What information is available and what is missing for energy and water cycle process modeling efforts, and the ways to address the gaps

Eric F Wood

With help from
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NORTHERN EURASIA LANDSURFACE PROPERTIES AND CHANGE AND ITS ROLE IN THE GLOBAL EARTH SYSTEM AND MODELS

August 12 – 17, 2007, Aspen, CO

Basic water budget equation

$$\frac{d\theta_{SM}}{dt} + \frac{d\theta_{SW}}{dt} = P - ET - Q$$

Soil moisture, Drainage, Baseflow

Lakes, Rivers. Snowpack

Observed, Reanalysis

Evapotranspiration

River discharge Groundwater fluxes

Observations

Parameterized

Basic energy budget equation

$$R_S(1-\alpha)+R_L-\varepsilon k T_S^4=\lambda E+H+G$$

- $R_S(1-\alpha)+R_L$: Observations, Reanalysis
- $\varepsilon k T_S^4$: Longwave ↑
- λE: Latent heat flux
- H: Sensible heat flux
- G: Ground heat flux

Observations

Parameterized

"What information is needed for energy and water cycle modeling?"

1. Forcing data: Surface Meteorology, incoming/downward radiation

2. Data used in process parameterizations:
   -- Land cover and, for vegetation, its related phenology
   -- Soil data including composition, hydraulic and thermal properties
   -- Topography, including micro-topography that controls fens and bog areas

3. Data used to validate process parameterizations:
   -- River discharge
   -- Snow cover extent
   -- Lake and reservoir levels
   -- Soil moisture, groundwater levels
   -- Bore hole temperature logs for permafrost and seasonal freezing
   -- Evapotranspiration

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Some examples of the needed data sets

Precipitation Gauge Network

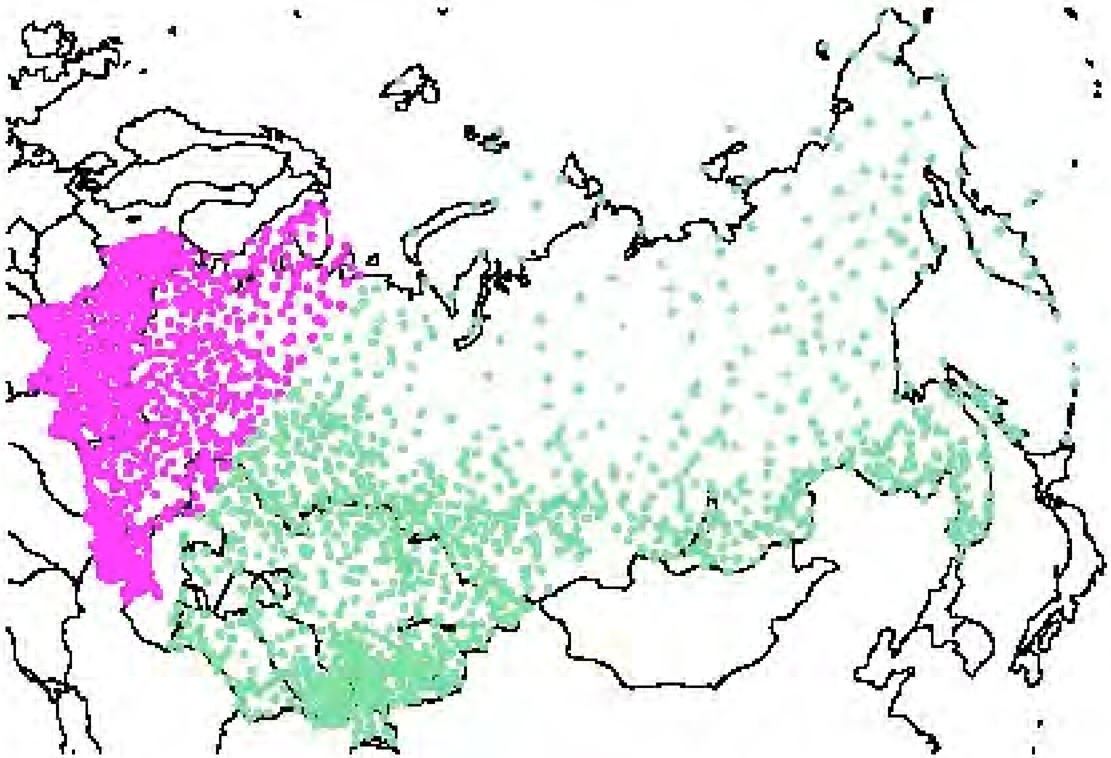
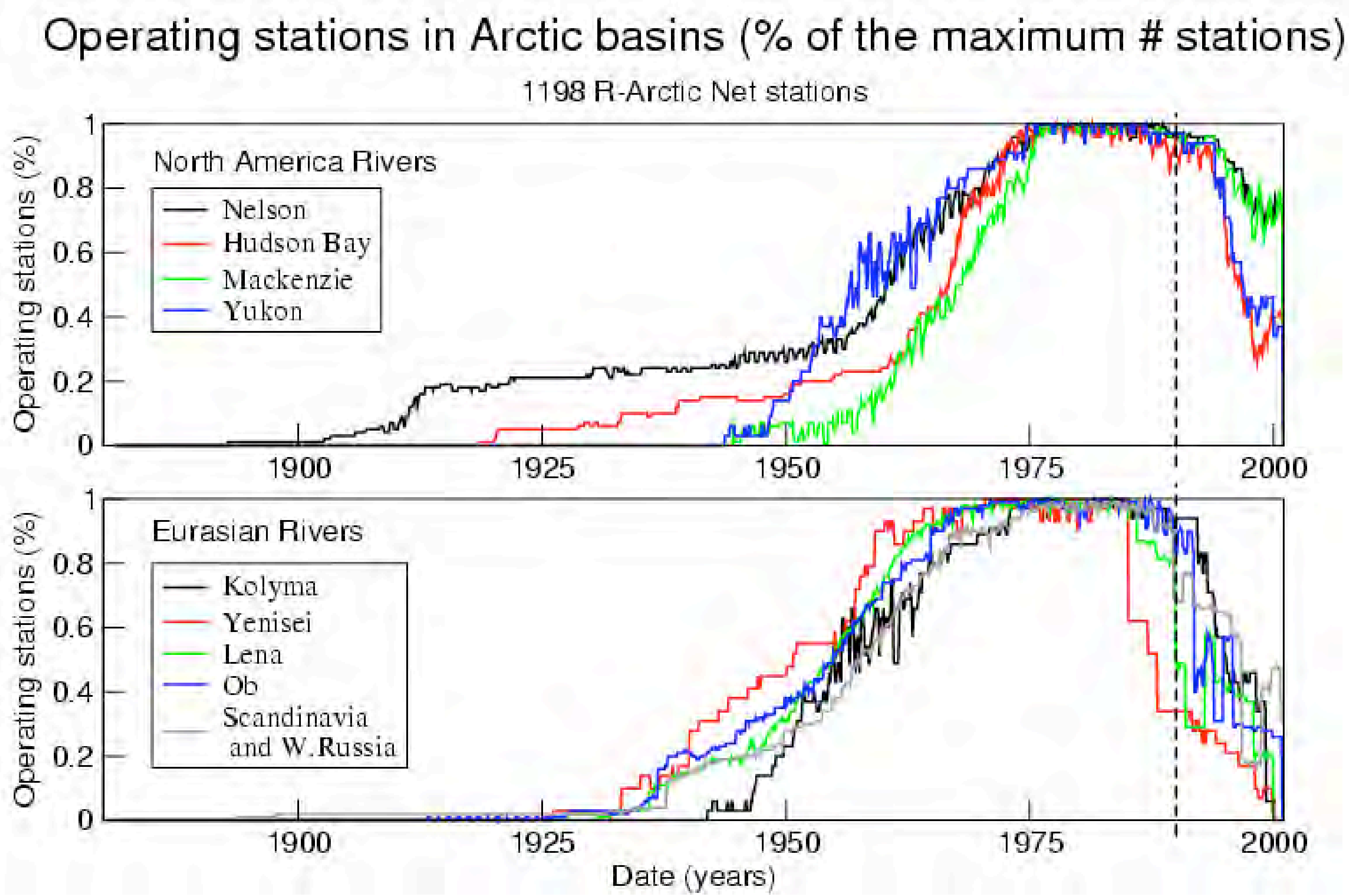
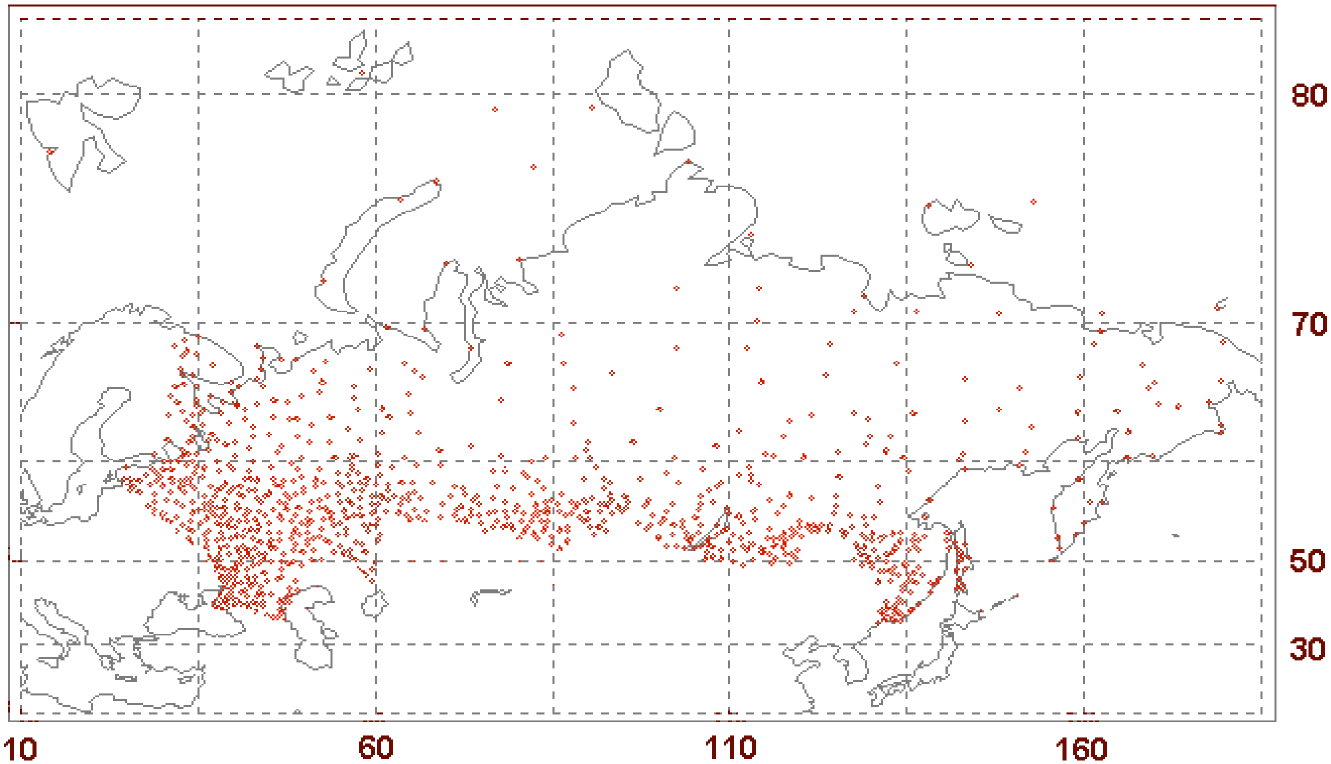


Figure taken from NCDC Documentation for Dataset 9813:
Daily and Sub-daily Precipitation for the Former USSR.

Discharge Gauge Network



In Situ Observations



Data on snow cover characteristics includes the following information:

- snow cover thickness along snow courses over different landscapes,
- degree of the area covered by snow cover along a snow course;
- snow cover density
- Snow Water Equivalent

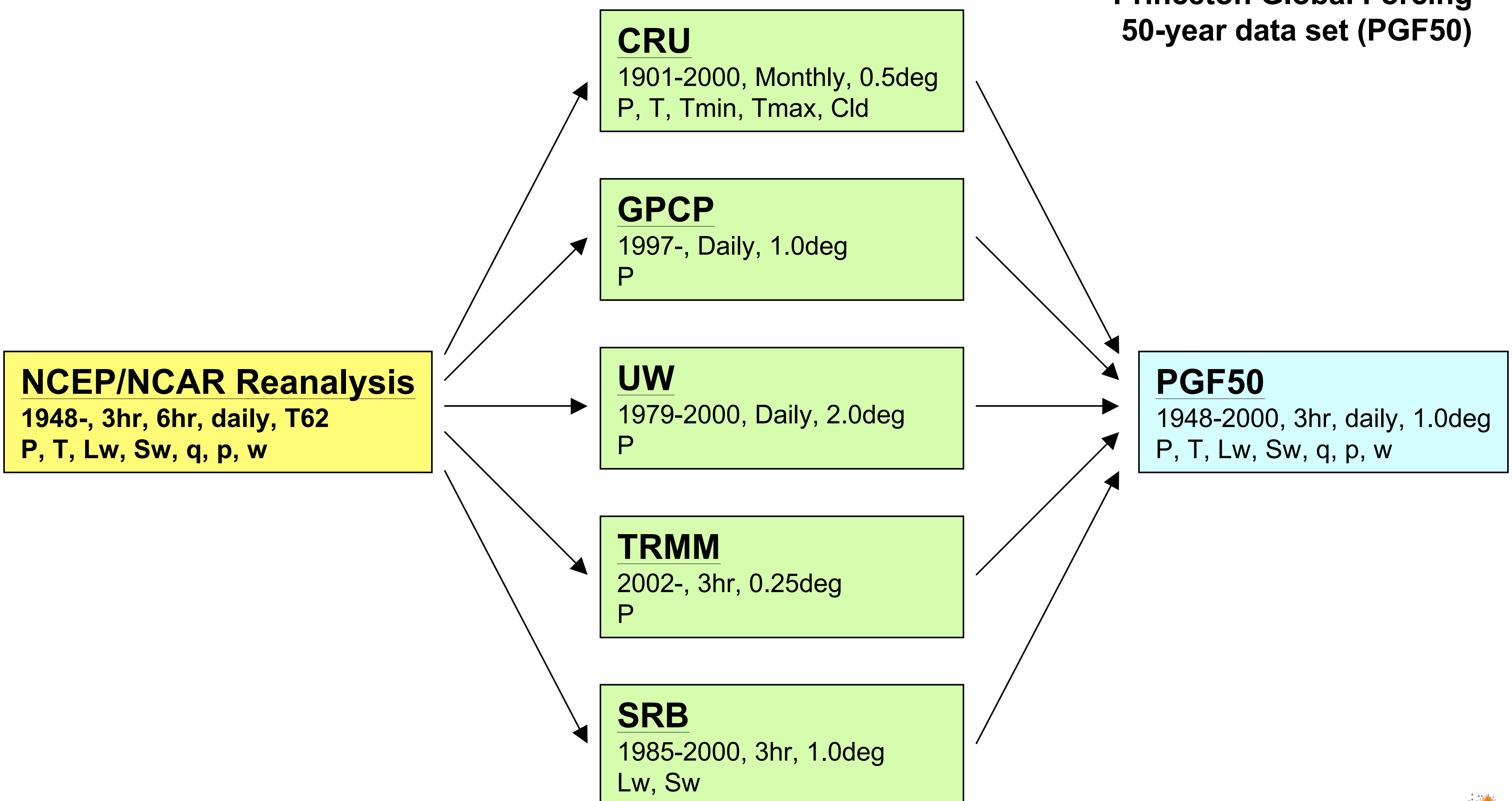
Source: Nina Speranskaya, State Hydrological Institute, Russia

Global Forcing Dataset (see Sheffield et al 2006, *J Climate*)

Reanalysis
High temporal/low spatial resolution

Observations
Generally low temporal/high spatial resolution

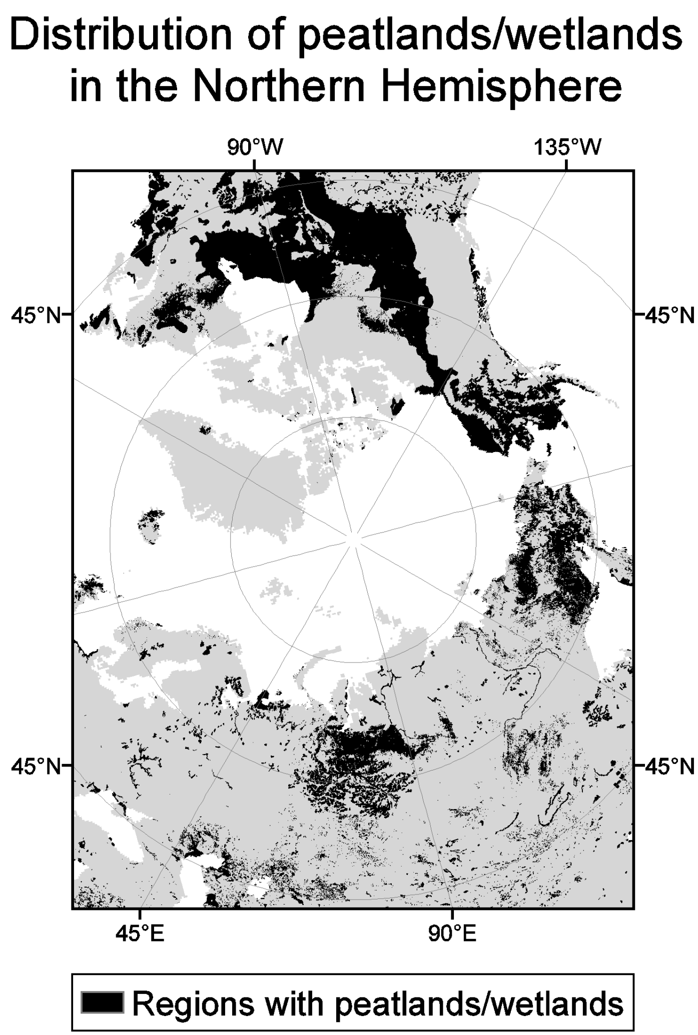
Bias-Corrected
High temporal/high spatial resolution: Princeton Global Forcing 50-year data set (PGF50)

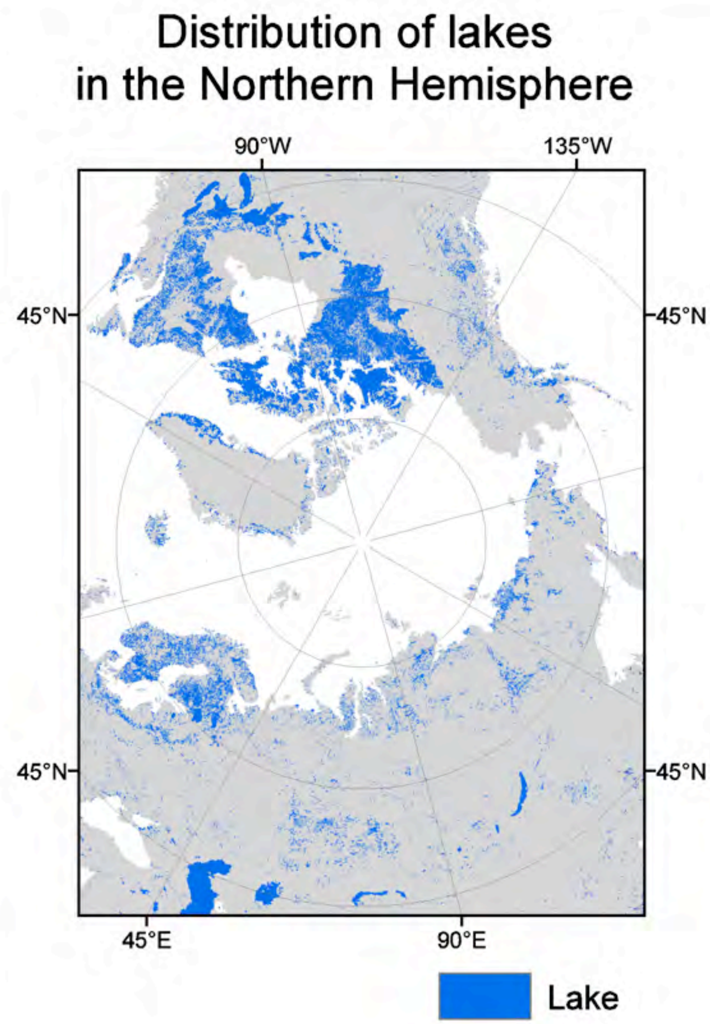


Princeton University

Is the accuracy and resolution sufficient?
Is the accompanying phenology available?

Where do we find peatlands, what is the distribution of lakes?





Lehner, B., and P. Doll (2004), Development and validation of a global database of lakes, reservoirs and wetlands, *Journal of Hydrology*, *296*, 1-22.

What information is available and what is missing for energy and water cycle process modeling efforts, and the ways to address the gaps

"…energy and water cycle process modeling efforts?"

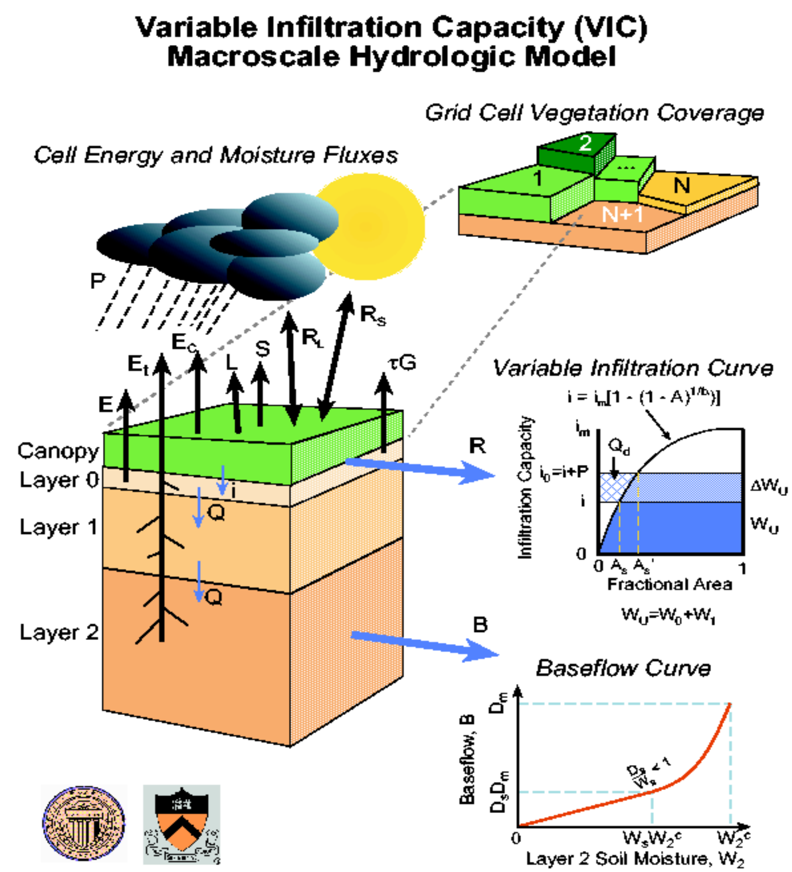
In-situ observations are too sparse to support land surface modeling forcing data sets having spatial resolutions finer than about 1-degree.

Thus, to what extent are we capturing the temporal and spatial dynamics of energy and water cycle dynamics across the NEESPI domain?

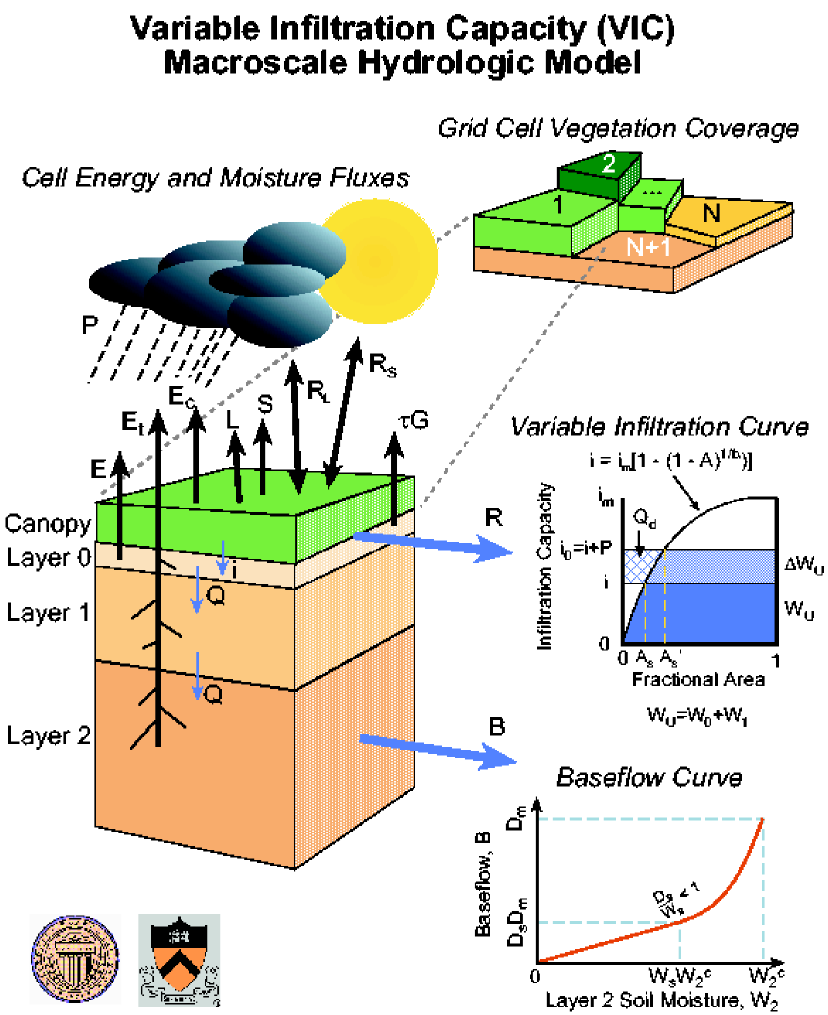
Are the energy and water cycle process parameterizations sufficiently accurate that they can be used to attribute LULCC and climate change attribution?

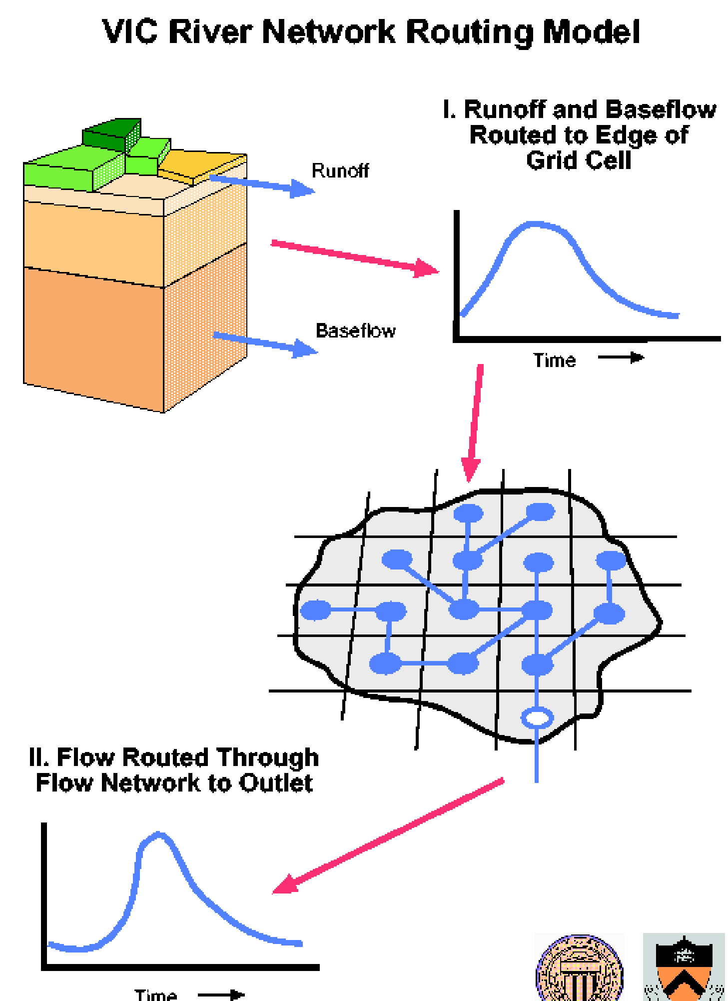
Typical Land Surface Modeling Framework

- VIC hydrology model
  - Large, “flat” grid cells (e.g. 100x100 km)
  - Land cover “tiles” (vegetation types)
  - On hourly to 3-hrly time step, simulate:
    - Soil moisture/water table
    - Snow pack
    - Runoff
    - Lake/surface water
    - Evapotranspiration/Latent heat flux
    - Soil temperature
    - Sensible heat flux
    - Ground heat flux

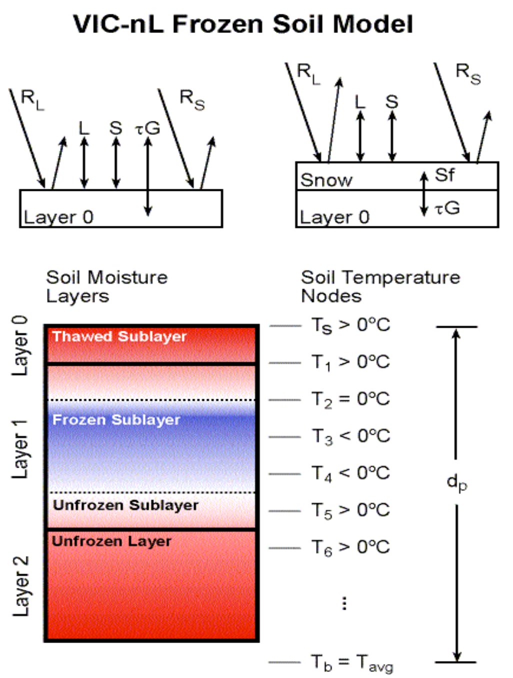


The Variable Infiltration Capacity (VIC) Model

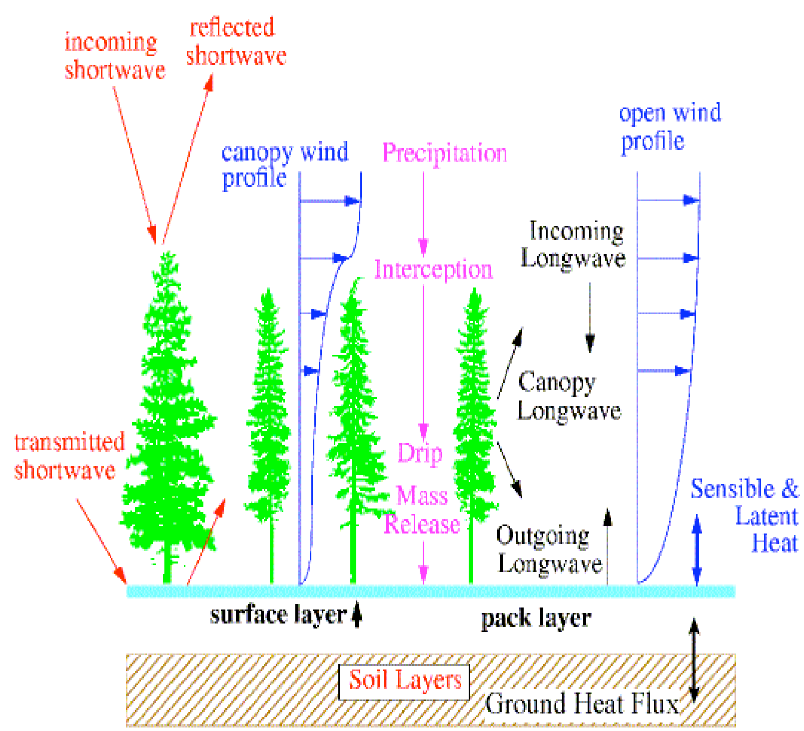




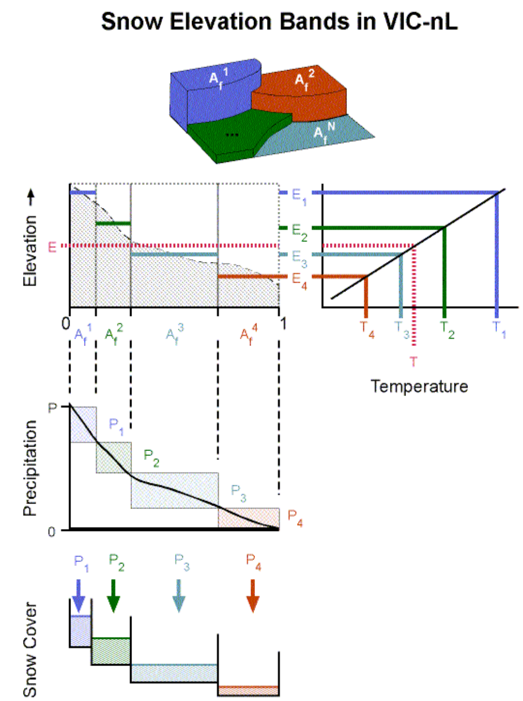
VIC Cold Season Schematic



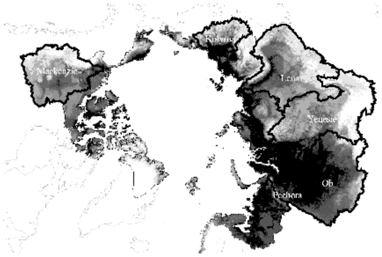
Frozen soil model



Snow energy model

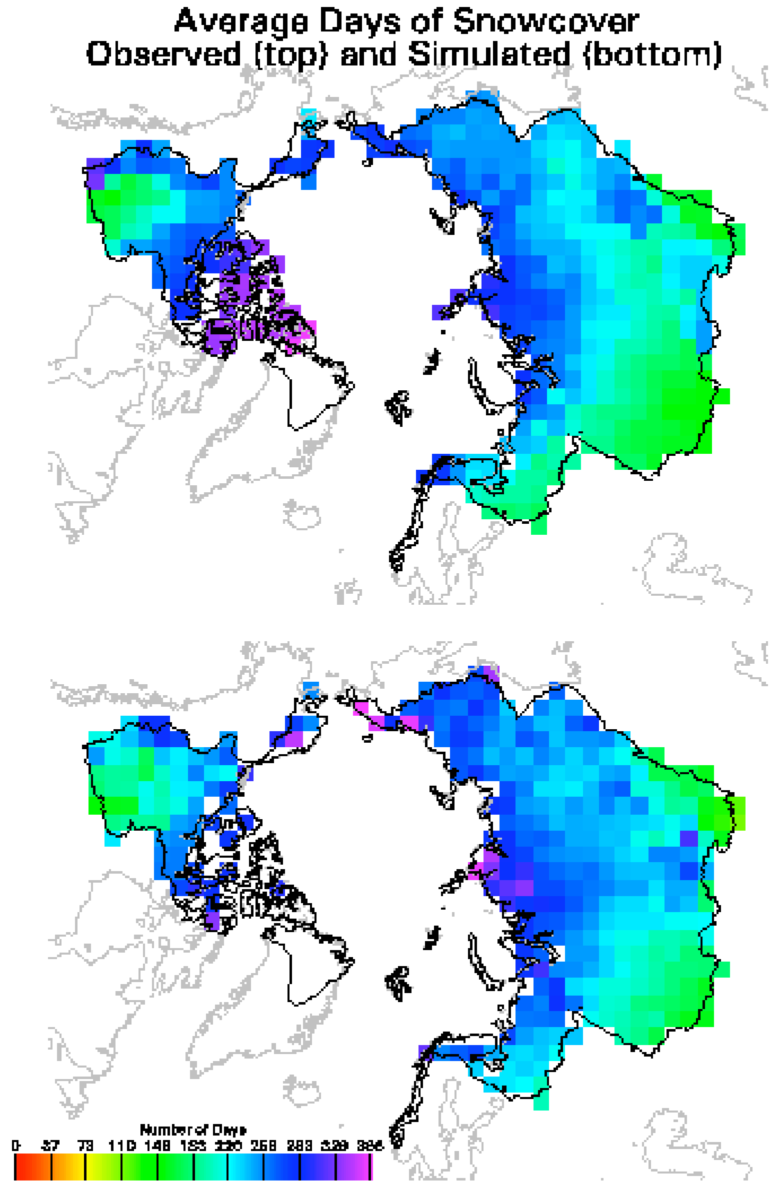


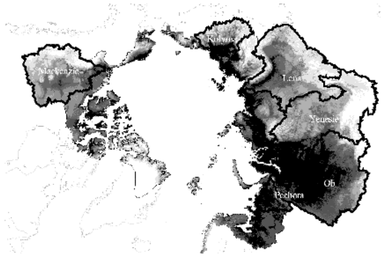
Snow elevation bands



VIC Arctic Modeling

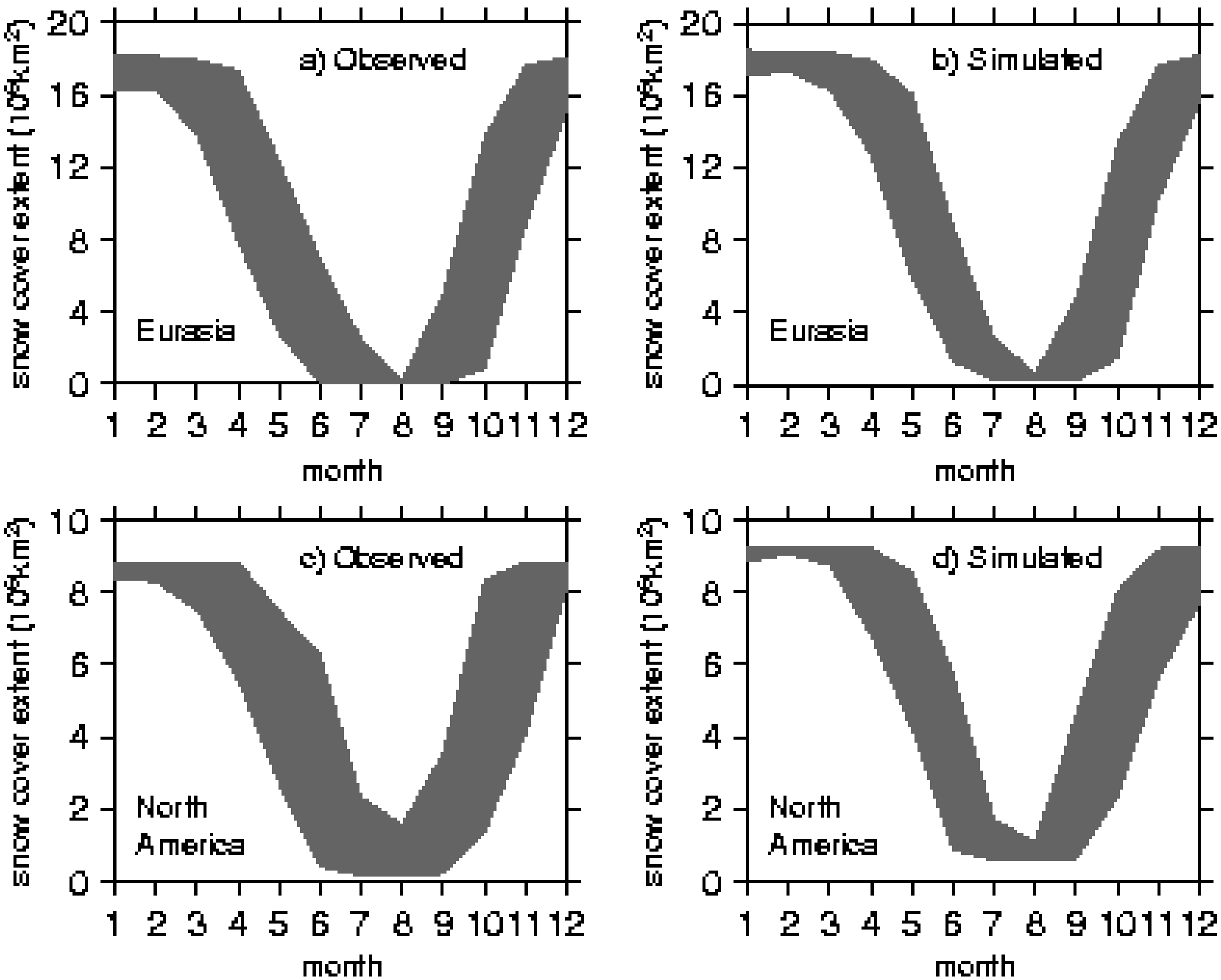
Annual average days of snow cover for the entire Arctic basin





VIC Arctic Modeling

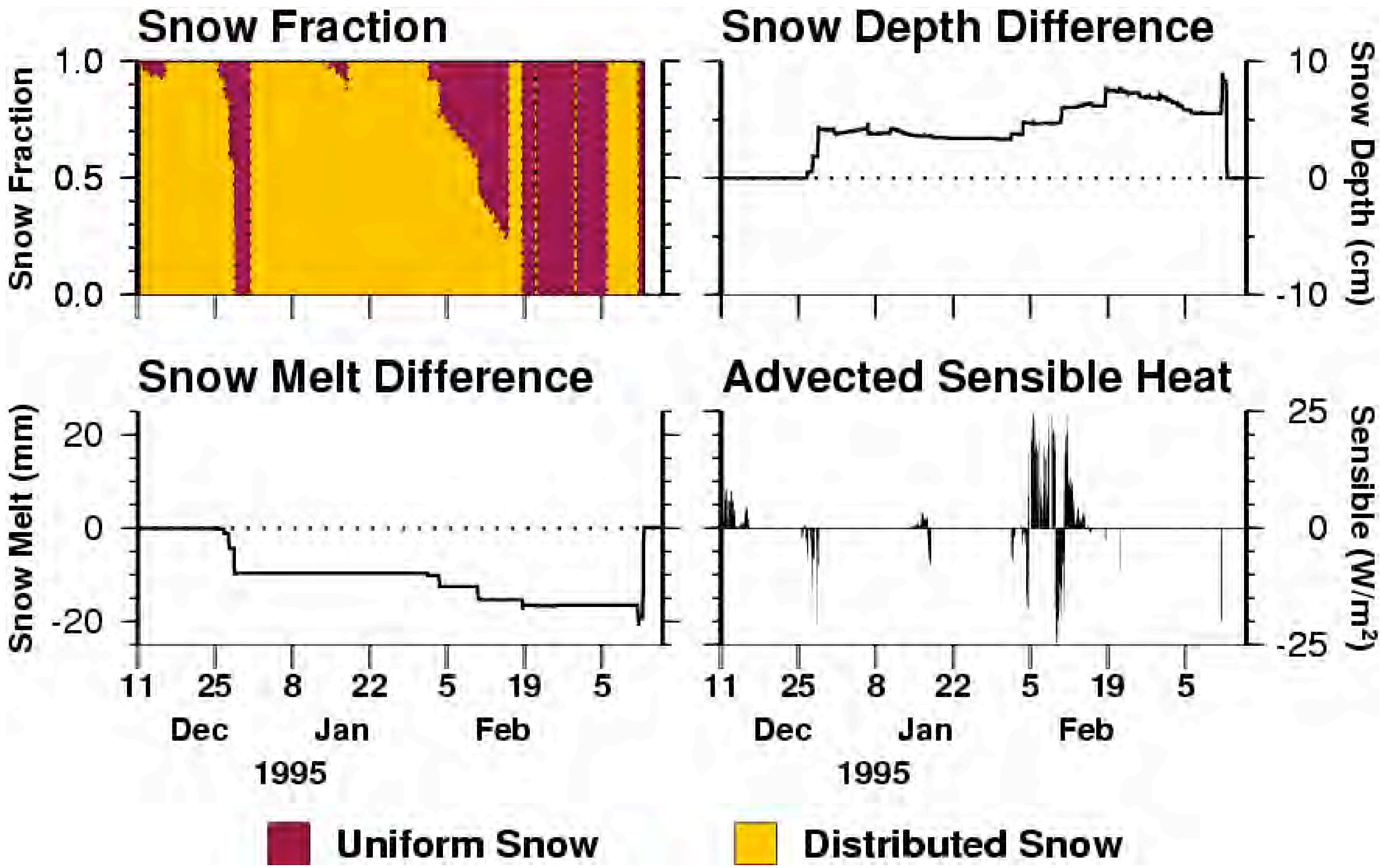
Monthly variation in snow cover extent (1980-1993)

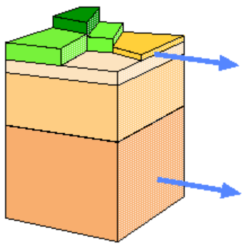


Spatial versus Uniform Snow Algorithm

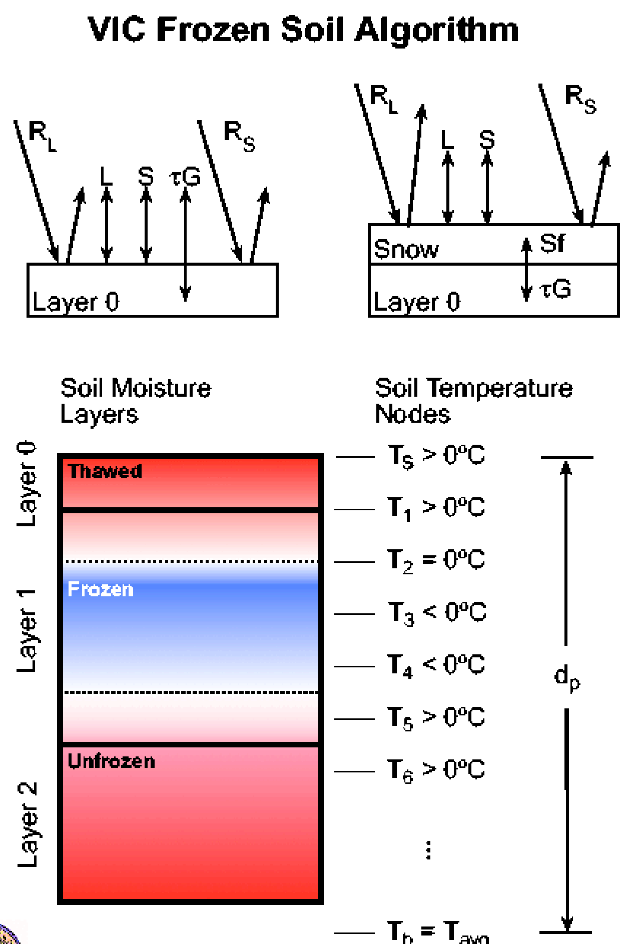
Winter 1994-1995 – Rosemount, Minn.

Algorithm Development



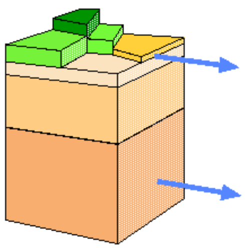


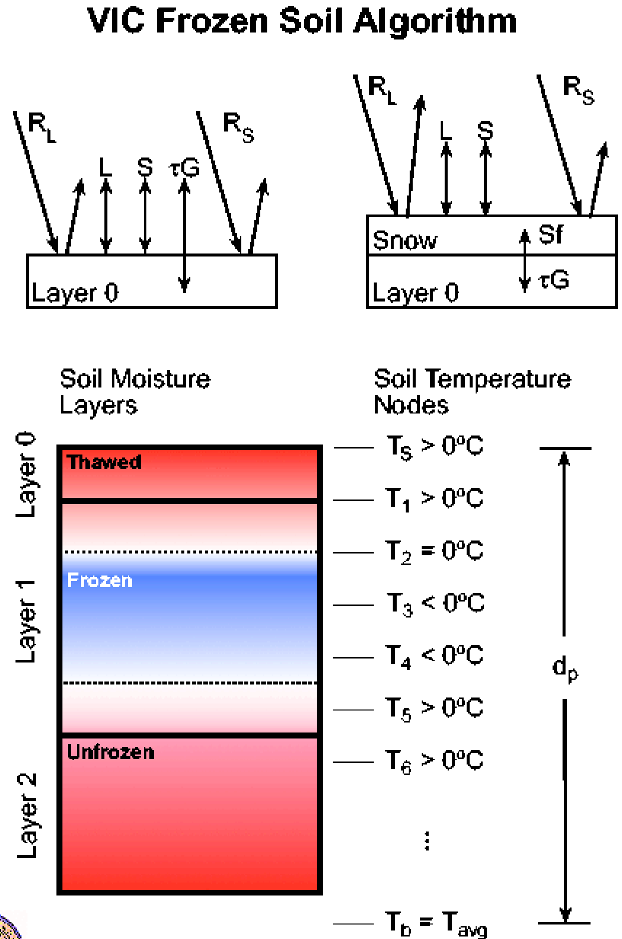
Spatially-distributed frozen soils

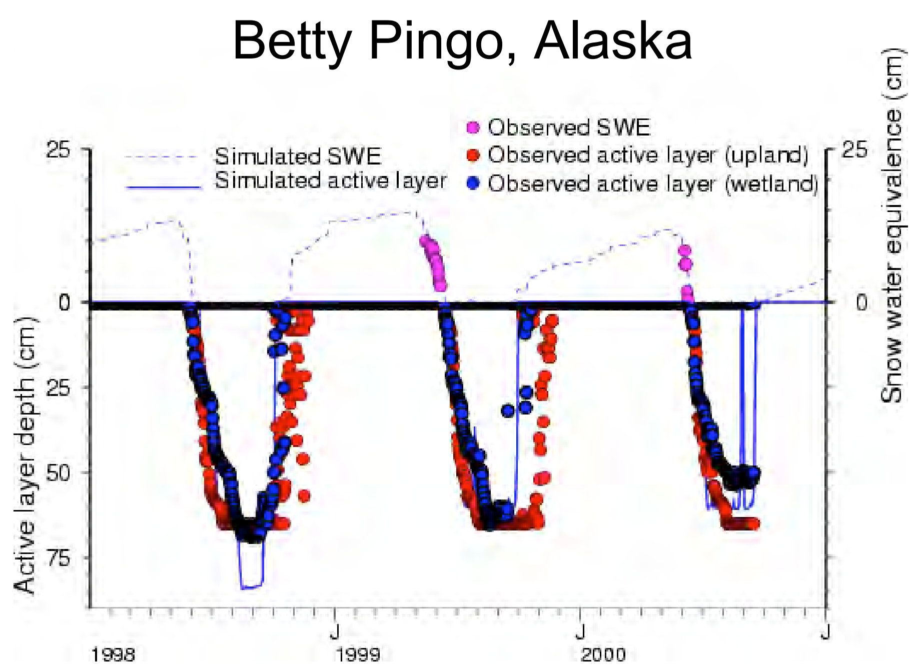


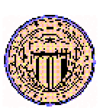
- Soil node temperatures solved via heat diffusion equation
- Ice content, infiltration rate and heat capacity calculated at nodes
- Assumed uniform temperature distribution across the grid cell allows spatial variation of infiltration capacity

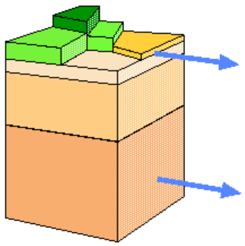
Spatially-distributed frozen soils







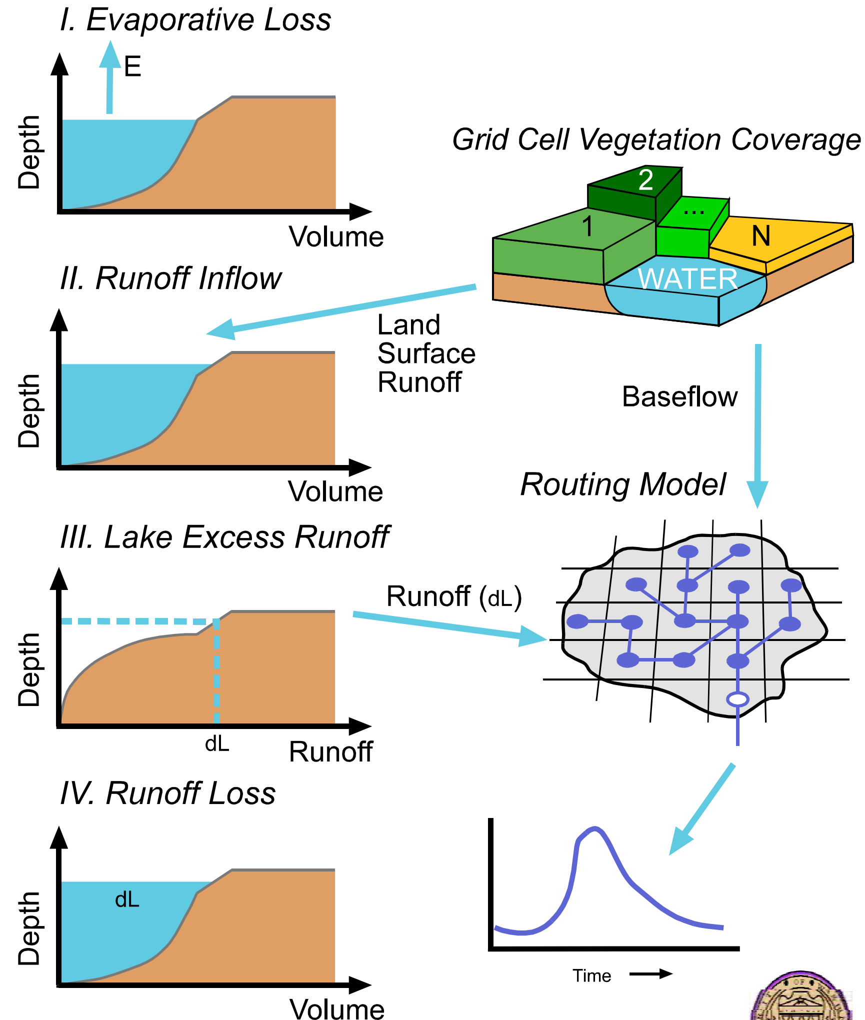


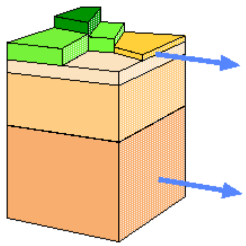


Lakes and Wetlands

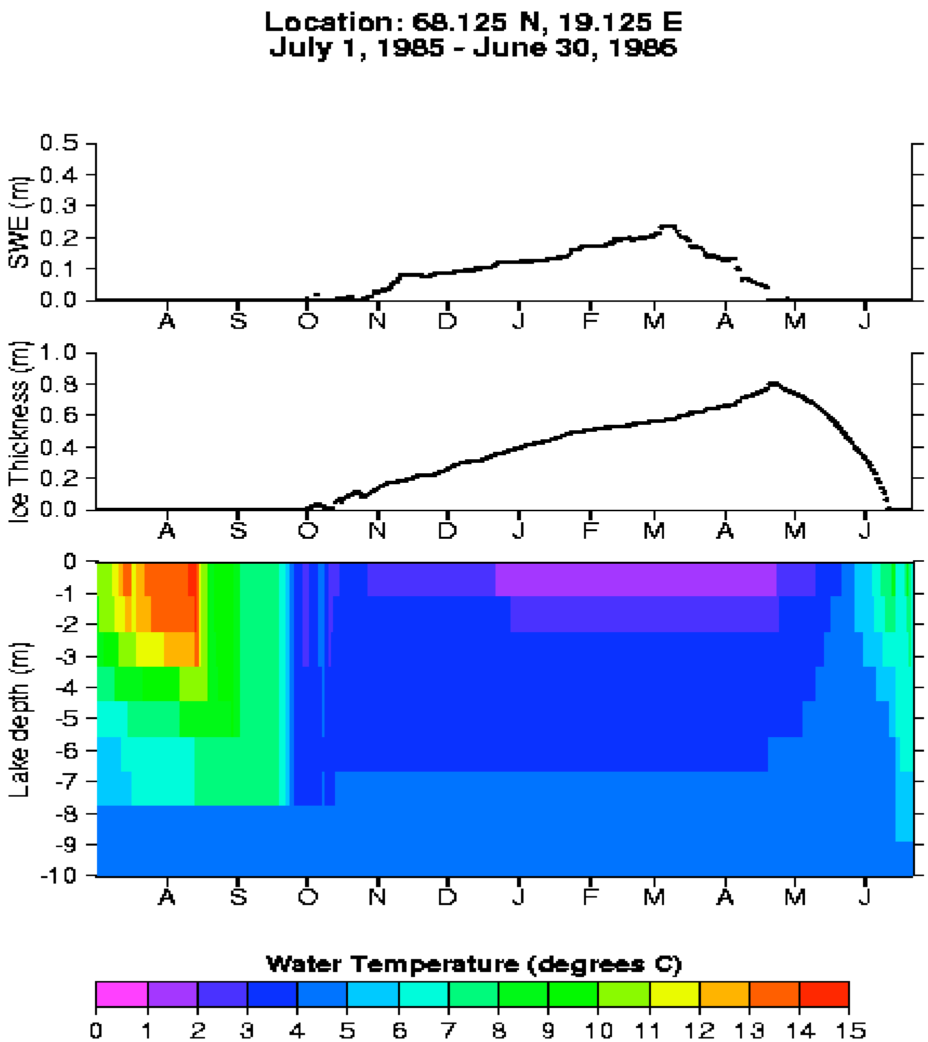
- Lake energy balance based on:
  - Hostetler and Bartlein (1990)
  - Hostetler (1991)
- Assumptions:
  - One “effective” lake for each grid cell;
  - Laterally-averaged temperatures; and
  - Non-linear rule curve for release of runoff from grid cell lake.

VIC Lake Algorithm

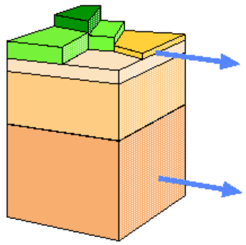




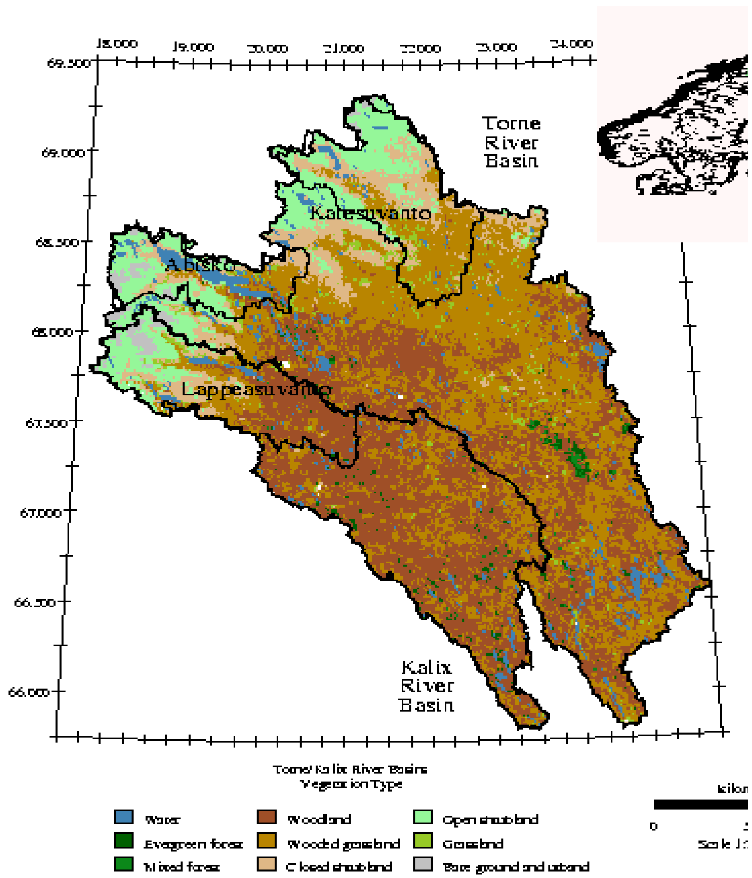
Lakes and Wetlands - Snow and Ice

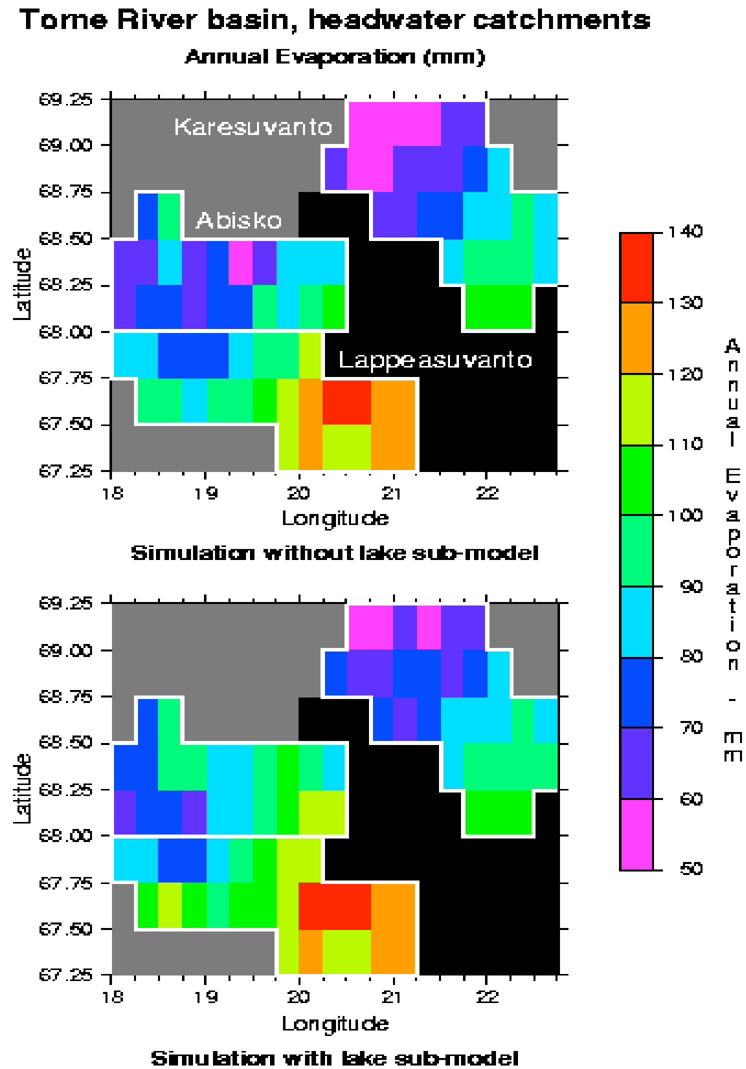


- Snow depth simulated on top of lake ice
- Lake ice - stays too long?
- Temperature profile - complete mixing in fall and spring

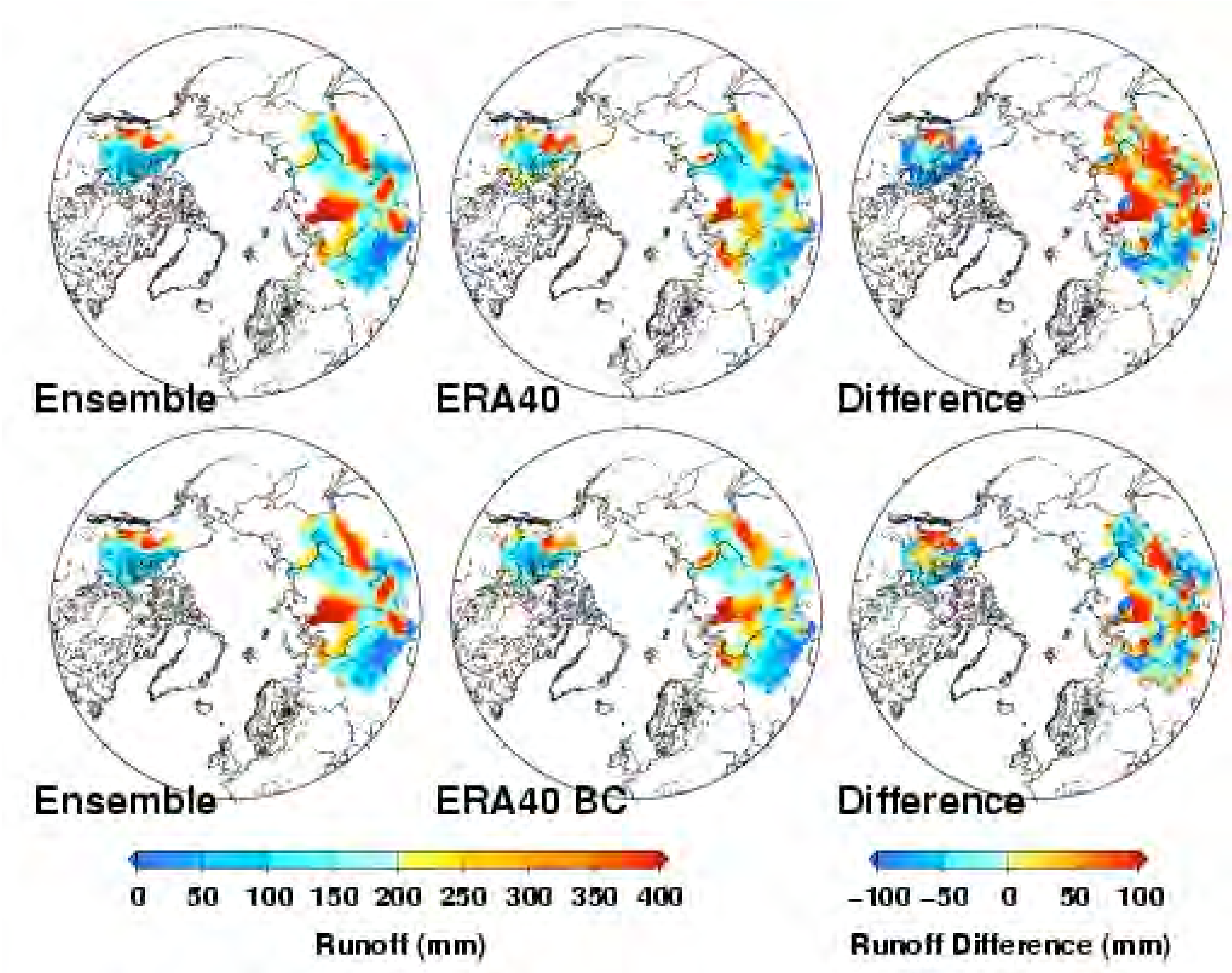


Lakes and Wetlands Evaporation



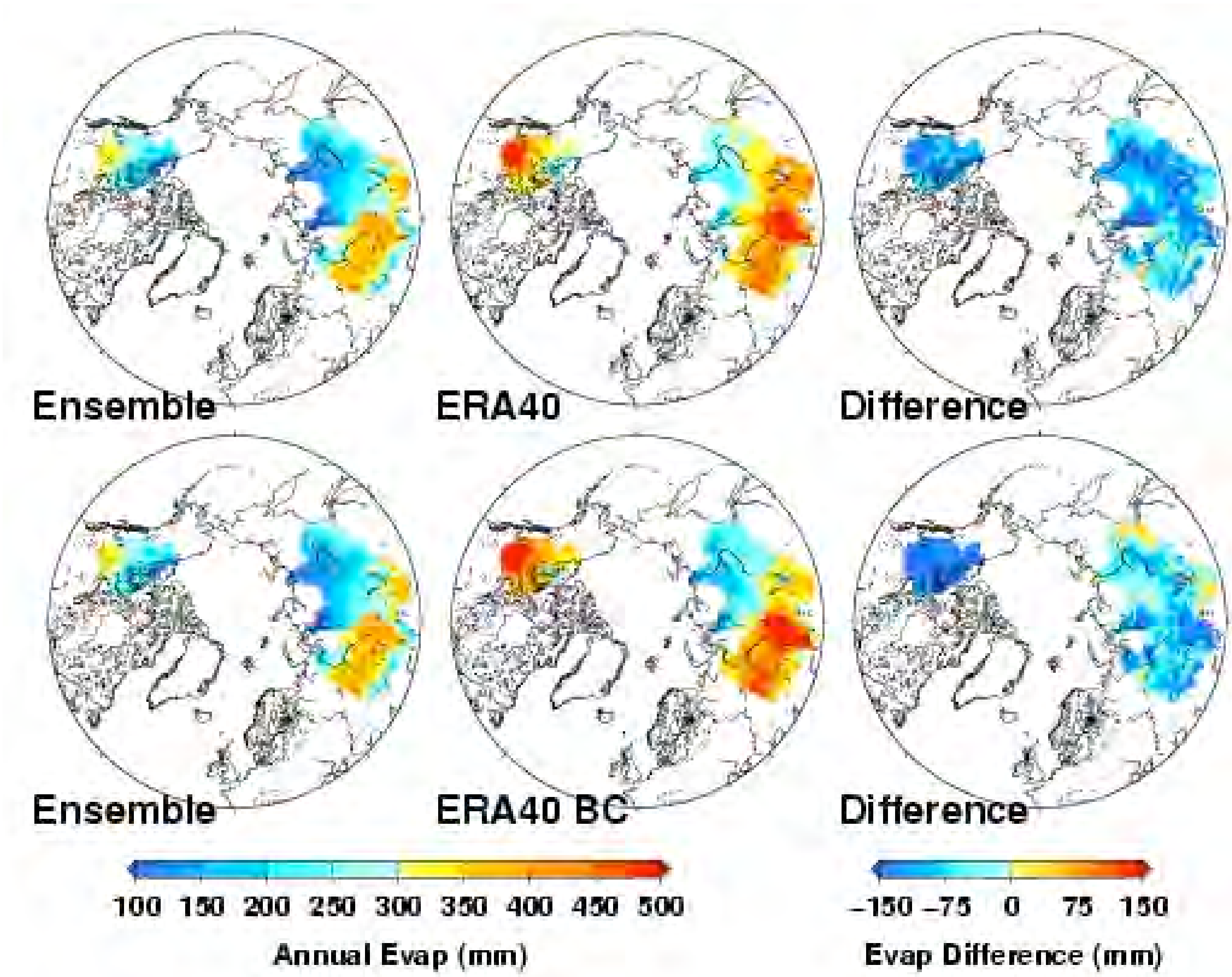


Annual runoff across the pan-Arctic



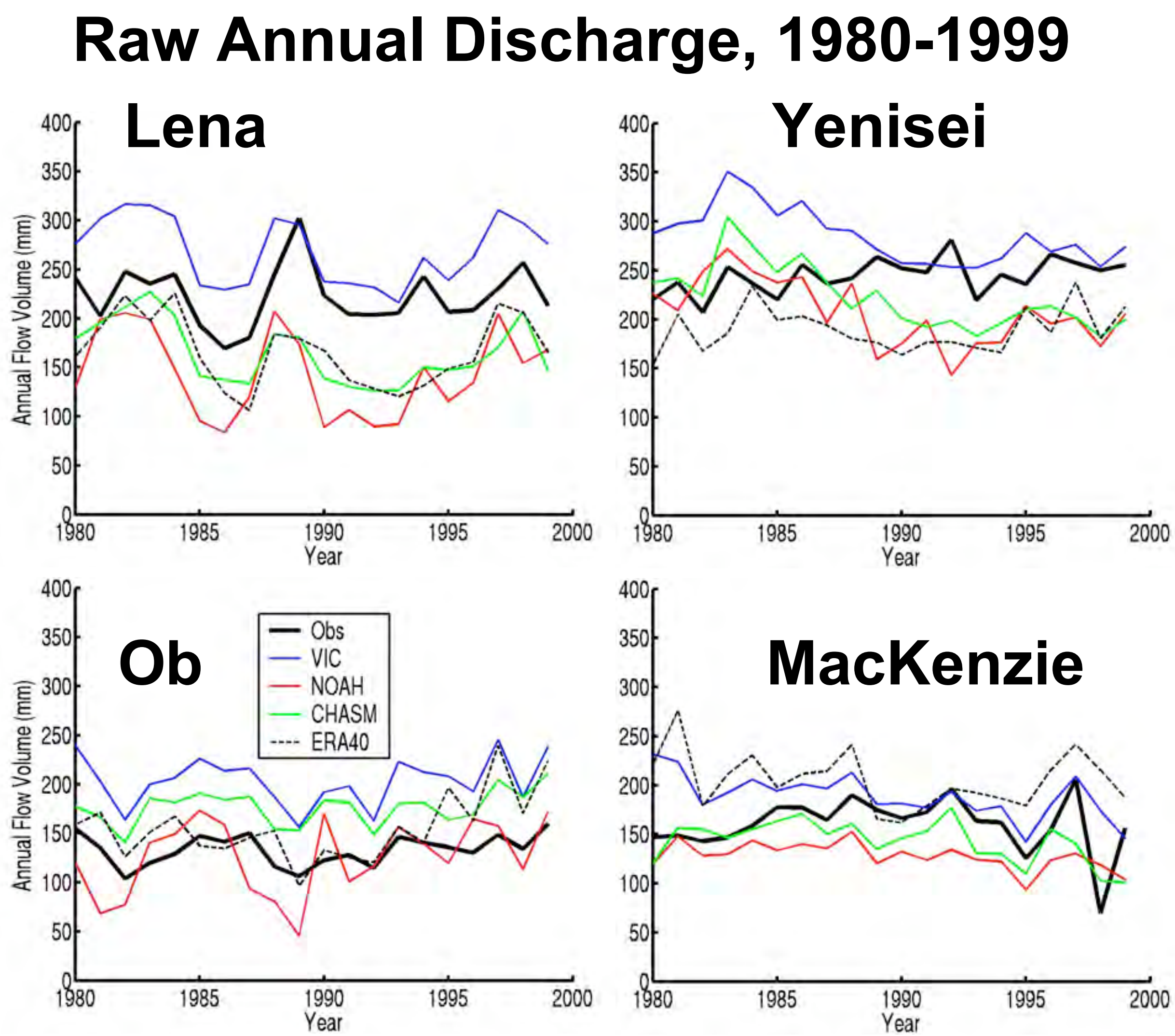
From Bohn et al. 2005 (Multi-model estimates of Arctic land surface conditions, AGU Dec 2005)

Annual evapotranspiration across the pan-Arctic



From Bohn et al. 2005 (Multi-model estimates of Arctic land surface conditions, AGU Dec 2005)

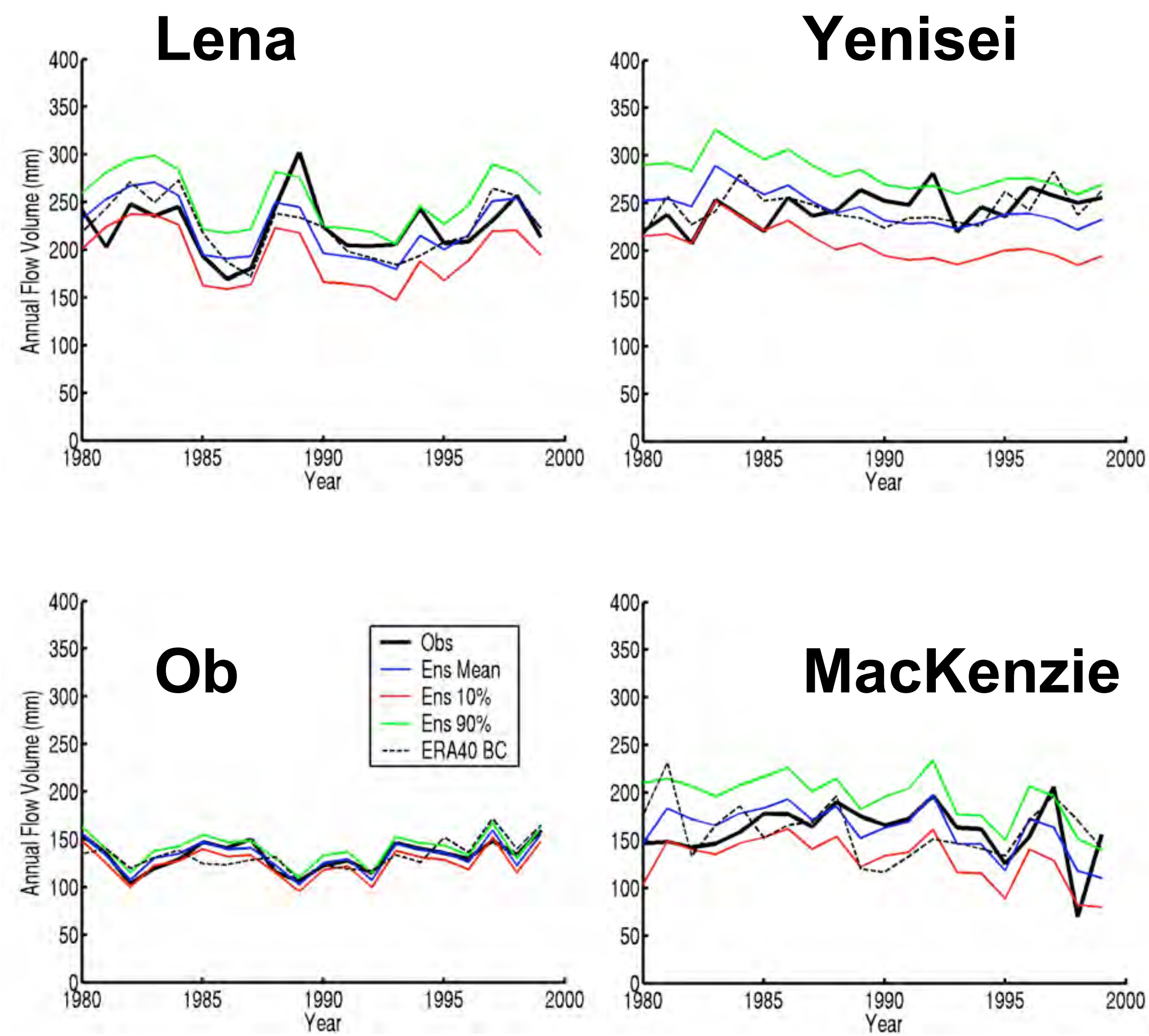
Multi-model runoff across the pan-Arctic



From Bohn et al. 2005 (Multi-model estimates of Arctic land surface conditions, AGU Dec 2005)

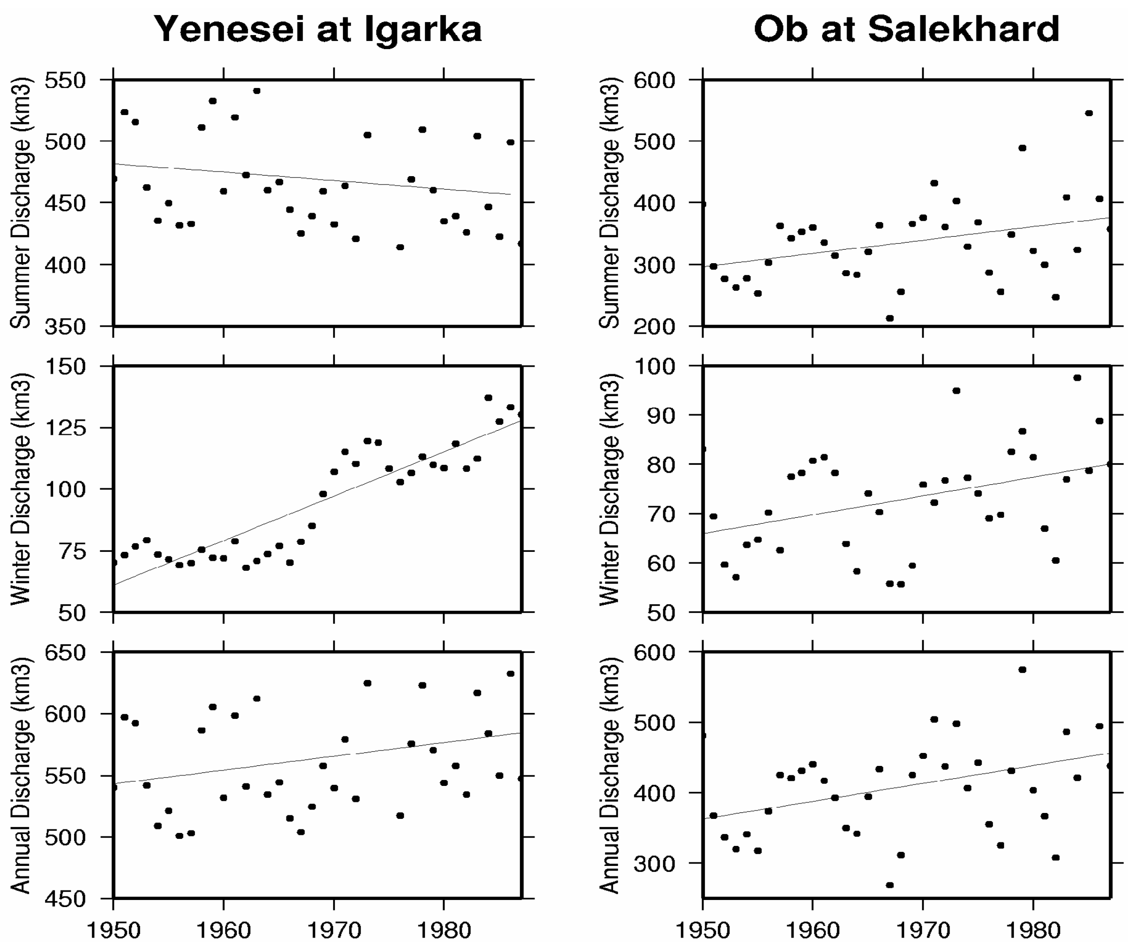
Multi-model runoff across the pan-Arctic

Ensemble Discharge, 1980-1999



From Bohn et al. 2005 (Multi-model estimates of Arctic land surface conditions, AGU Dec 2005)

Time series of discharge of the Yenesei and Ob Rivers over the last 50 years.



Conflicting Explanations for Discharge Trends

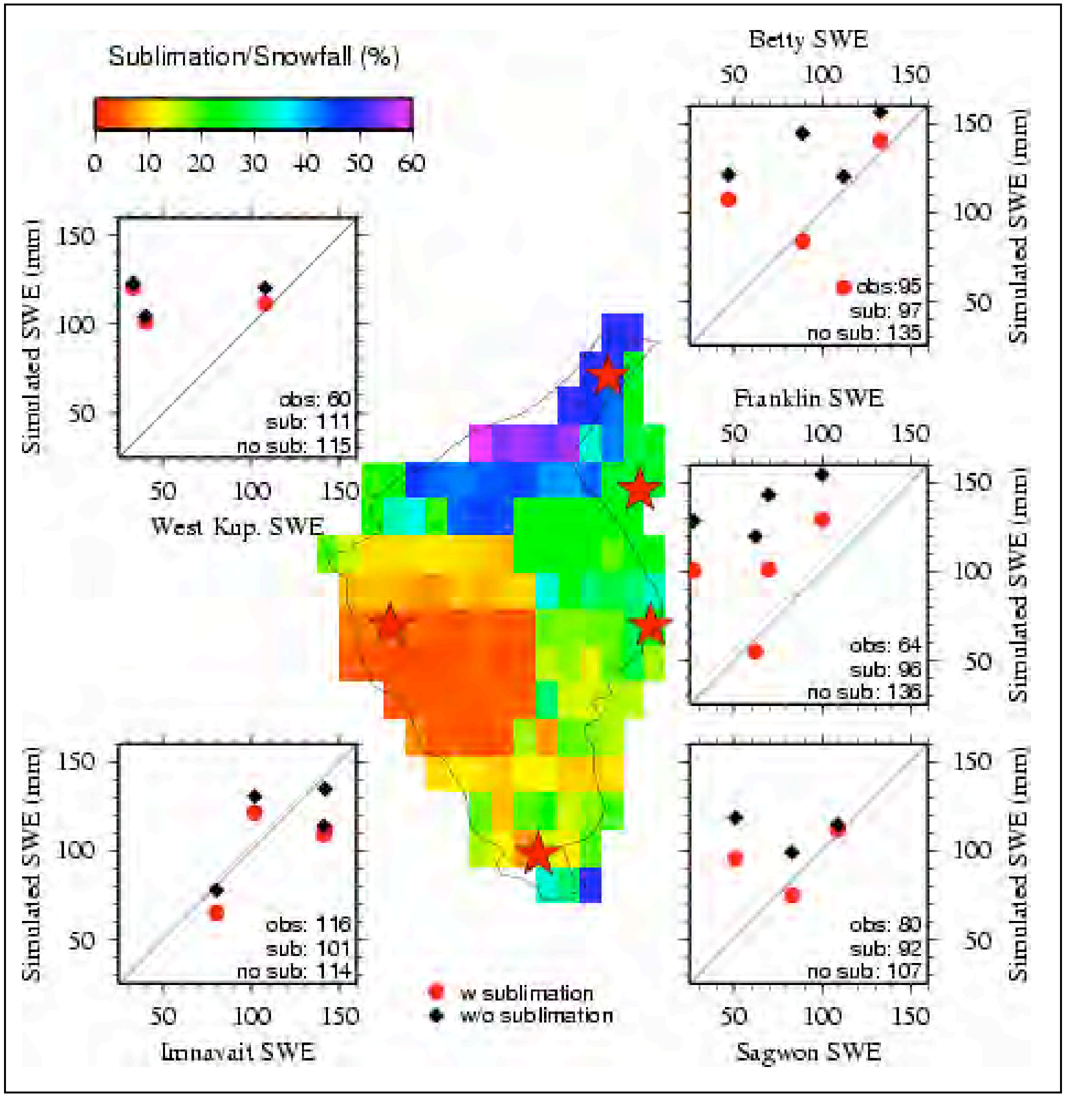
Increased northward atmospheric moisture transport	Nijssen et al. (2001), Wu et al. (2005), Arnel (2005)
Human effects (reservoir construction)	Yang et al. (2004), Ye et al. (2003), McClelland et al. (2004)
Release of water from permafrost degradation	Frauenfield et al. (2004), Zhang et al. (2003), Ye et al. (2003)
Climate-induced changes to the land surface (increased fire frequency)	McClelland et al. (2004), Conrad and Ivanova (1997)
Changes in lake areal extent and storage	Smith et al. (2005)
Change in evapotranspiration	Gedney et al. (2006)
Change in snow accumulation / ablation patterns	Brown (2000), Groisman et al. (1994), Robinson et al. (1990)

Snow (Re)Distribution

- Sublimation during blowing snow
  - Increase in winter latent heat
  - Decrease in snow available for melt

- Variable snow coverage
  - Variable melt water availability
  - Advection of sensible heat from bare areas

Sublimation from transported snow



What information is available and what is missing for energy and water cycle process modeling efforts, and the ways to address the gaps

"…energy and water cycle process not well understood"

- Permafrost processes (how to model at large scales)
- Surface runoff and baseflow in permafrost environments
- Lake/wetland extent at large scales
- Fire/land cover change effects
- Peatlands – significant in the NEESPI region
- Inertia of the system – some of the processes, such as permafrost dynamics, occur over large time scales that we may or may not be capturing in our modeling

We have made progress on process-based modeling:

-- Lake extent and processes
-- Blowing snow
--Active layer development
-- Water - Carbon cycle interactions

Extent of shallow Lakes and wetlands are highly variable over snow free season

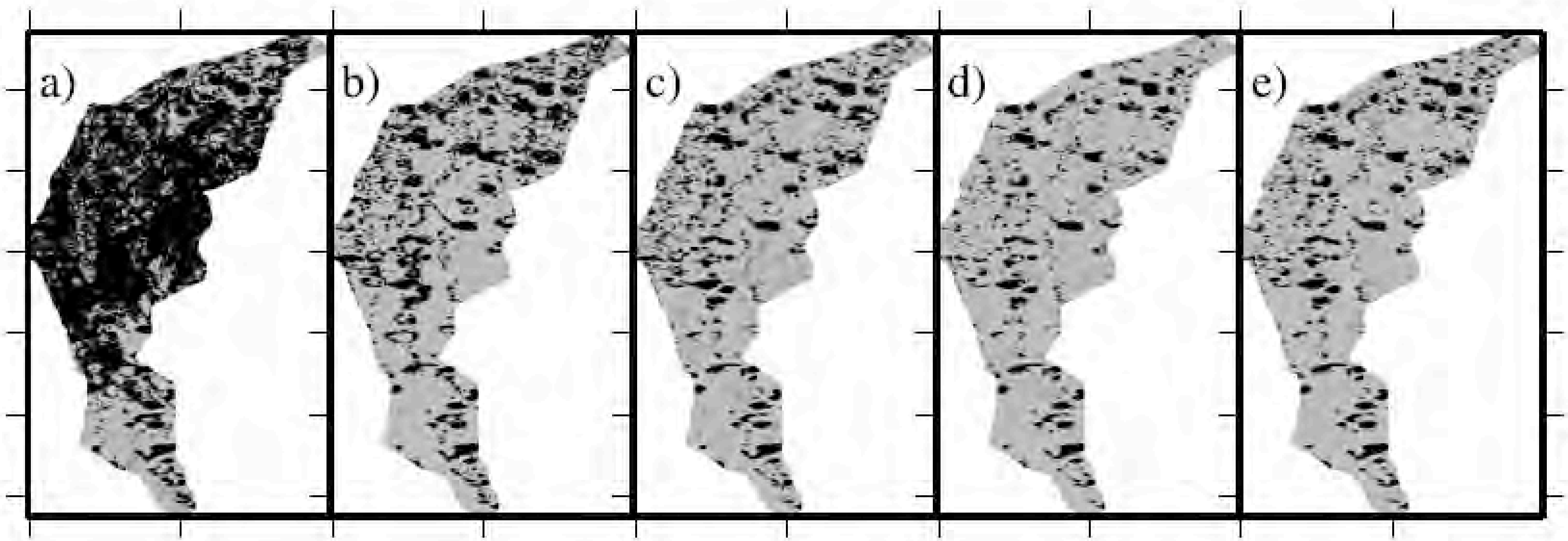
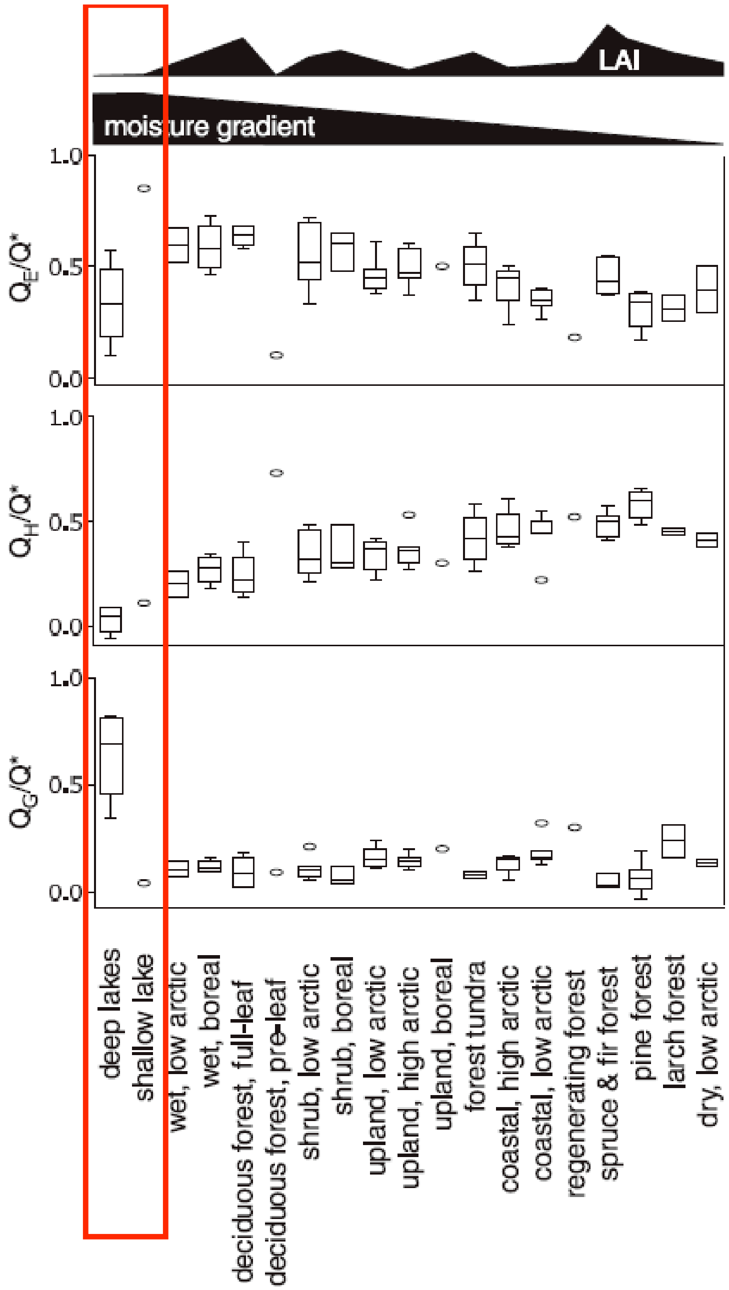


Figure 7. Change in saturated extent (solid areas) of the Putuligayuk River basin from classified SAR images: (a) 14 June 2000, (b) 21 June 2000, (c) 5 July 2000, (d) 22 July 2000, and (e) 7 September 2000.

Bowling, L. C., et al. (2003), The role of surface storage in a low-gradient Arctic watershed, *Water Resources Research*, *39*, -.

Shallow and Deep lakes very different



Evapotranspiration in Kuparuk Basin, AK
Eddy covariance measurements of H_2O flux between1994-1996 (note: data below may be from different years!)

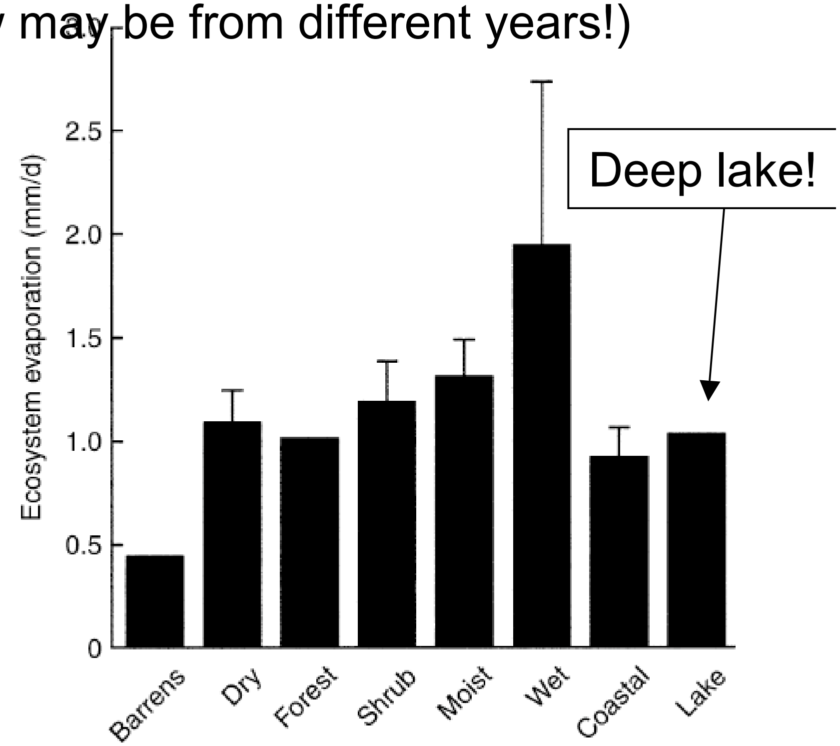
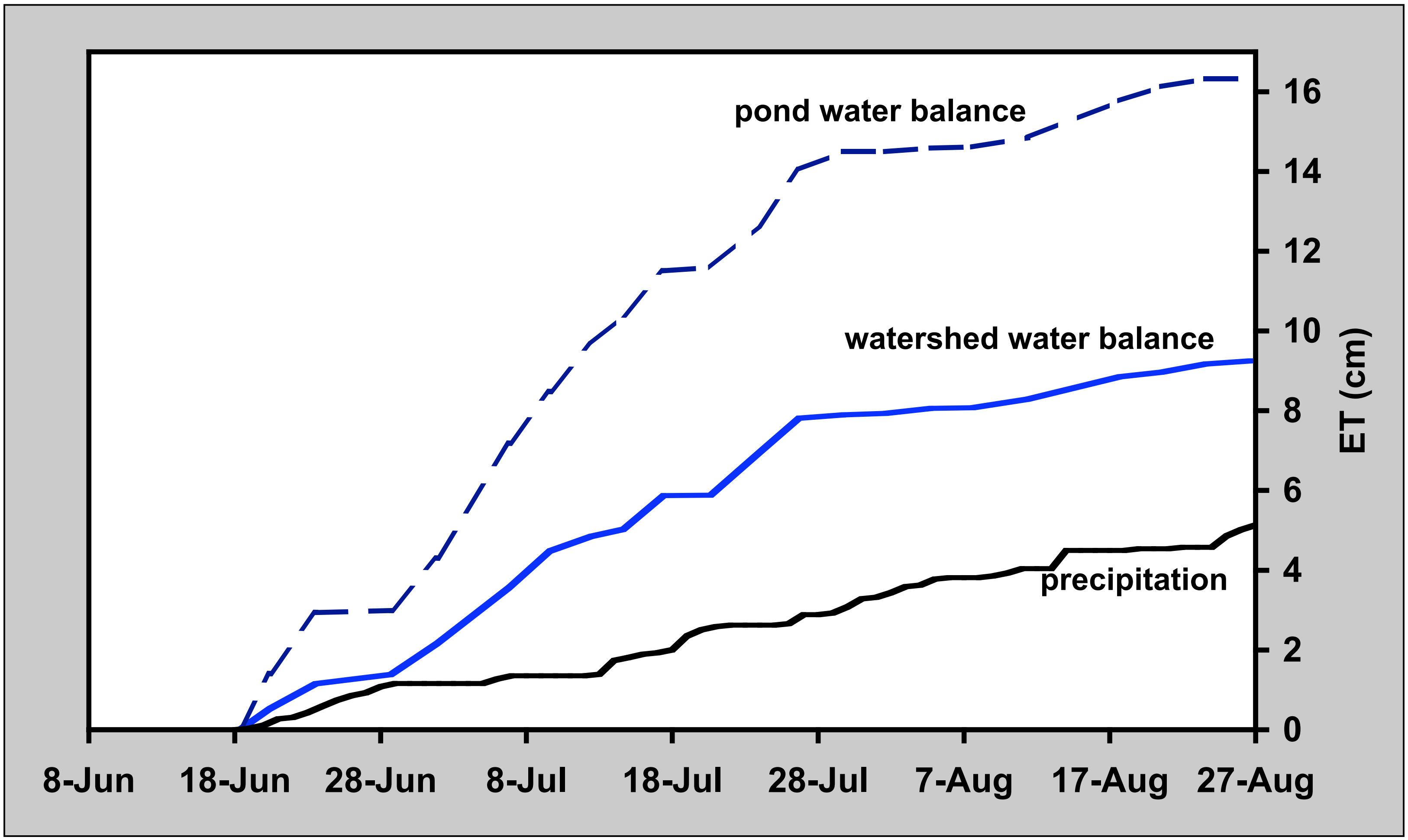


FIG. 7. Total ecosystem evaporation in seven arctic ecosystem types and a lake. Data are means, and error bars represent +1 SE.

McFadden, J. P., et al. (2003), A regional study of the controls on water vapor and CO2 exchange in arctic tundra, *Ecology*, *84*, 2762-2776.

Eugster, W., et al. (2000), Land-atmosphere energy exchange in Arctic tundra and boreal forest: available data and feedbacks to climate, *Global Change Biology*, *6*, 84-115.

Cumulative wetland complex evapotranspiration, Summer 1996



Lake dynamics

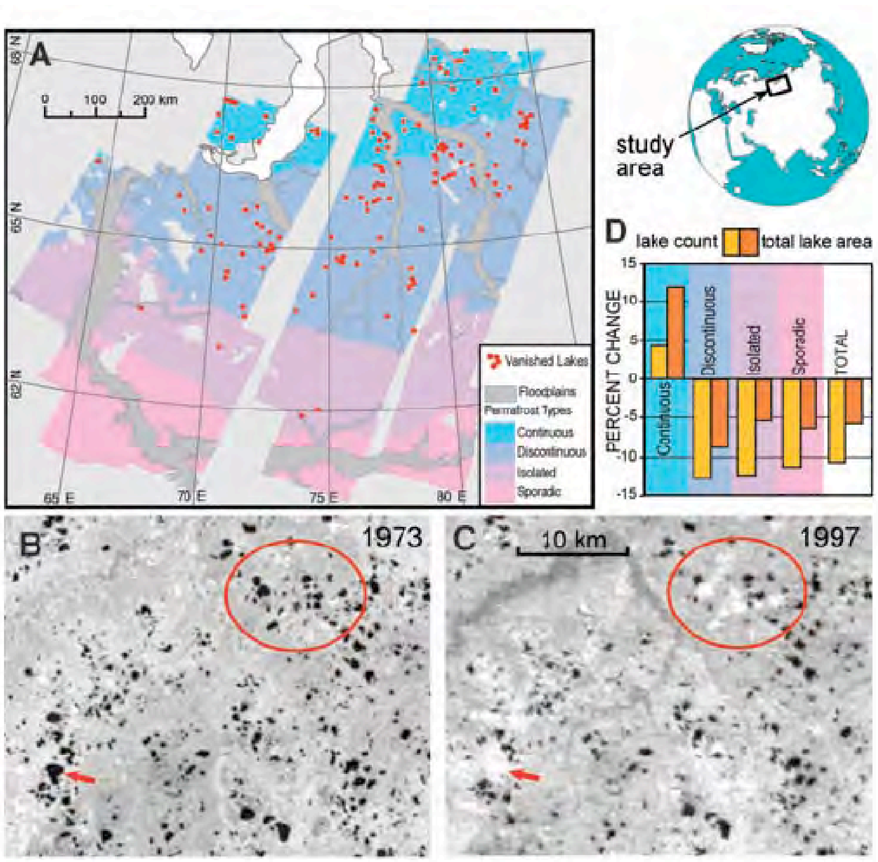
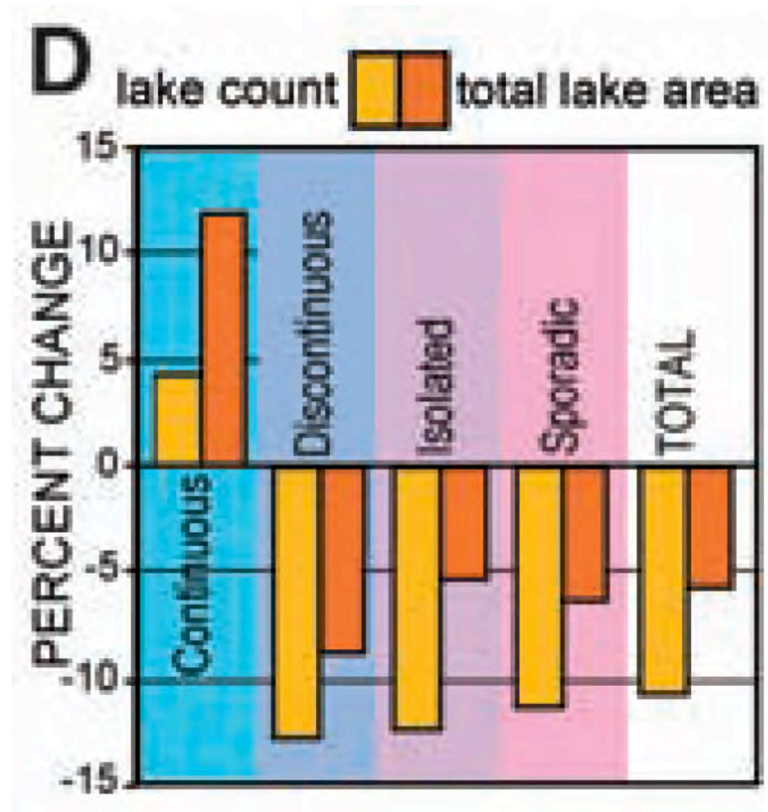
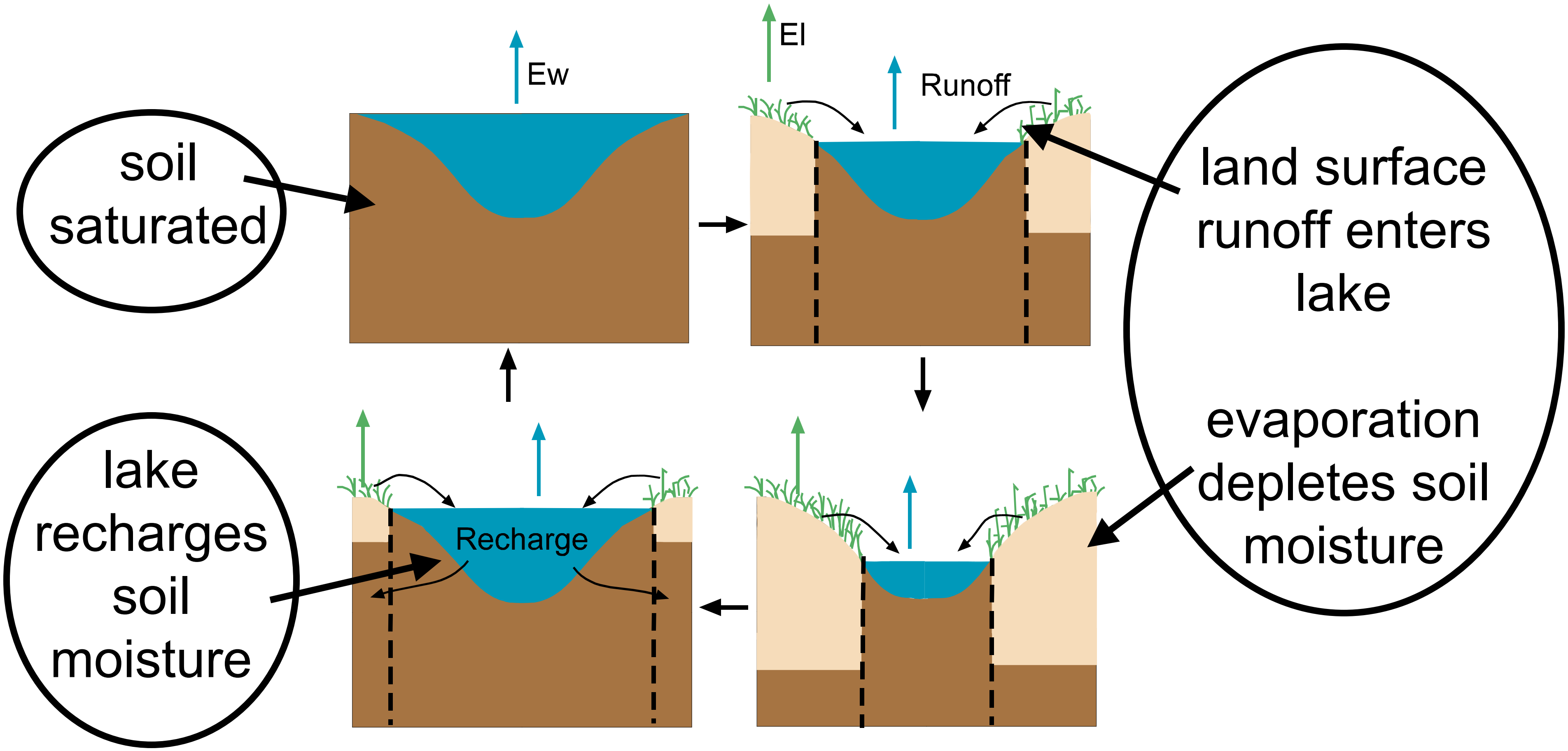


Fig. 1. (**A**) Locations of Siberian lake inventories, permafrost distribution, and vanished lakes. Total lake abundance and inundation area have declined since 1973 (**B**), including (**C**) permanent drainage and revegetation of former lakebeds (the arrow and oval show representative areas). (**D**) Net increases in lake abundance and area have occurred in continuous permafrost, suggesting an initial but transitory increase in surface ponding.



Smith, L. C., et al. (2005), Disappearing Arctic lakes, *Science*, *308*, 1429-1429.

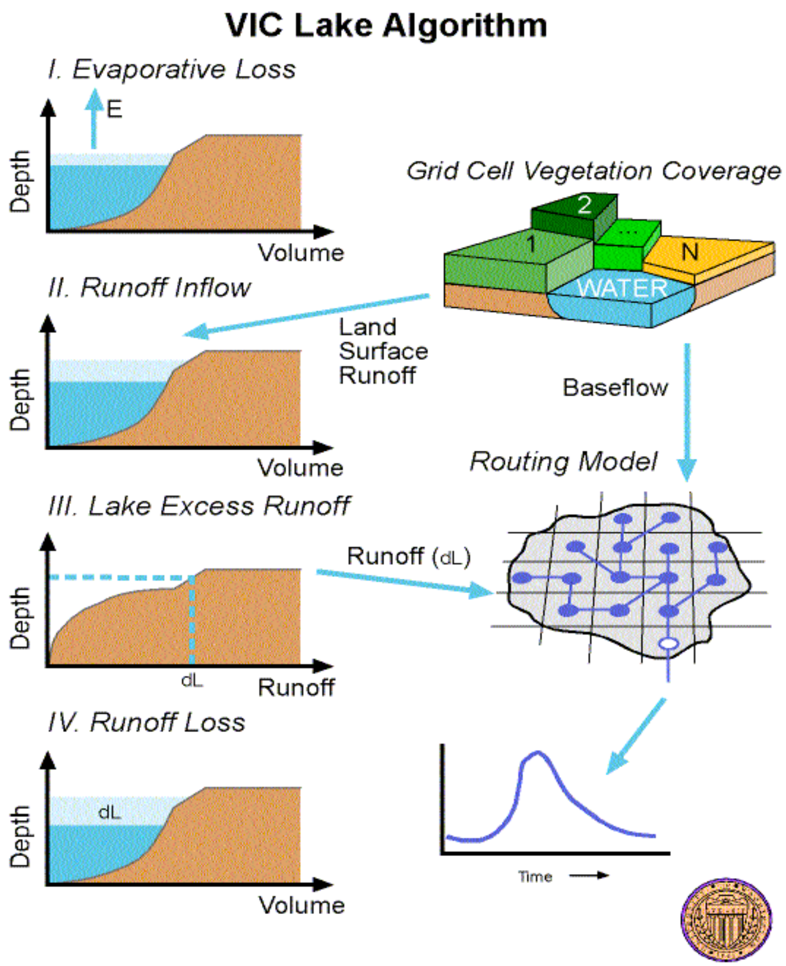
Lakes and wetland modeling (VIC Lake/Wetland Algorithm)

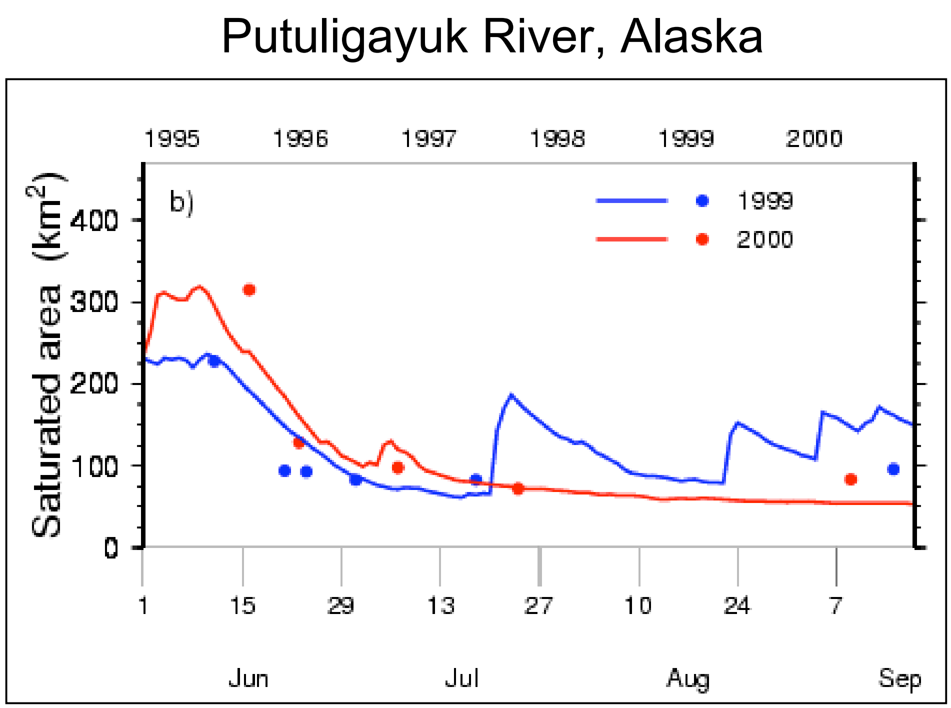


Lake drainage = f(water depth, calibration parameter)

(From T. Bohn, U. Washington)

Seasonal variation in surface water extent





Lake and wetland extent

- Problem:
  - Evaporation/carbon flux from shallow water lake and wetland systems is an important component of the energy balance/carbon cycle
  - Water extent is changing due both to ET changes and permafrost thaw, but direction of change depends on the permafrost dynamics
- Needs:
  - Spatial distribution of depth of permafrost
  - Ground ice content
  - Model algorithm development

How does peatland differ?

Model parameters describing the soil. The peat soil values are the median values found for fibric (little decomposed) and sapric (highly decomposed) peat found by Letts et al. (2000) in their literature review of parameter values, except heat capacity and heat conductivity that were calculated according to Williams and Smith (1989) and Campbell and Norman (1998). The values for the third and fourth soil layers represent coarse mineral soil texture and are taken from Table 2 in Cox et al. (1999).

peat

Mineral soil

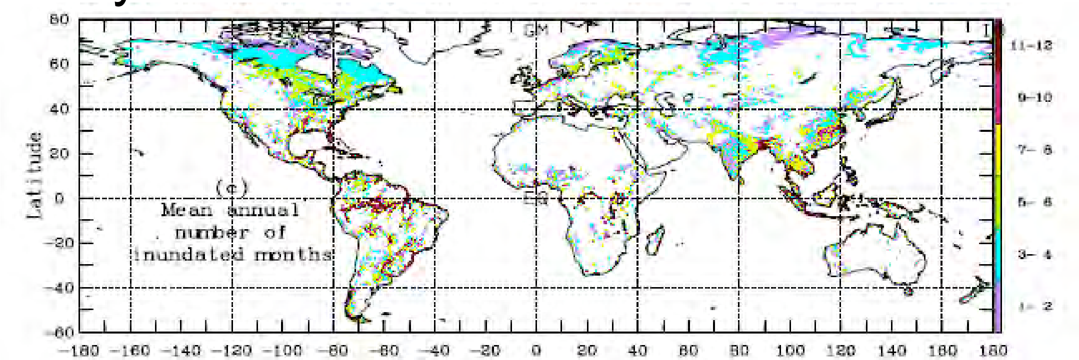
Parameter	Upper soil layer (peat)	Second soil layer (peat)	3rd and 4th soil layer (mineral soil)
Layer thickness	0.1 m	0.25 m	0.55 and 2 m, respectively
Saturated hydraulic conductivity	2.8×10^{-4} m s^{-1}	1.0×10^{-7} m s^{-1}	7.57×10^{-6} m s^{-1}
Saturated hydraulic suction	1.03×10^{-2} m	1.01×10^{-2} m	3.29×10^{-2} m
Clapp-Hornberger's *B* constant	2.7	12	4.5
Soil-moisture content at wilting point	0.04 m^3 m^{-3}	0.15 m^3 m^{-3}	0.06 m^3 m^{-3}
Soil-moisture content at critical point (field capacity)	0.24 m^3 m^{-3}	0.70 m^3 m^{-3}	0.15 m^3 m^{-3}
Soil-moisture content at saturation	0.90 m^3 m^{-3}	0.80 m^3 m^{-3}	0.40 m^3 m^{-3}
Dry-soil heat capacity	0.25×10^6 J m^{-3} K^{-1}	0.60×10^6 J m^{-3} K^{-1}	1.25×10^6 J m^{-3} K^{-1}
Dry-soil heat conductivity	0.03 W m^{-1} K^{-1}	0.04 W m^{-1} K^{-1}	0.272 W m^{-1} K^{-1}

	peat	peat	Mineral soil
Soil-moisture content at saturation	0.90 m^3 m^{-3}	0.80 m^3 m^{-3}	0.40 m^3 m^{-3}

Rennermalm, A. K., et al. (2005), Interannual variability in carbon dioxide exchange from a high arctic fen estimated by measurements and modeling, *Arctic Antarctic and Alpine Research*, *37*, 545-556.

How does peatlands alter the water and energy balance?

Wetland/peatlands in Northern Hemisphere Inundated 1-4 months a year



Prigent, C., et al. (2007), Global inundation dynamics inferred from multiple satellite observations, 1993-2000, *Journal of Geophysical Research-Atmospheres*, *112*, -.

Wetland/peatlands:
- Higher evapotranspiration

Fen = peatland

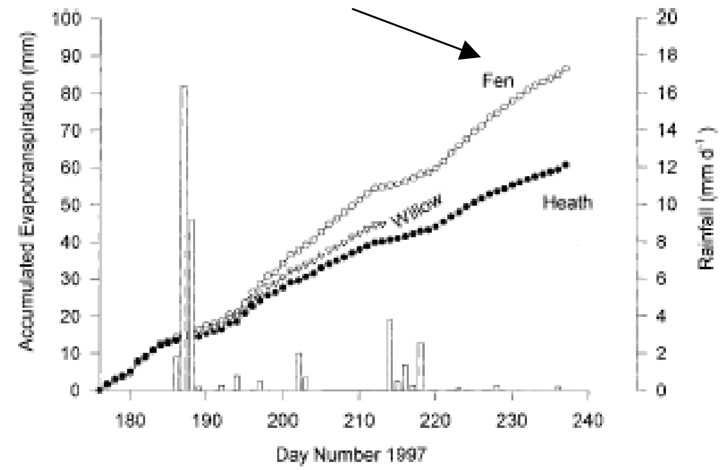


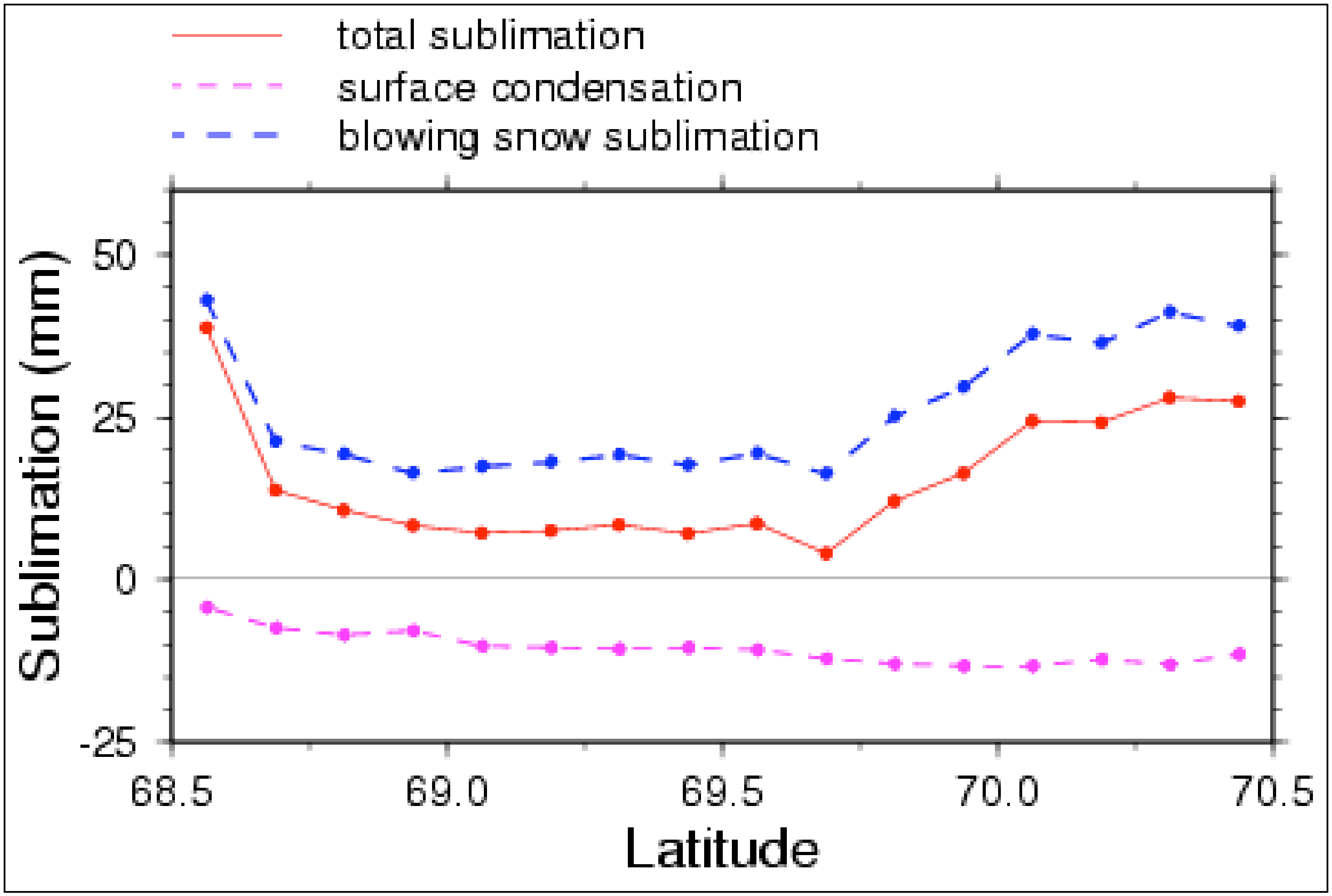
Fig. 4. Daily rainfall and accumulated evapotranspiration from three ecosystems throughout the 1997 growing season

Soegaard, H., et al. (2001), Surface energy- and water balance in a high-arctic environment in NE Greenland, *Theoretical and Applied Climatology*, *70*, 35-51.

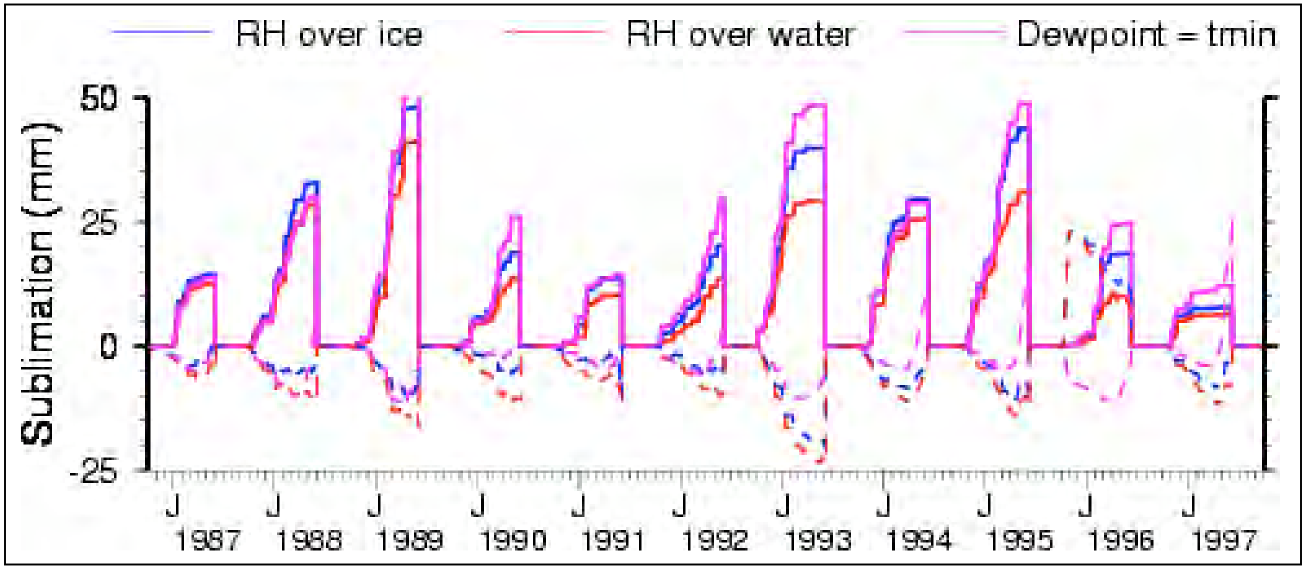
Vapor pressure uncertainty

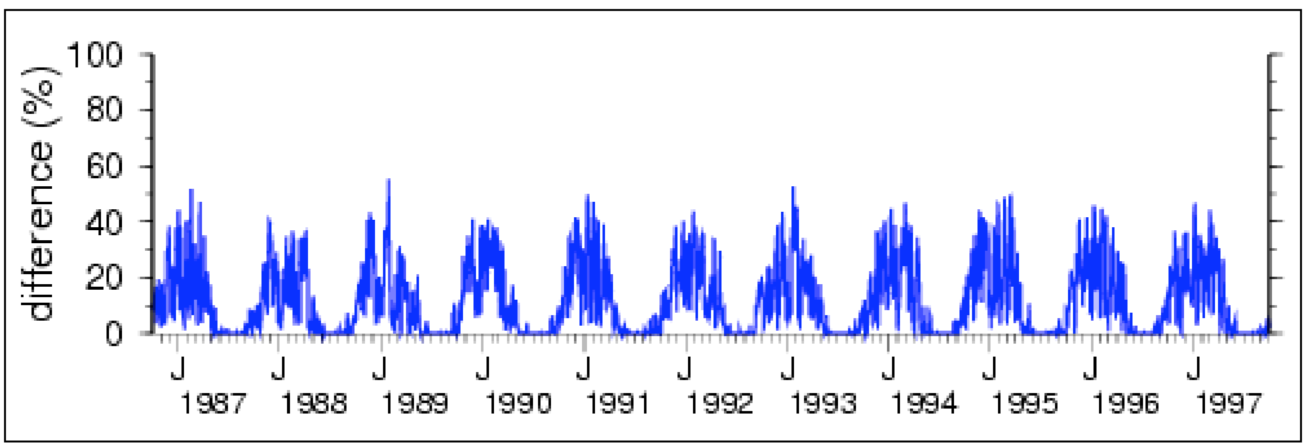
- Problem:
  - Extremely low winter temperatures in the arctic lead to low saturated vapor pressure values
  - Existing parameterizations (e.g. Tdew = daily Tmin) are not adequately tested in the arctic
  - In-situ observations are rare and uncertainty often exists whether the observations are taken assuming equilibrium with water or ice
- Implications:
  - Evaporation/sublimation may be limited by vapor pressure rather than water or energy
  - The direction of net over-winter vapor flux in unknown
- Needs:
  - Over-winter eddy covariance and humidity measurements?

Annual average sublimation
Kuparuk River



Sensitivity to vapor pressure





Average annual surface sublimation:

RH w.r.t. ice
-5.3 mm

RH w.r.t water
-9.2 mm

Tdew = Tmin
+6.6 mm

“What’s missing..” New Directions and Research Needs

1) Data -

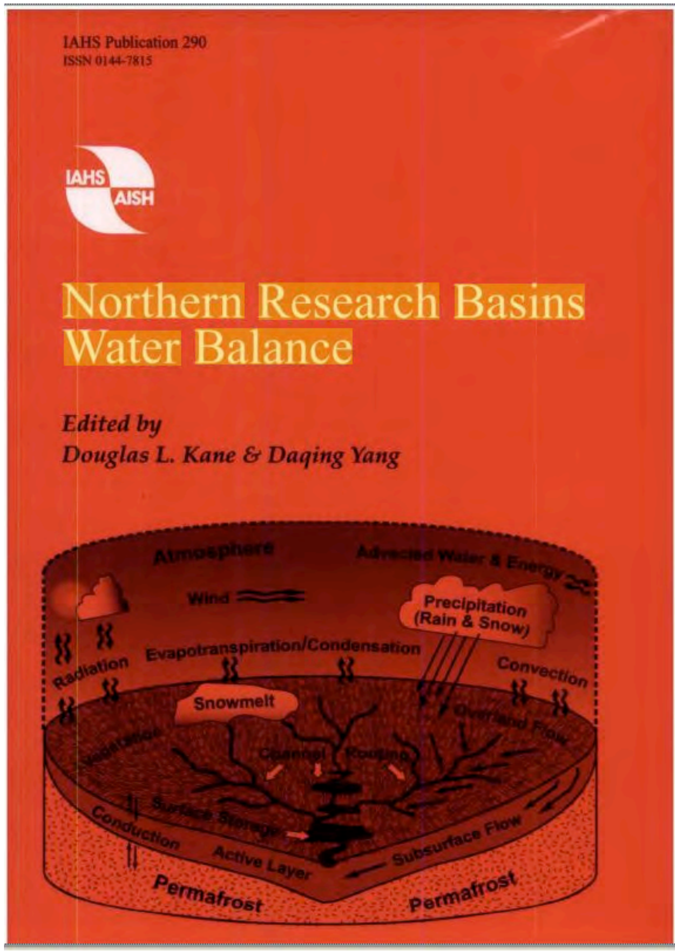
Primary need is to assemble a best quality retrospective precipitation data set, duration at least one decade, with best current attempts at gauge catch correction.

What is the potential of remote sensing to supplement the sparse in situ observation network?

2) Modeling

- We tend to focus on an entire basin. Process and validation tends to be at ‘experimental basin scale. Issues of process scaling
- Continue improving and testing process representations
  - Energy balance - - snow, ET
  - Subgrid snow distribution, partial coverage, sublimation from blowing snow
  - Frozen soils and permafrost
  - Lake and wetland storage, and linkages to the carbon cycle.
- Incorporate data assimilation approaches in off-line modeling?

“What’s missing..”
New Directions and Research Needs



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Thank you