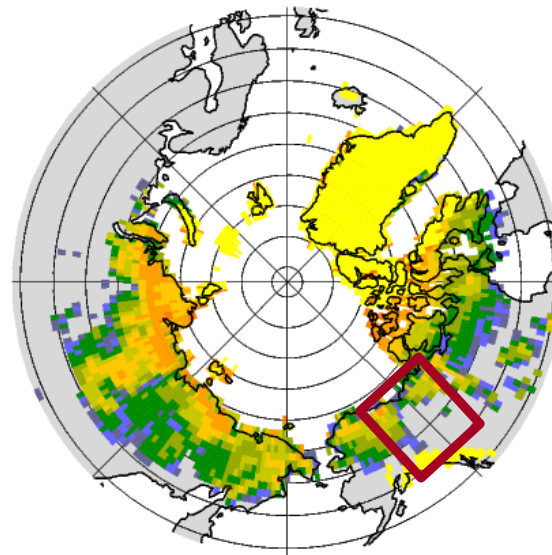
# Impact of biases in the simulated CCSM climate



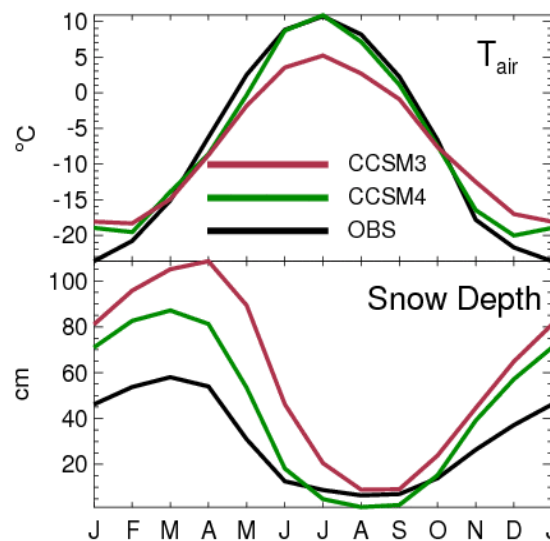
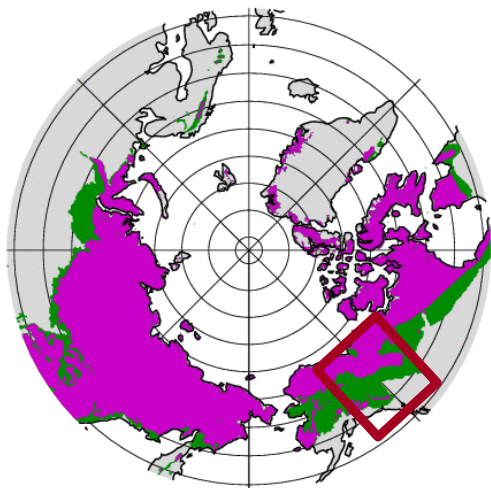
CCSM3 (10.7)



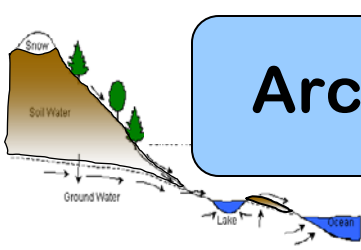
CCSM4 (11.4)



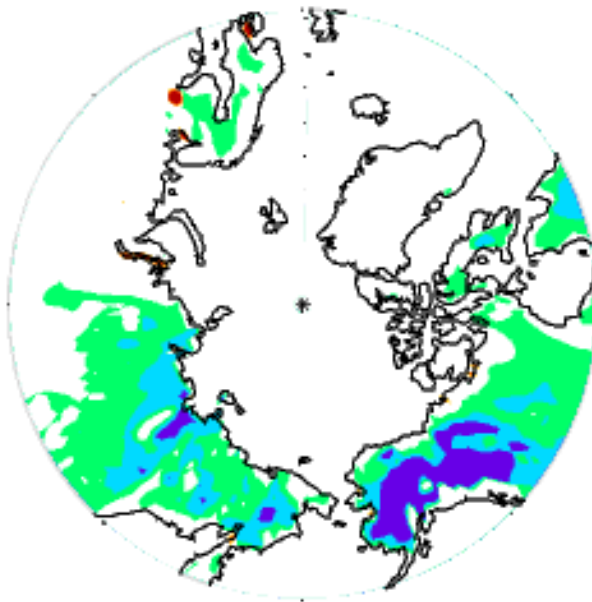
IPA Observed Extent



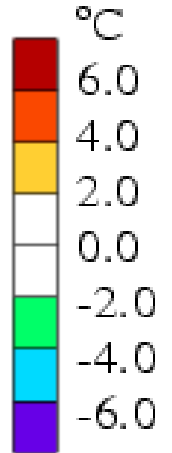
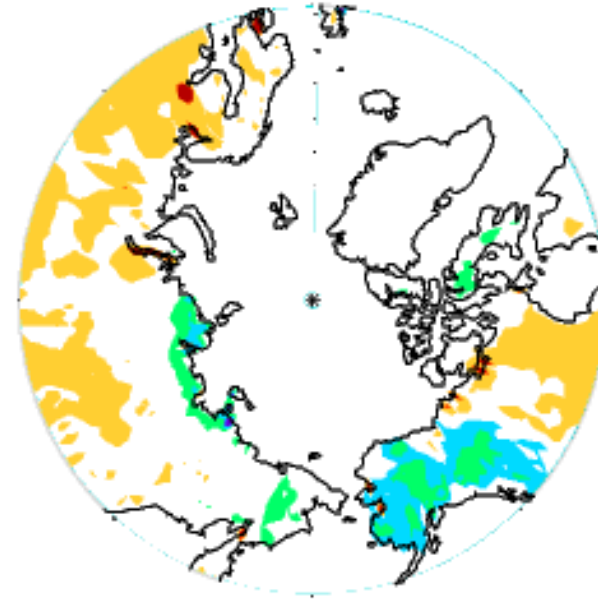
# Arctic land surface air temperature biases in CCSM



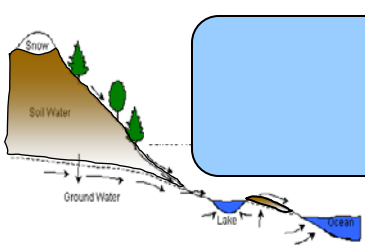
**CCSM3**  
Bias JJA =  $-3.0^{\circ}\text{C}$   
RMSE =  $3.1^{\circ}\text{C}$



**CCSM4**  
Bias JJA =  $+0.7^{\circ}\text{C}$   
RMSE =  $2.2^{\circ}\text{C}$

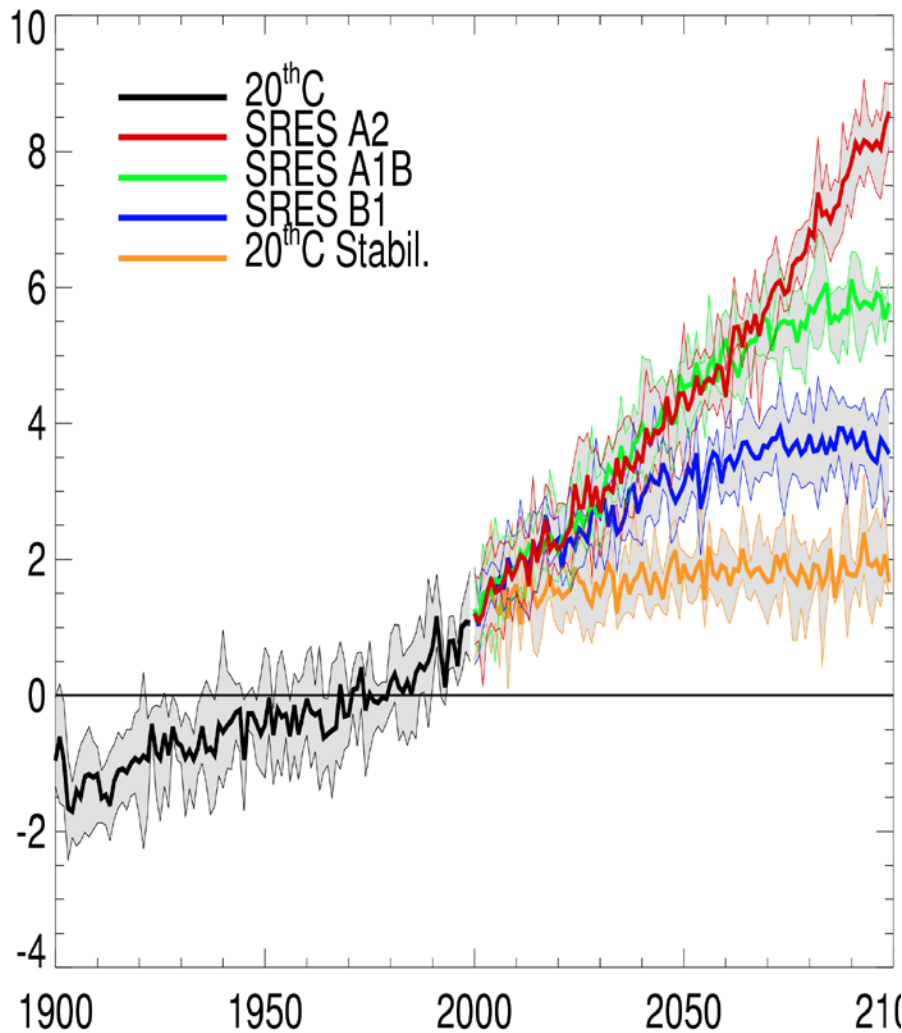


**Snowfall remains high and snowpacks too deep in many high-latitude regions in CCSM4**

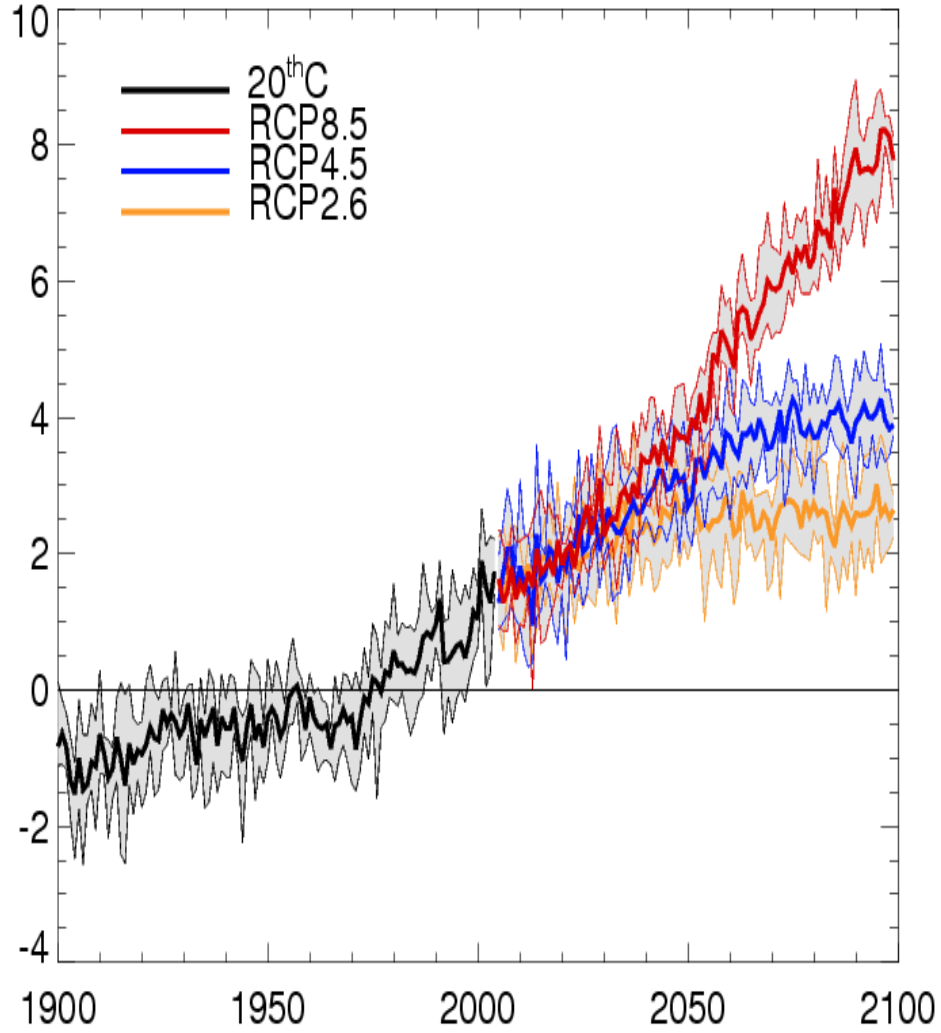


# Surface air temperature change (CCSM): Arctic land area

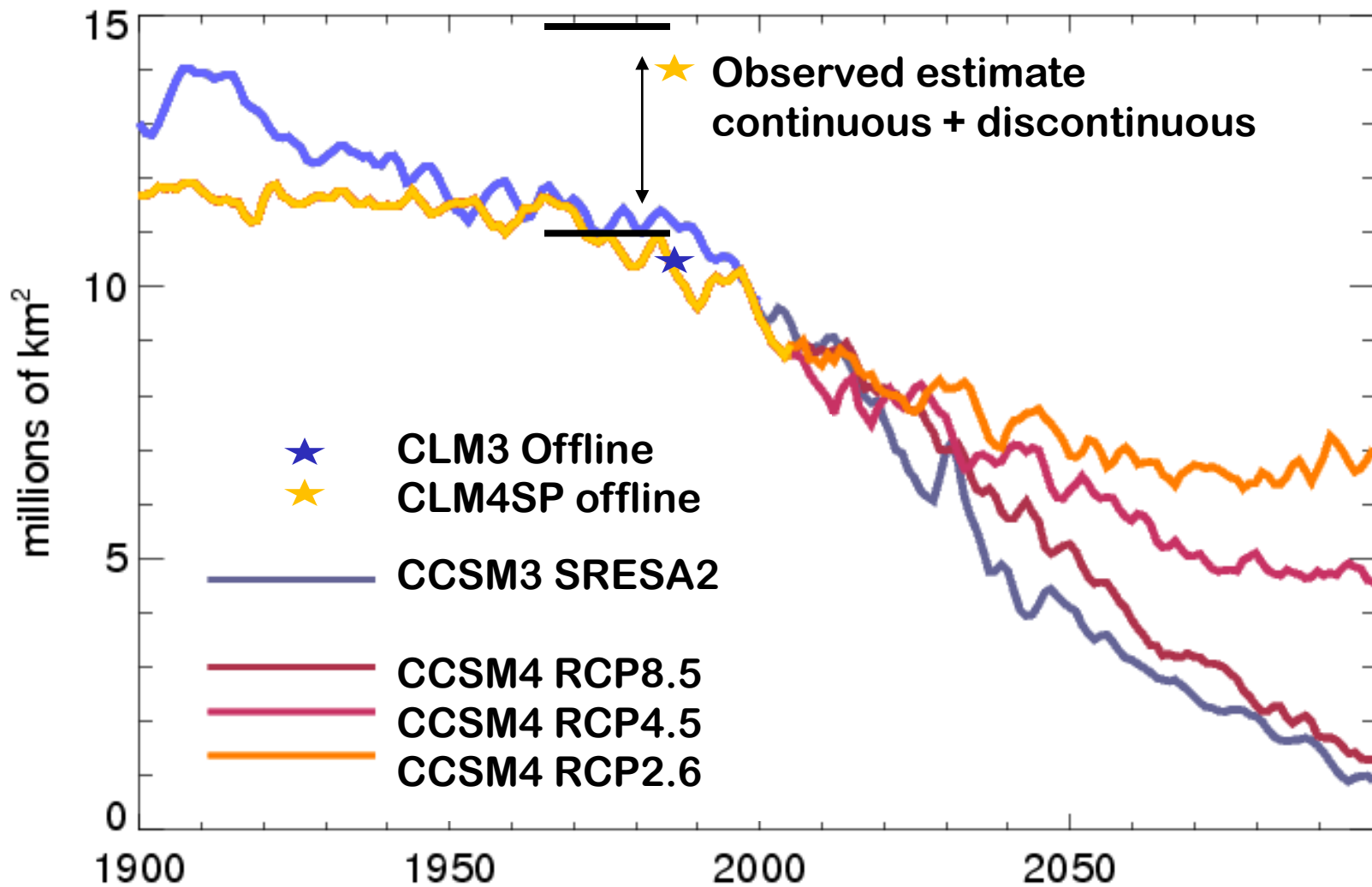
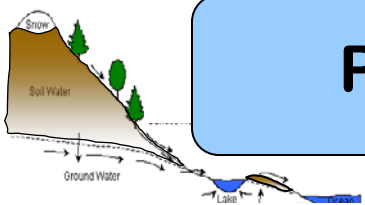
## CCSM3



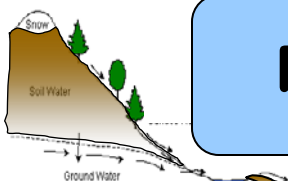
## CCSM4



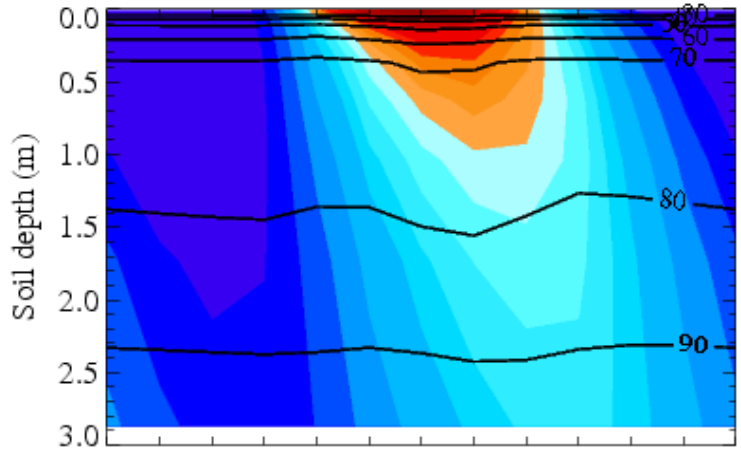
# Projections of near-surface permafrost extent



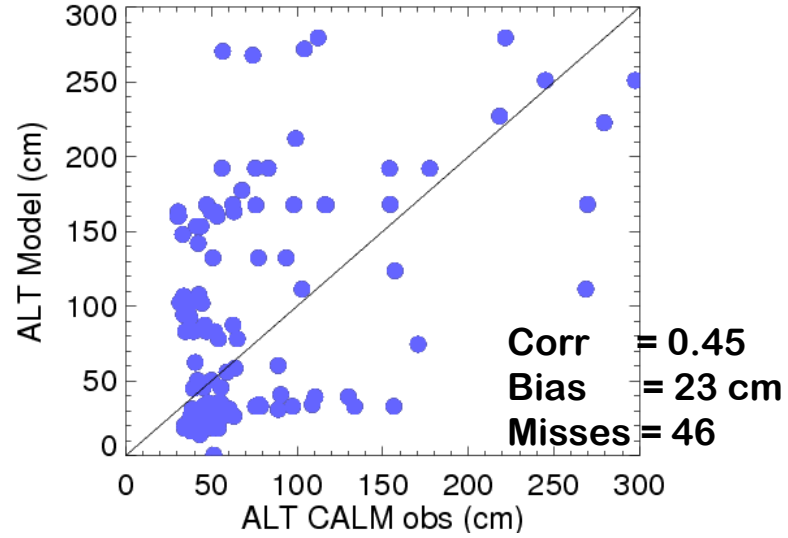
# Problems with permafrost/active layer hydrology?



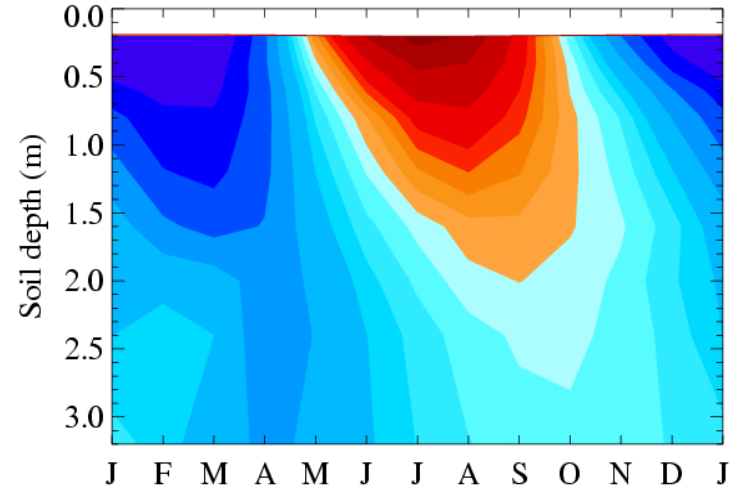
CLM4SP



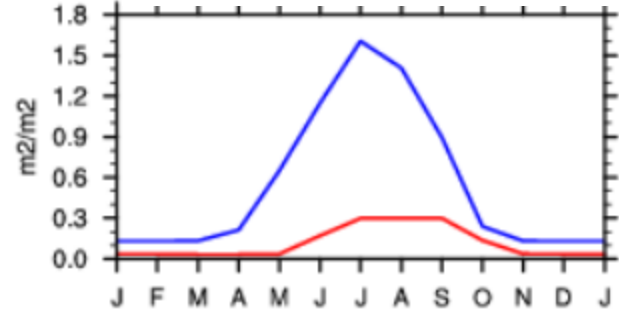
CLM4SP



Observations

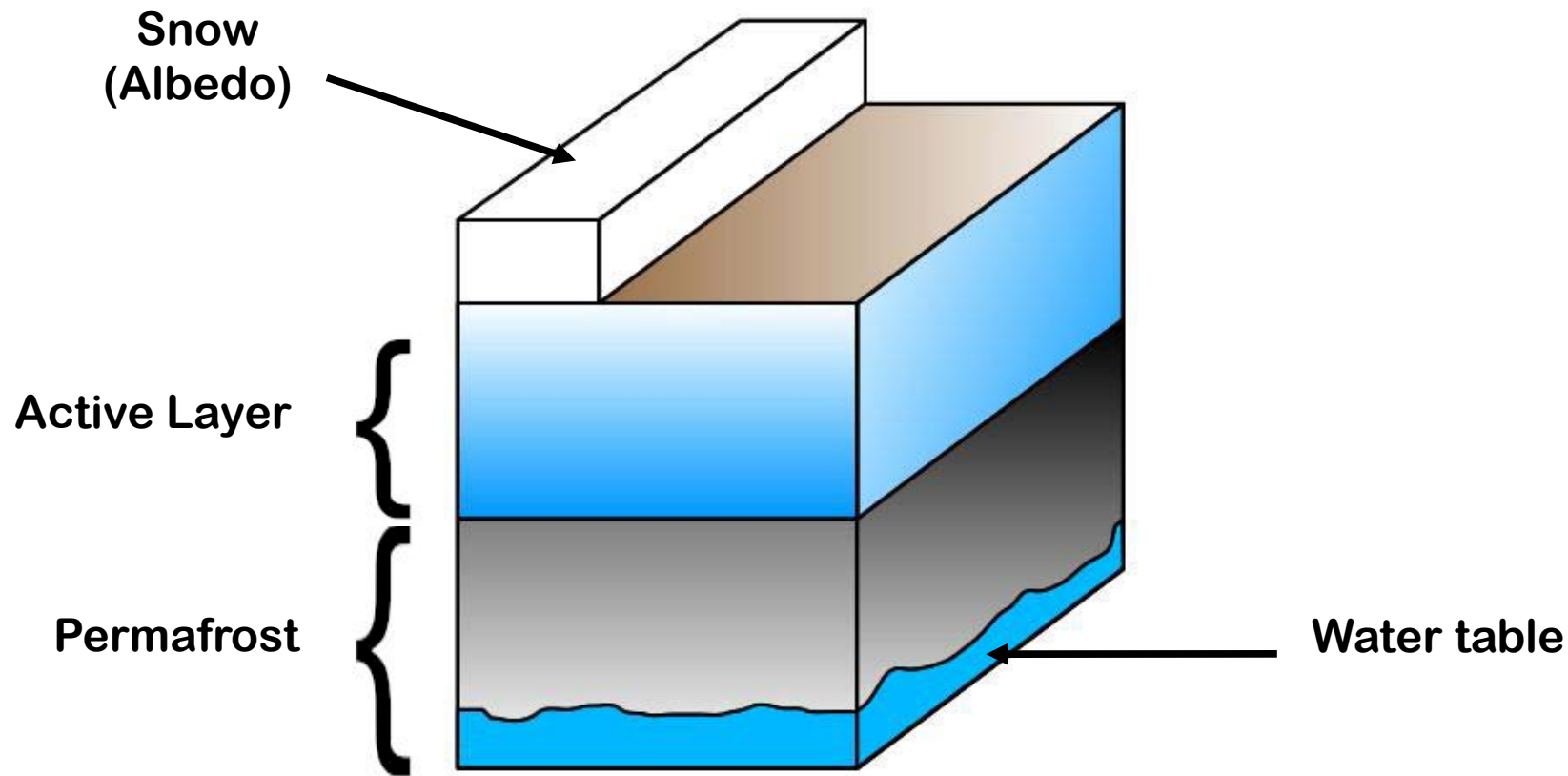
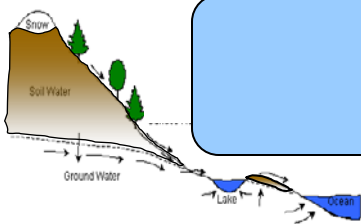


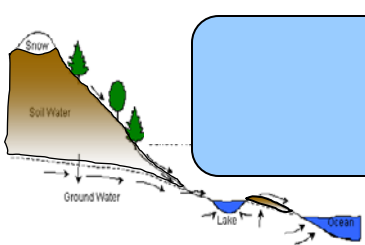
LAI: Alaskan Arctic





# CLM4 Cold Region Hydrology Schematic



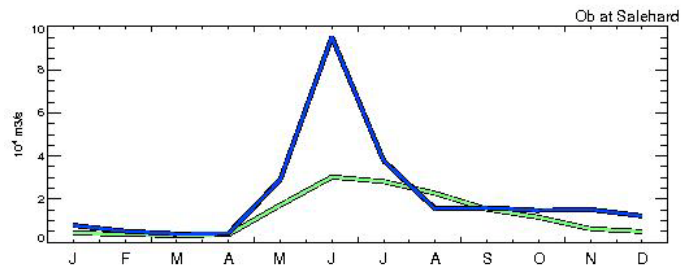
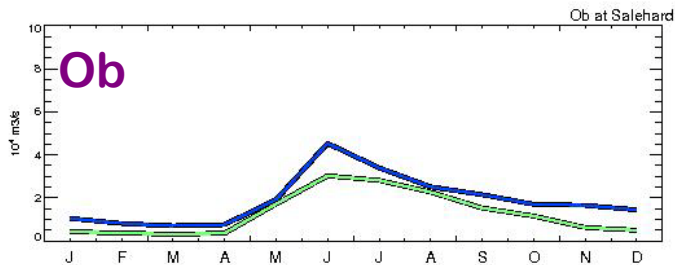


# River Discharge in Modified CLM4

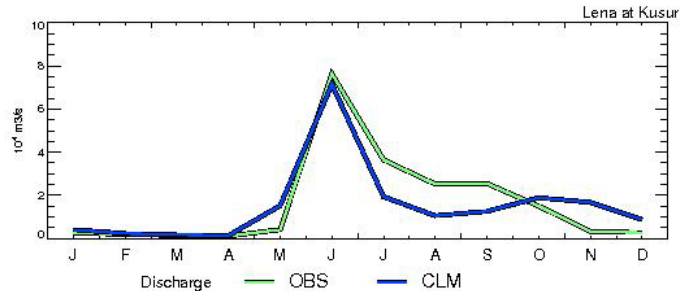
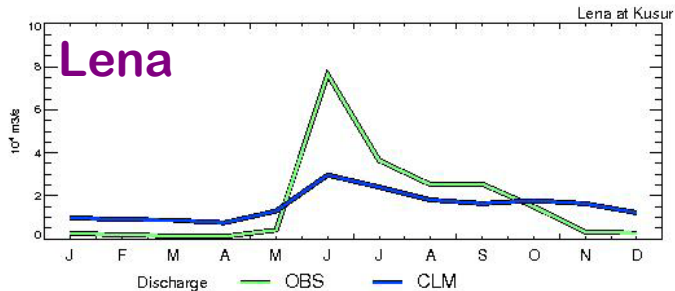
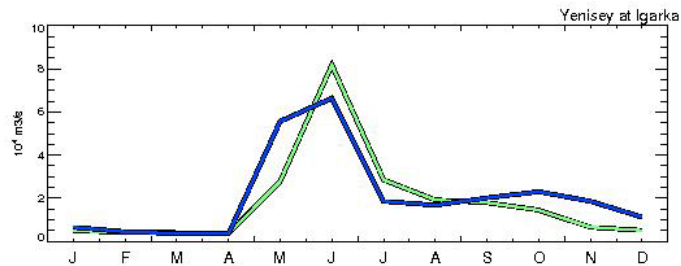
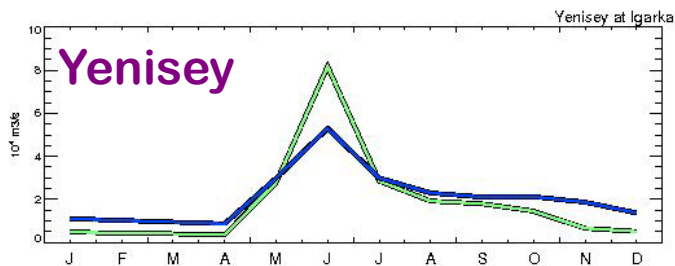
Results are mixed: better hydrographs for permafrost basins, but degraded simulation in non-permafrost basin

## Control

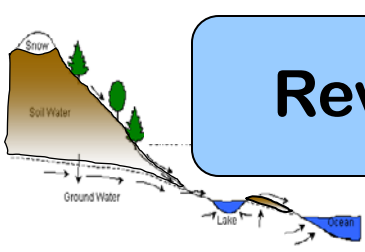
## Ice Impedance



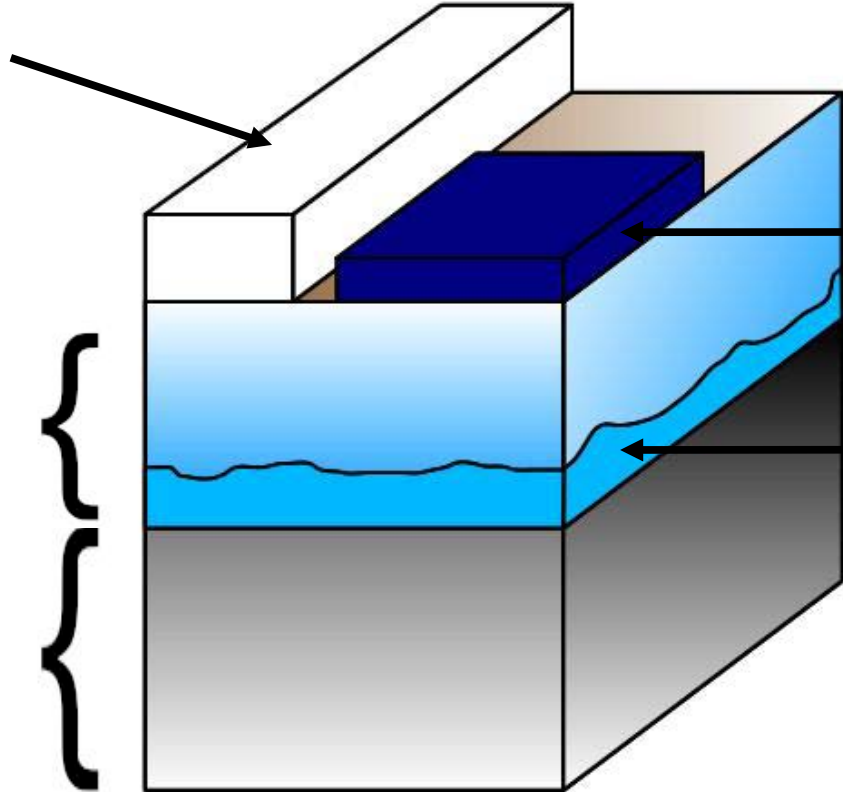
— OBS  
— CLM



# Revised CLM4 Cold Region Hydrology Schematic



Snow

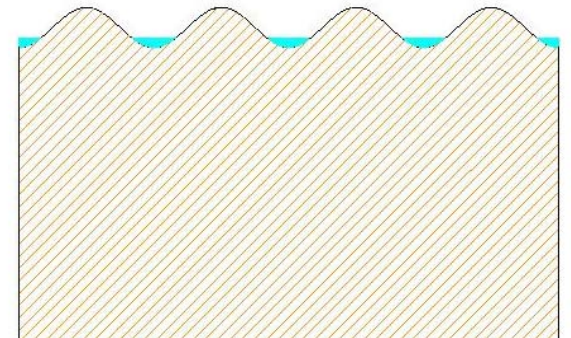


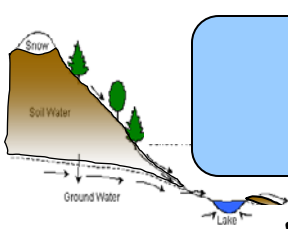
Surface water

Active Layer

Supra-permafrost  
Perched water table

Permafrost

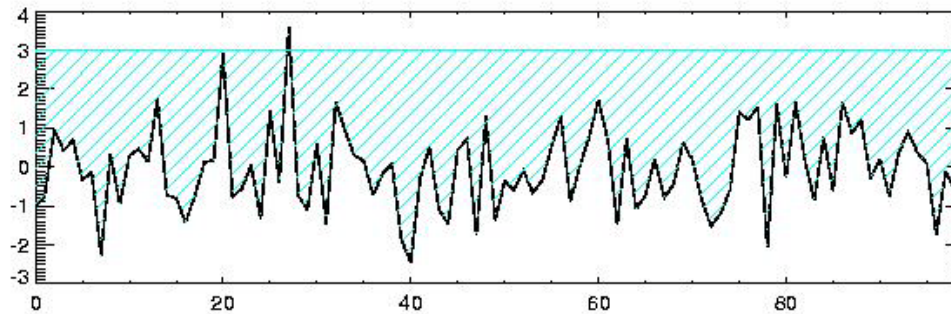




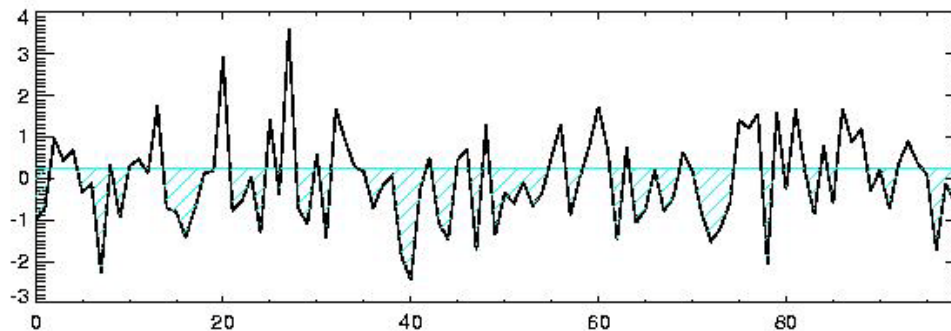
# Connectivity

- When storage is large compared to microtopography, “wet” areas are well connected, and surface runoff is high.
- When storage is small compared to microtopography, “wet” areas are generally not connected, and surface runoff is low.

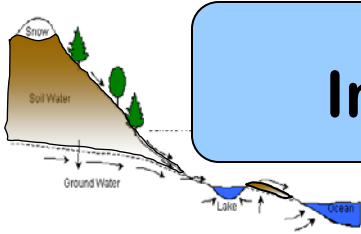
Well Connected



Poorly Connected

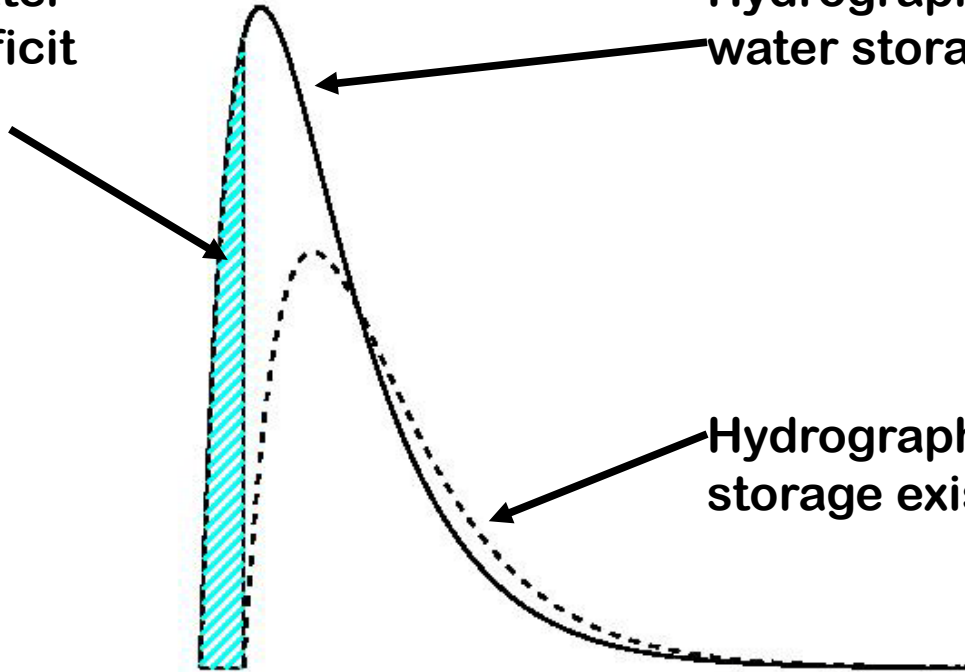


# Impact of Runoff Thresholds on Hydrograph



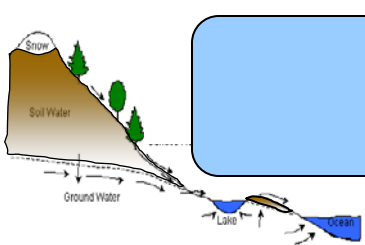
Surface water storage deficit

Hydrograph in absence of surface water storage



Hydrograph when surface water storage exists

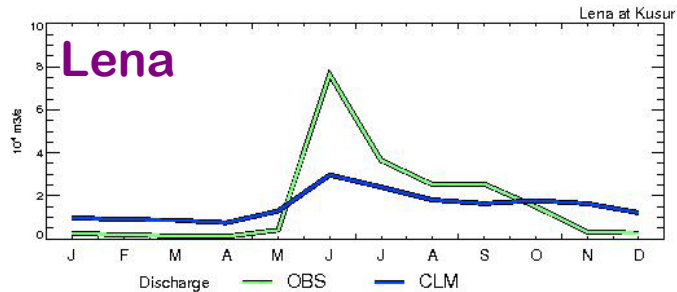
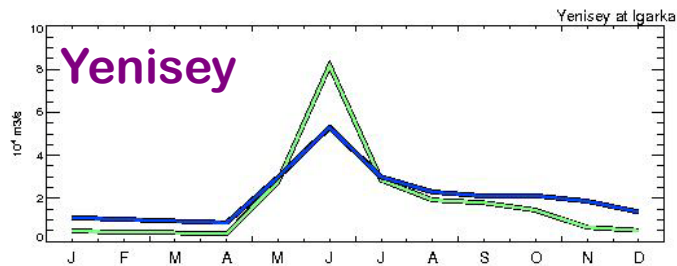
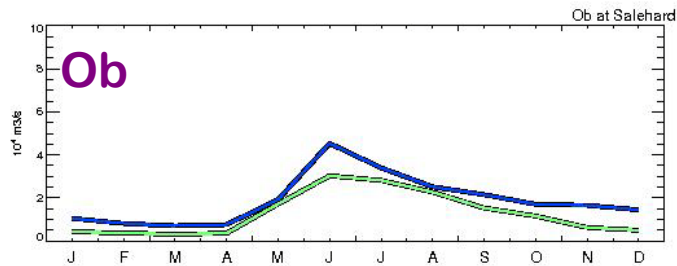




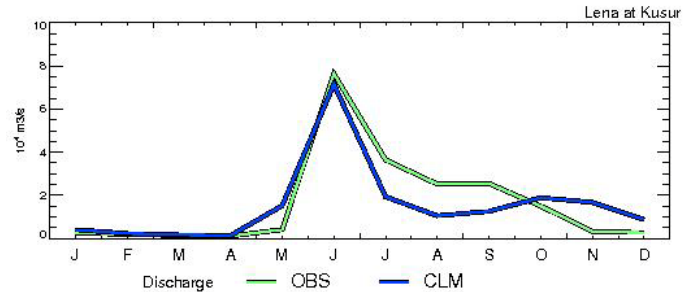
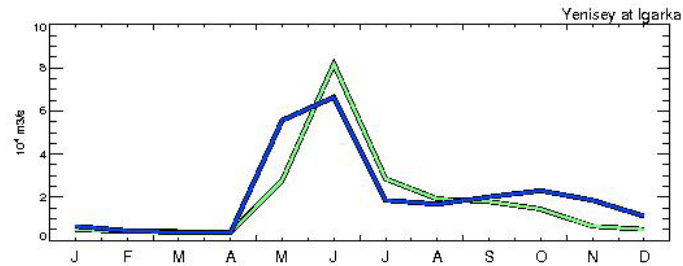
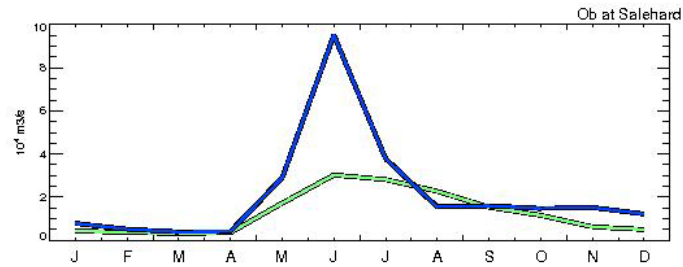
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Results are mixed: better hydrographs for permafrost basins, but degraded simulation in non-permafrost basin

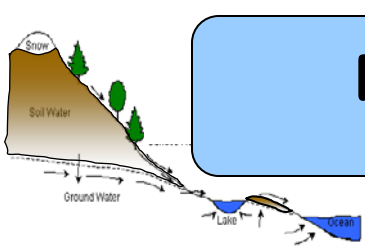
## Control



## Ice Impedance



— OBS  
— CLM

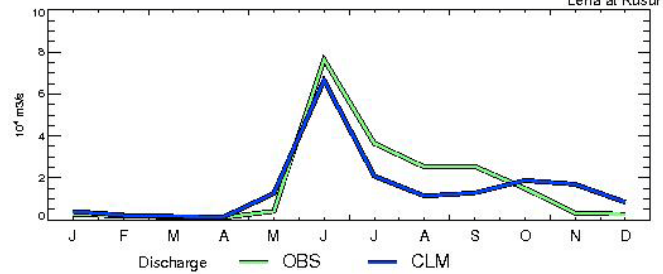
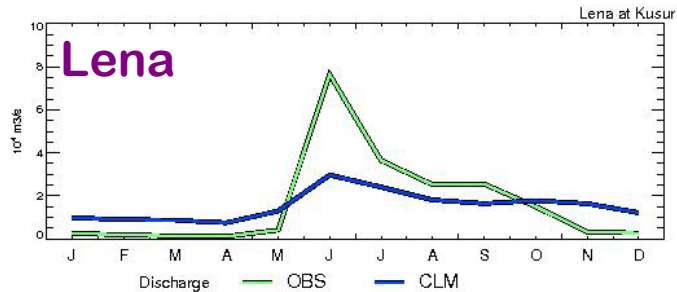
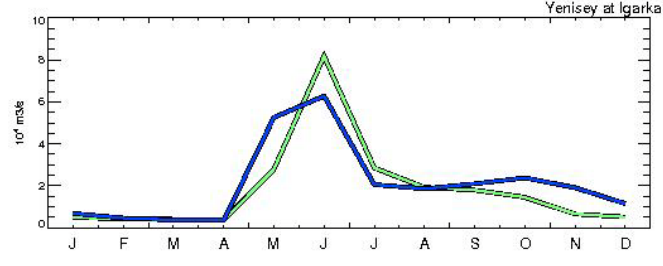
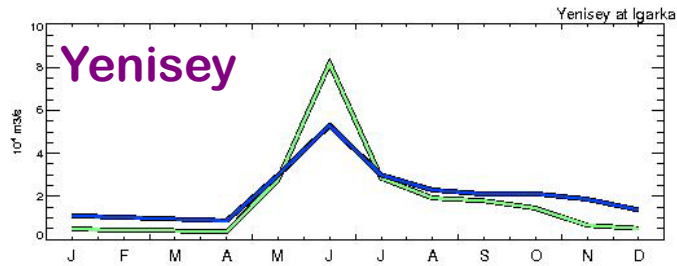
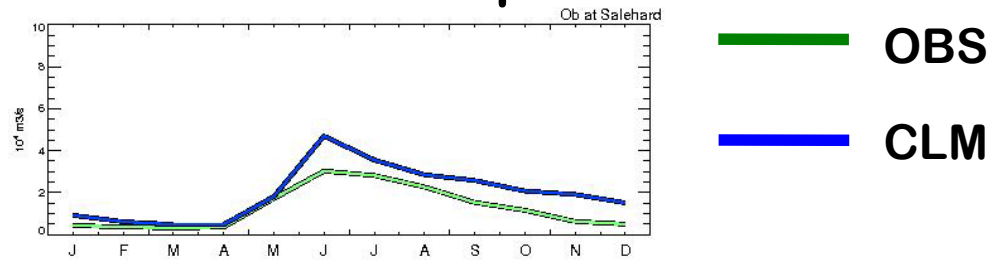
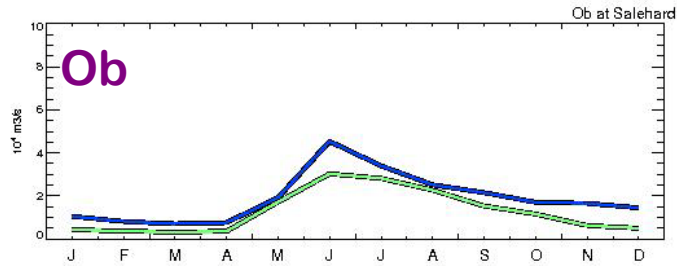


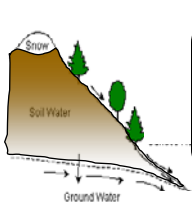
# River Discharge (Impedance + Surface Water)

Results: better hydrographs for both permafrost basins and non-permafrost basins

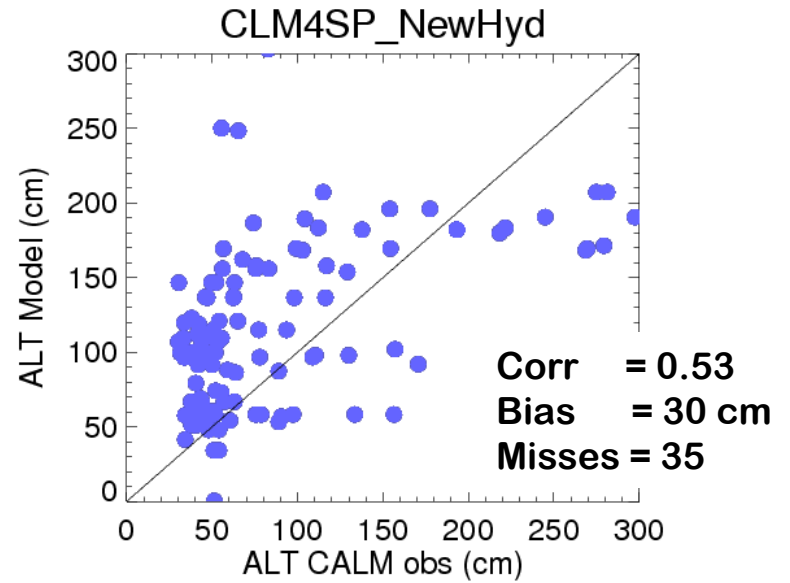
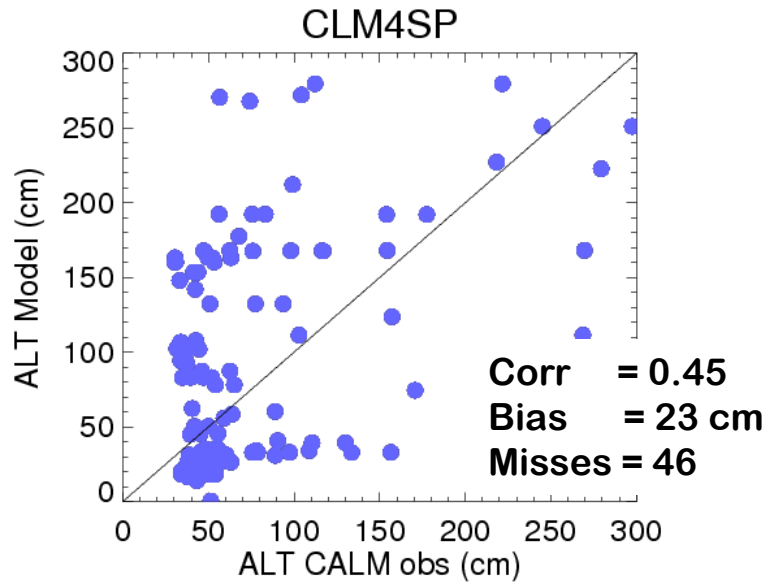
## Control

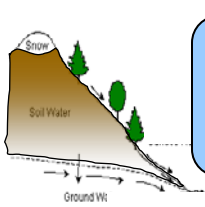
## Surface Water + Impedance





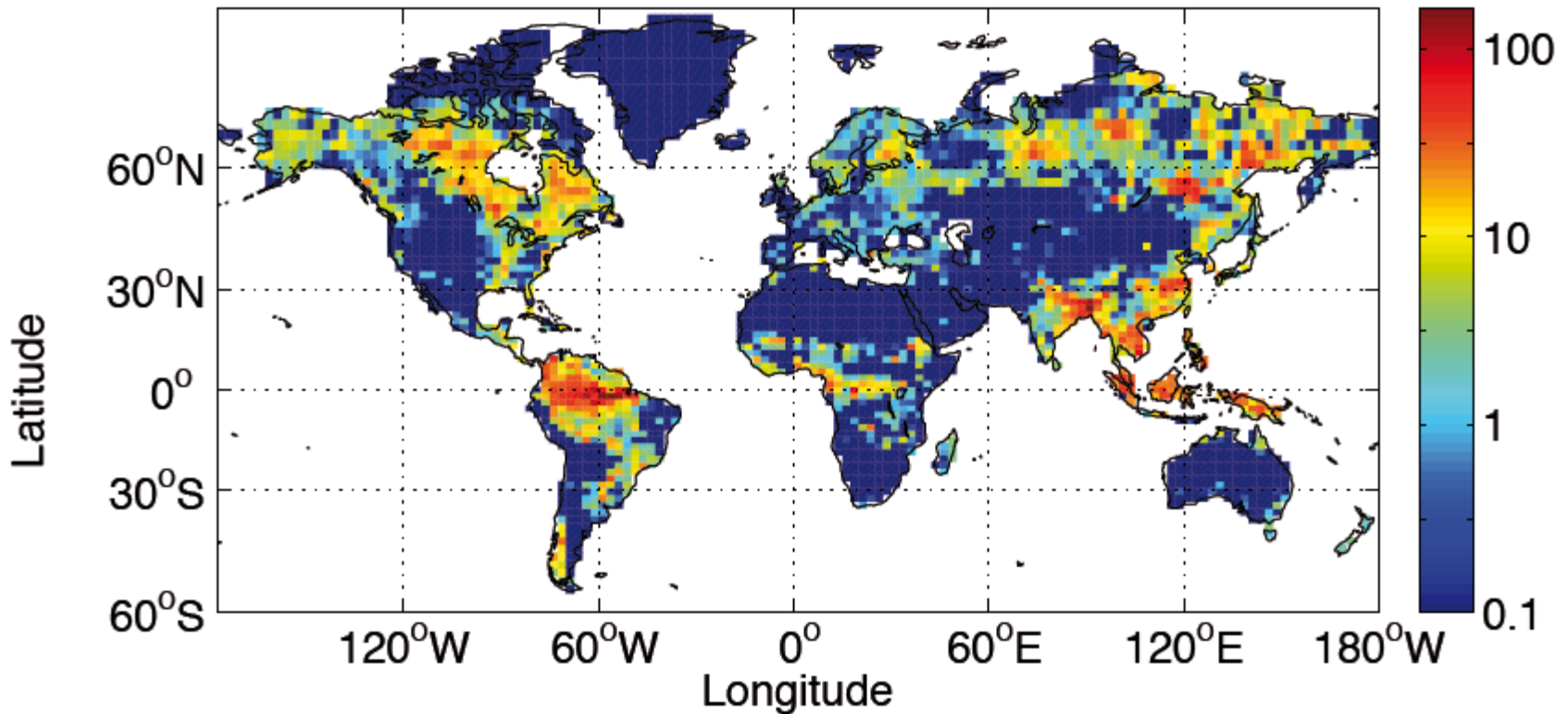
# Impact of new hydrology on ALT





# Wetland methane emissions

Net CH<sub>4</sub> Emissions (mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>)



Riley et al. (2011, submitted to JGR-Biogeosciences)

# Summary

- **Soil temperature and permafrost simulation improved in CLM4 and CCSM4; more realistic permafrost distribution and ALTs**
- **Climate biases, especially snow, degrade permafrost simulation in CCSM4**
- **Substantial 21<sup>st</sup> century near-surface permafrost degradation simulated in CCSM4; significant emissions scenario dependence**
- **Ongoing model development:**
  - **Permafrost hydrology**
  - **Prognostic wetland distribution**
  - **Permafrost carbon, CO<sub>2</sub>/ CH<sub>4</sub> emissions**



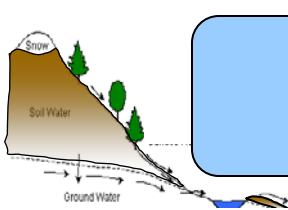


# CESM Tutorial: August 1-5, 2011

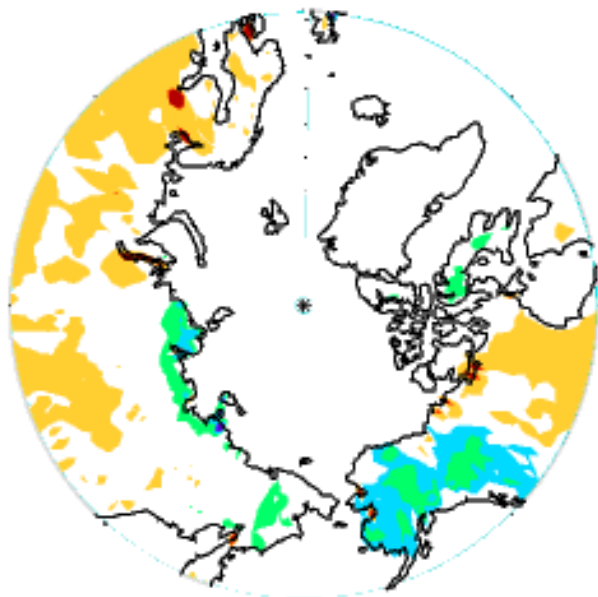
## NCAR, Boulder, CO

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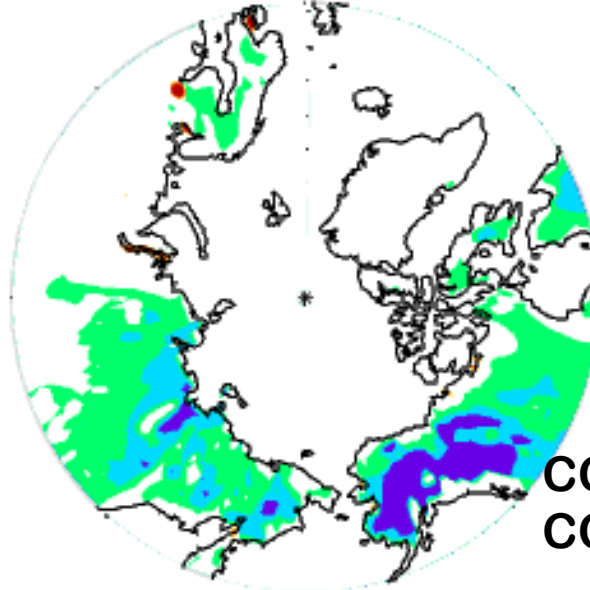
- Lectures on simulating the climate system
- Practical sessions on running CESM, modifying components, and analyzing data
- Targeted at graduate student level
  - Max 80 students with financial support for up to 40 students
  - Acceptance criteria:
    - Preference given to early career graduate students, though we will aim for a mix of graduate students, postdocs, and early career research scientists and faculty
    - Project descriptions and their fit with broader CESM goals and activities
    - Balance attendees across institutions
- How to Apply:
  - Application website online at [www.cesm.ucar.edu](http://www.cesm.ucar.edu) in early January, 2011
  - Application deadline: **March 25, 2011**
  - Accepted students informed by late April
  - Questions should be directed to Dave Lawrence ([dlawren@ucar.edu](mailto:dlawren@ucar.edu))



CCSM4: JJA 0.73°C

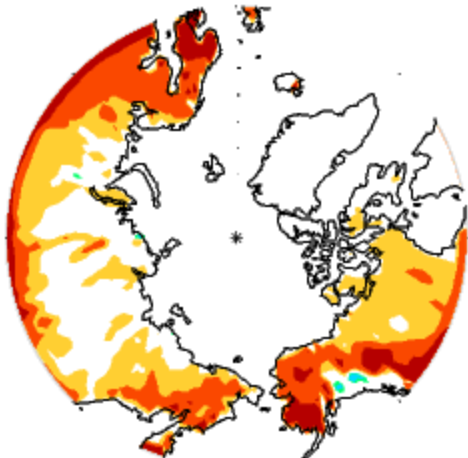


CCSM3: JJA -3.00°C

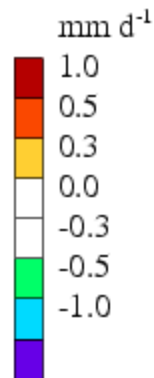
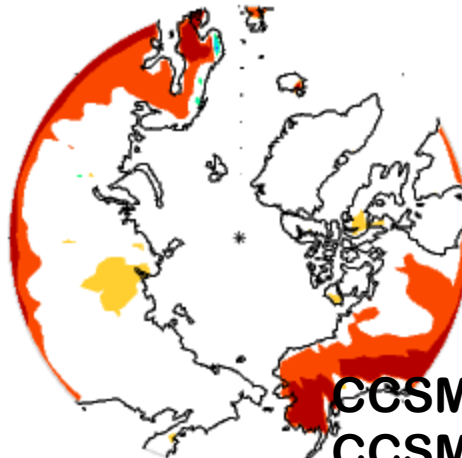


**CCSM4 RMSE = 2.2**  
**CCSM3 RMSE = 3.1**

CCSM4: DJF 0.47mm d<sup>-1</sup>

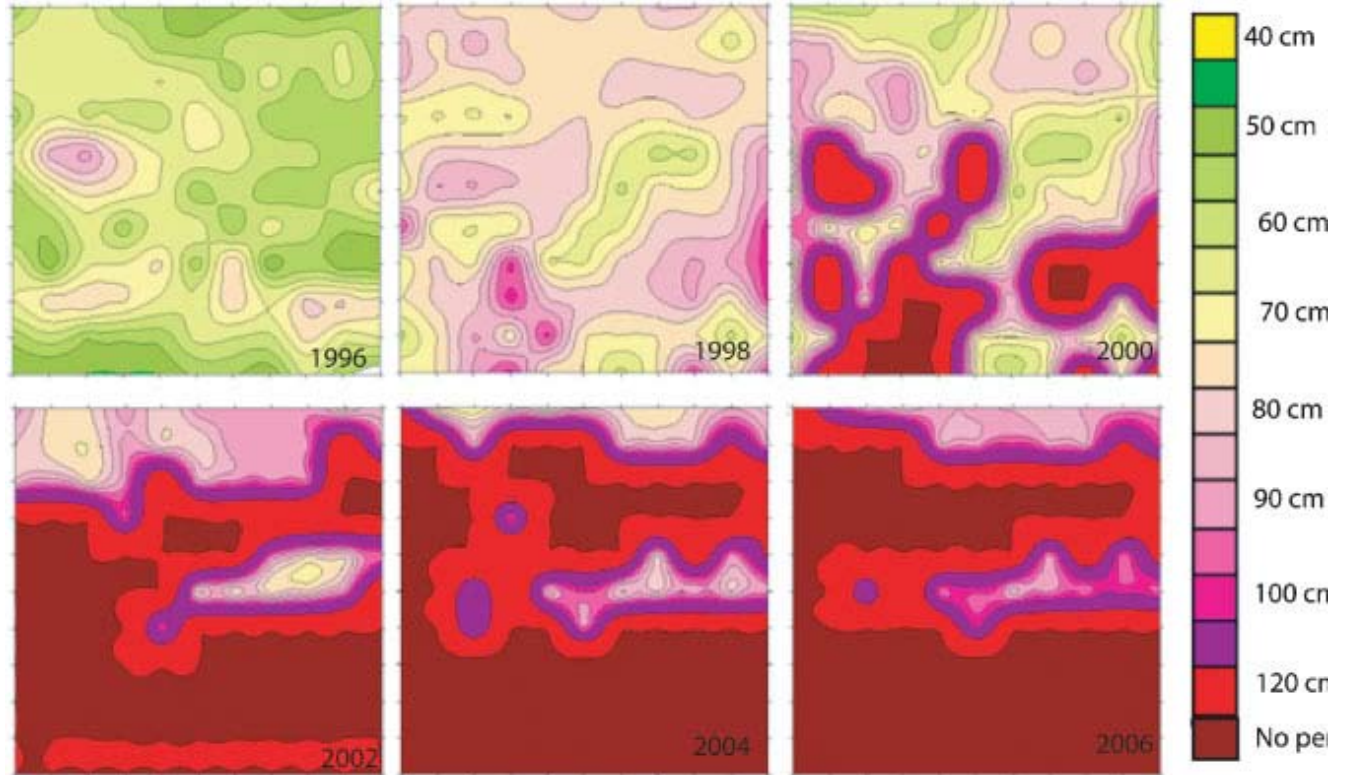
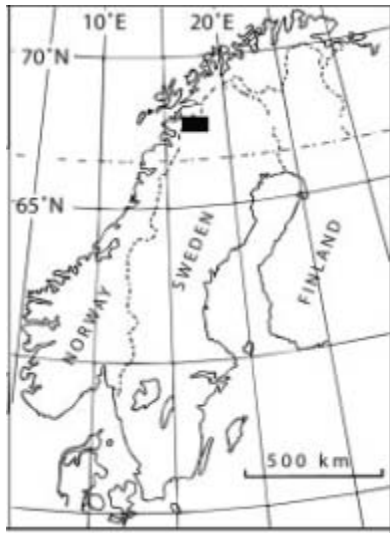
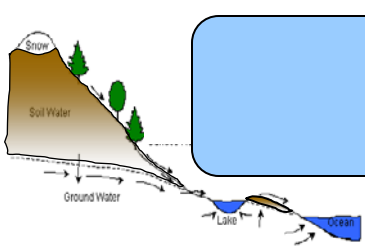


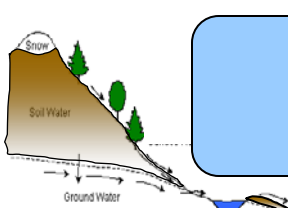
CCSM3: DJF 0.52mm d<sup>-1</sup>



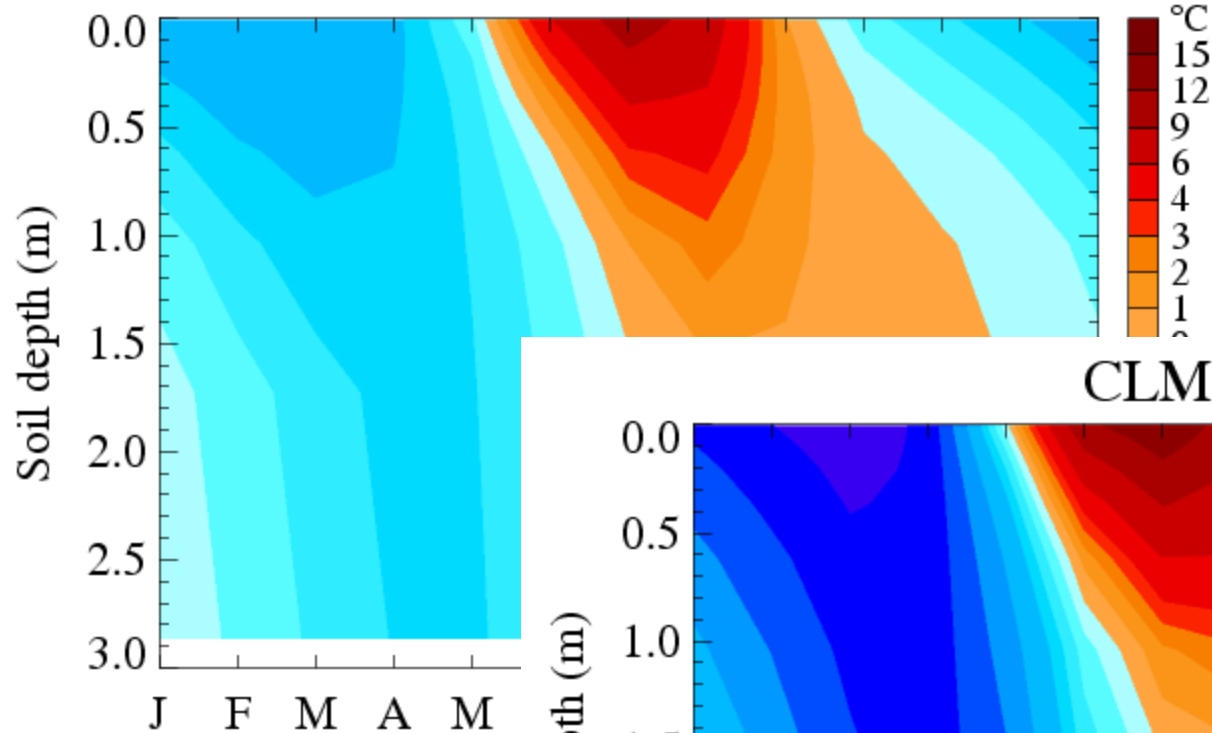
**CCSM4 Bias = 0.56**  
**CCSM3 Bias = 0.64**

# Observed permafrost degradation

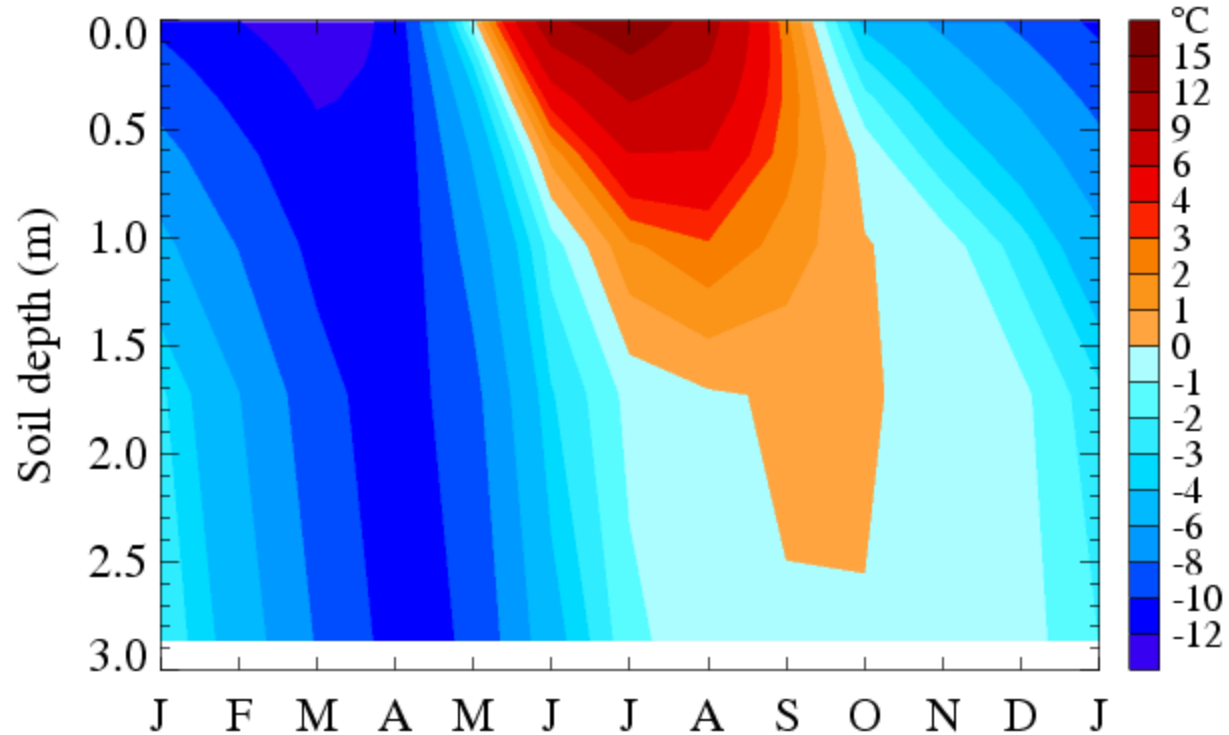


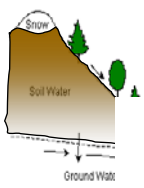


CCSM3

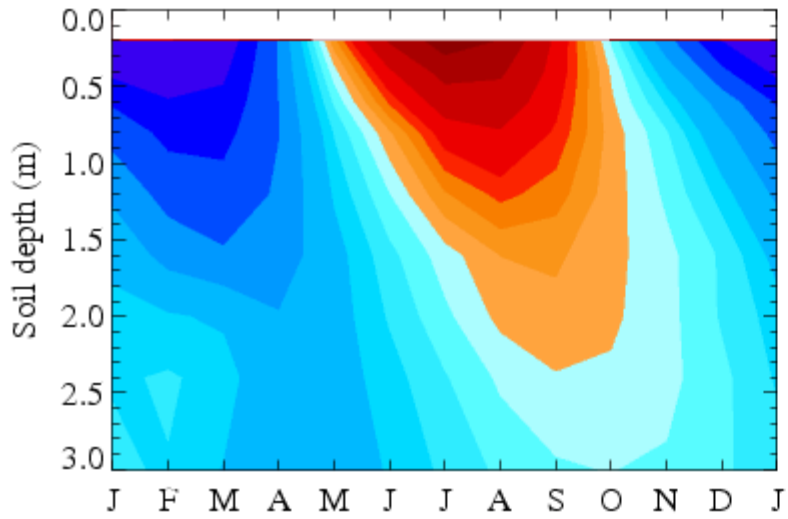


CLM3

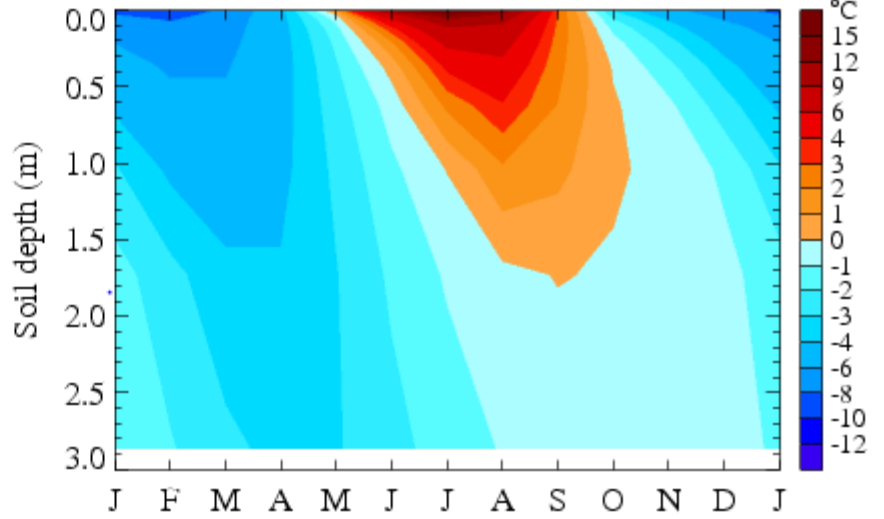




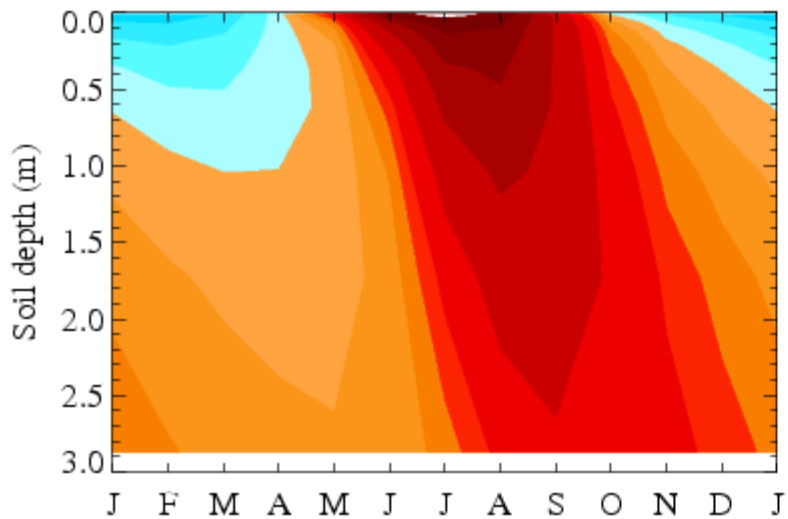
OBS



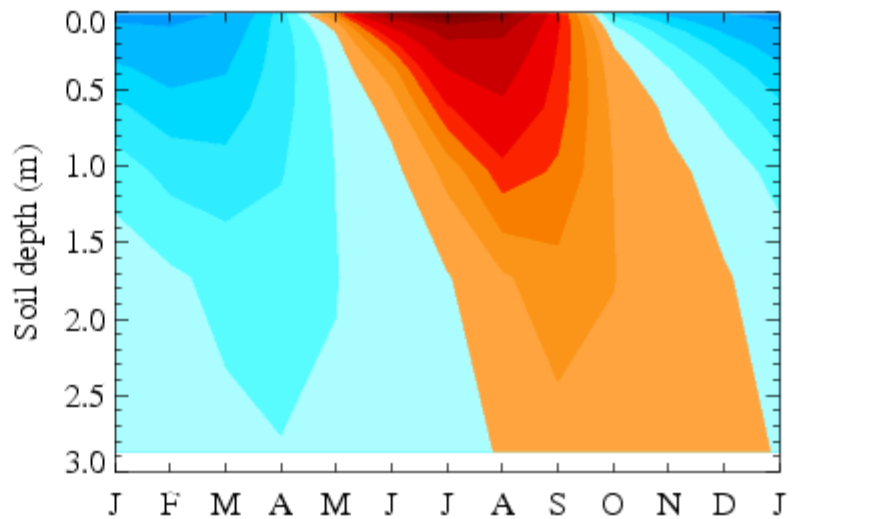
CCSM4

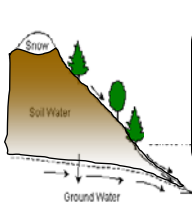


CCSM4 RCP8.5



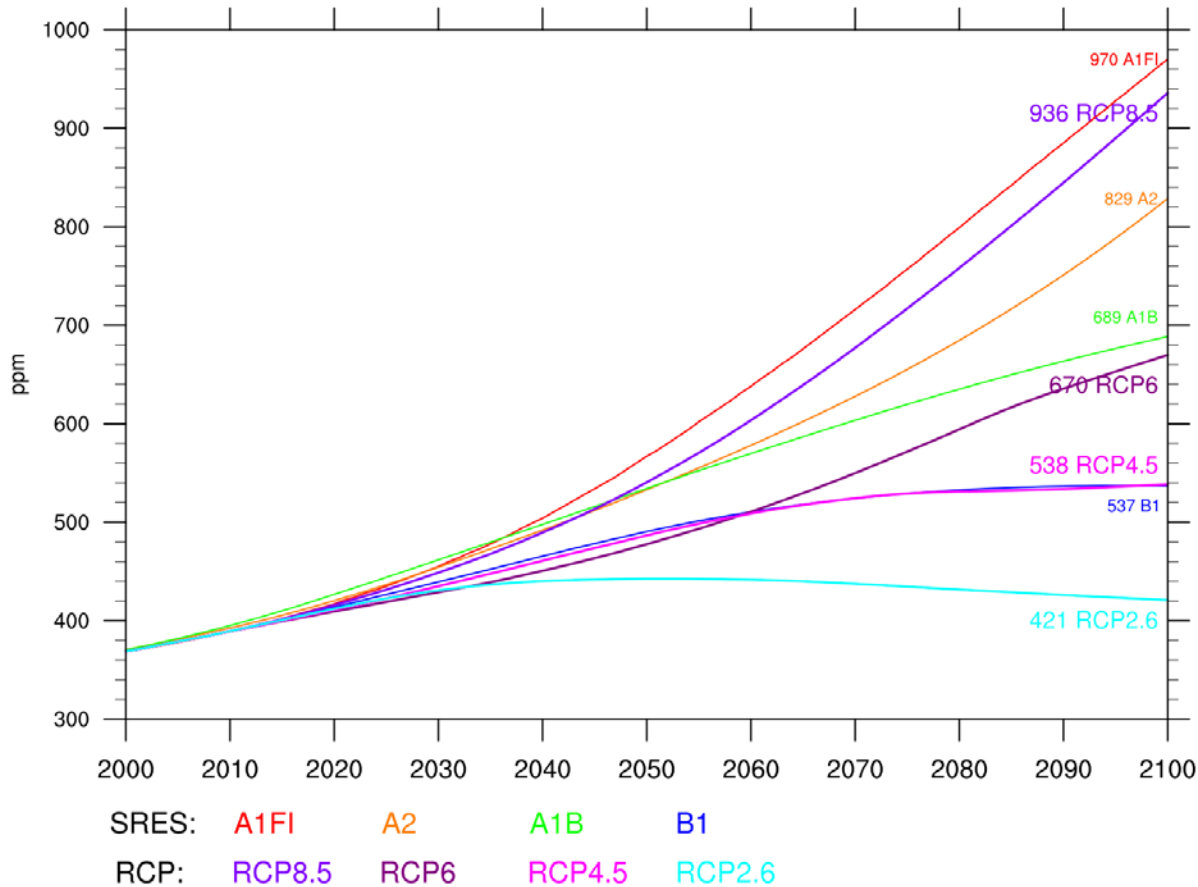
CCSM4 RCP2.6





# CCSM4 simulations for CMIP5

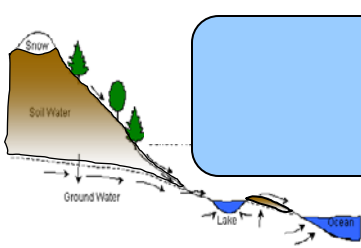
## Representative Concentration Pathway (RCP) and SRES CO<sub>2</sub> concentrations



**Most CORE CMIP5 simulations have been completed with CCSM4, incl historical and RCP 8.5, RCP 4.5, and RCP 2.6**



# CLM4 Cold Region Hydrology Schematic

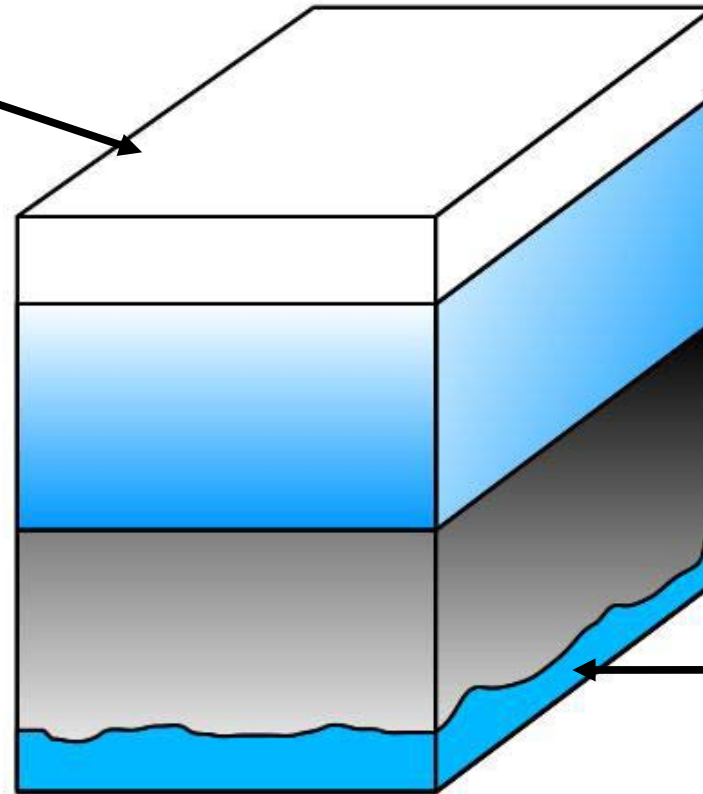


**Snow  
(Surface Fluxes)**

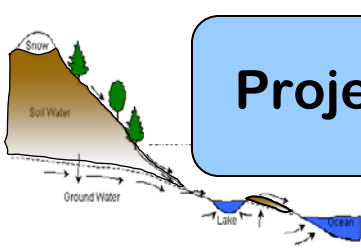
**Active Layer**

**Permafrost**

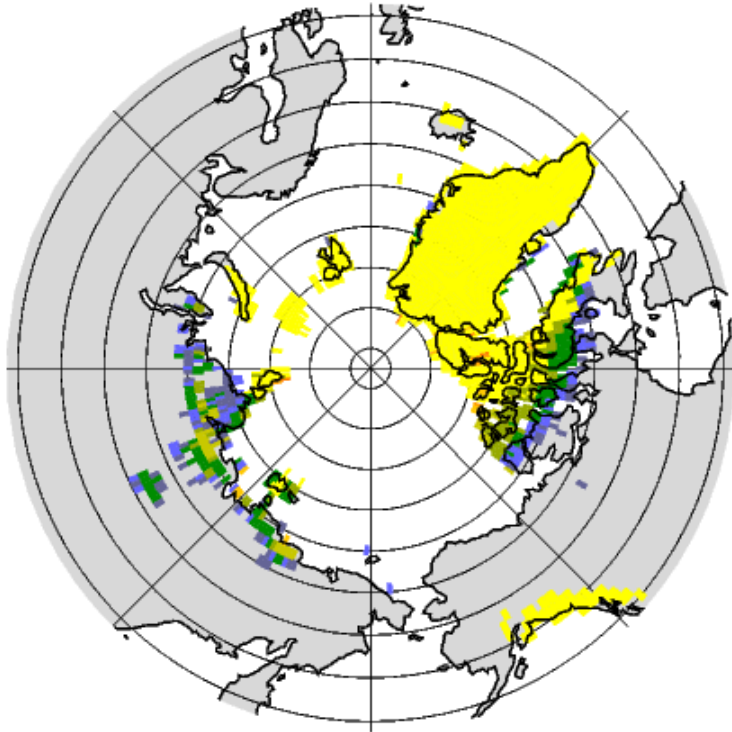
**Water table**



# Projected near-surface permafrost extent and ALT (2080-2099)



CCSM4 RCP8.5 (2.6)



CCSM4 RCP2.6 (7.5)

