

# Land Surface Modeling Hydrologic Modeling for the NEESPI domain: Developments, Challenges and Solutions

Eric F. Wood (PU)

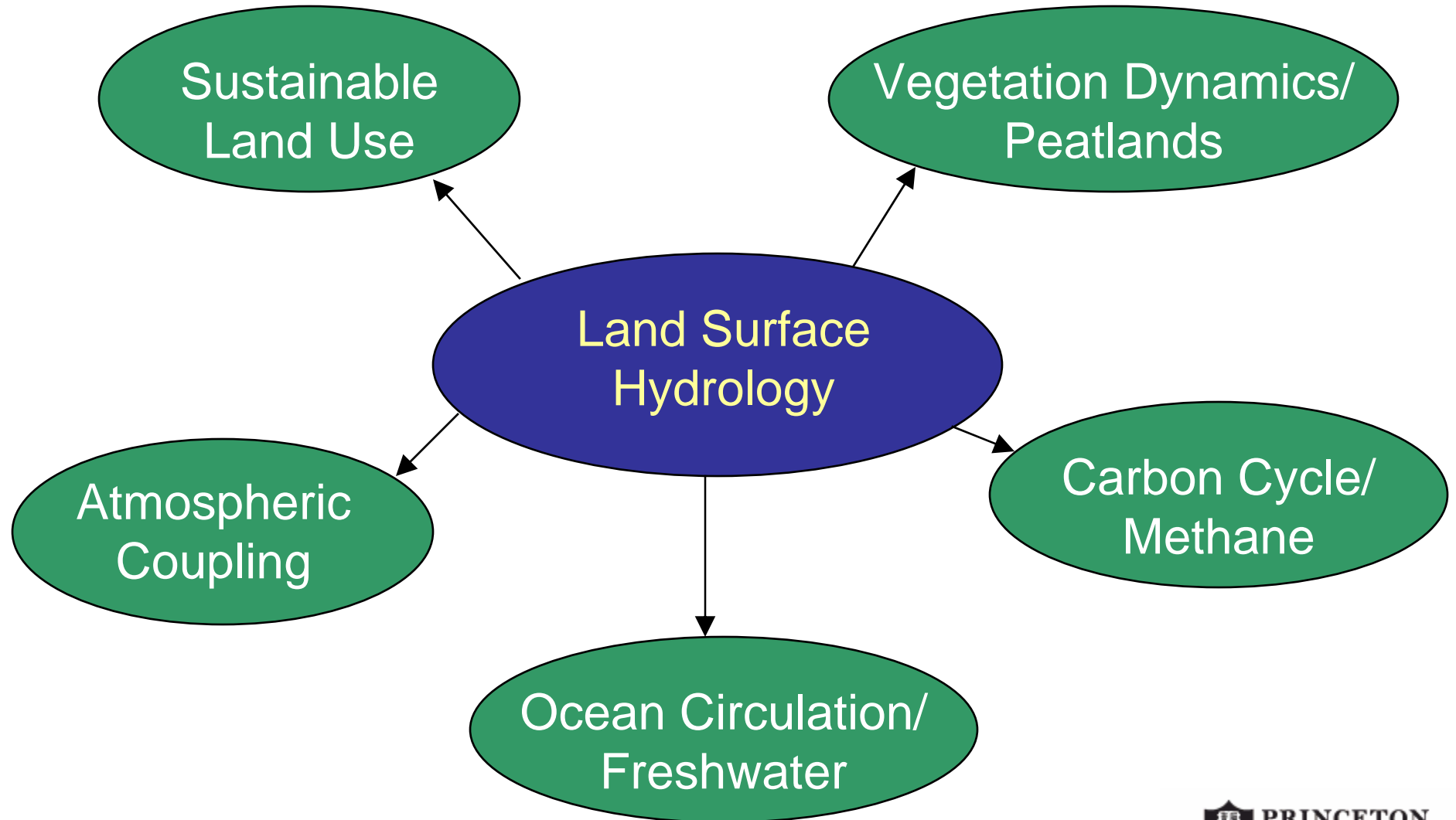
With

Tara Troy (PU), Laura Bowling (Perdue),  
Ted Bohn (UW) and Dennis Lettenmaier (UW)

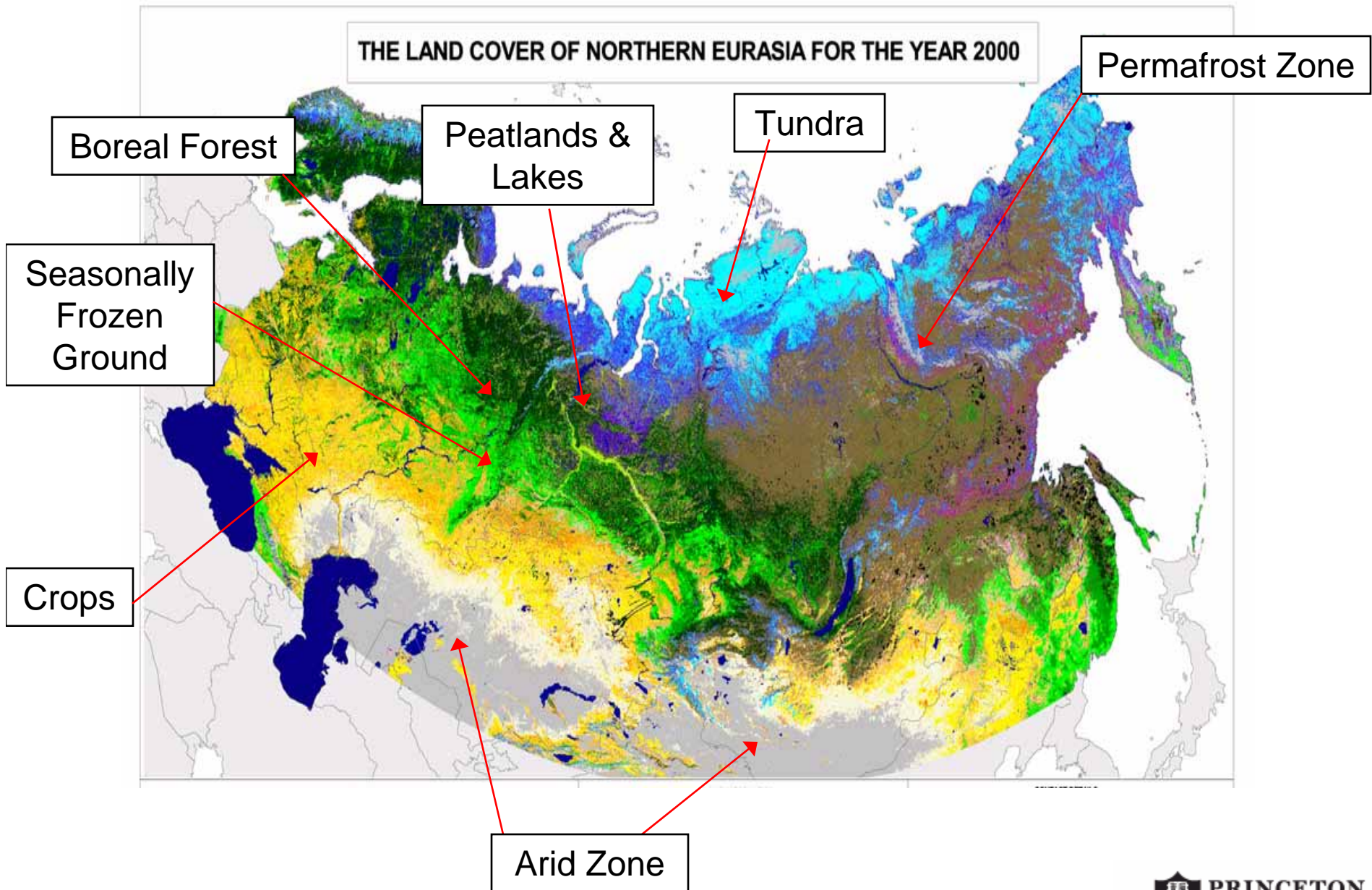
NEESPI Science Team Meeting  
Helsinki, Finland  
June 2-6, 2008



# Hydrology is central to our understanding of the earth system

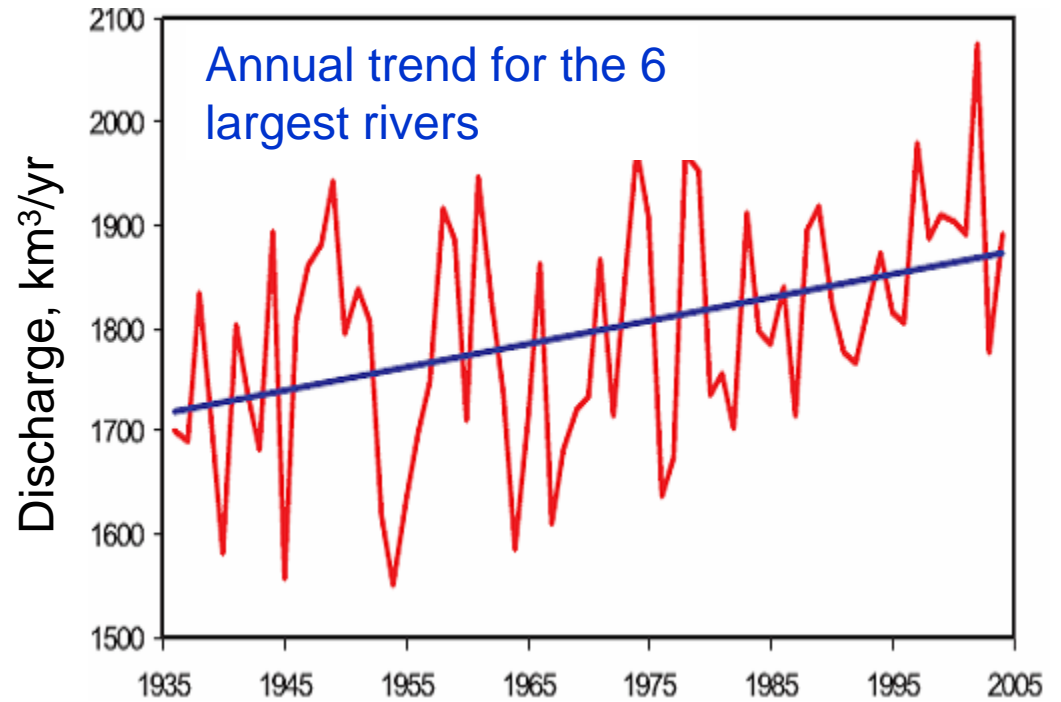


THE LAND COVER OF NORTHERN EURASIA FOR THE YEAR 2000

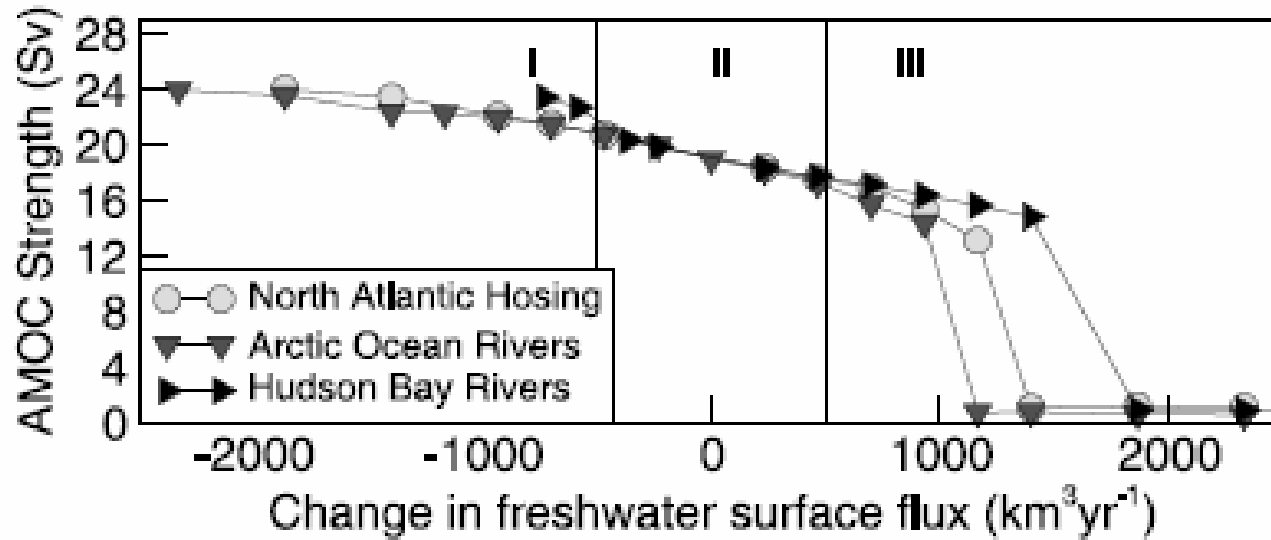


*Bartalev et al. 2003*

# Streamflow Trends & Global Effects



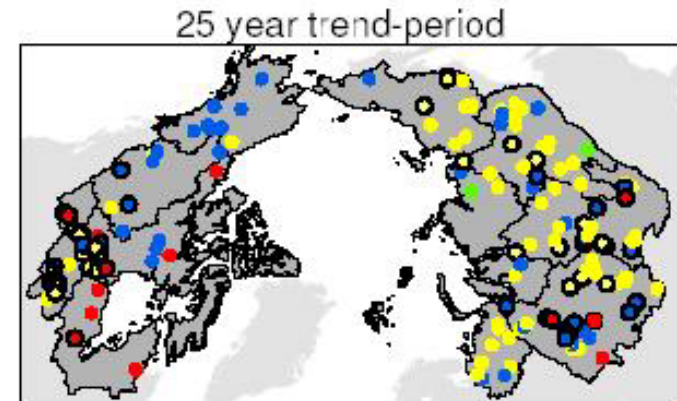
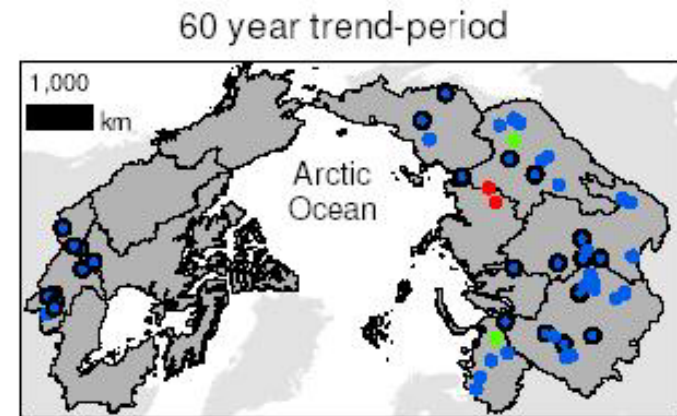
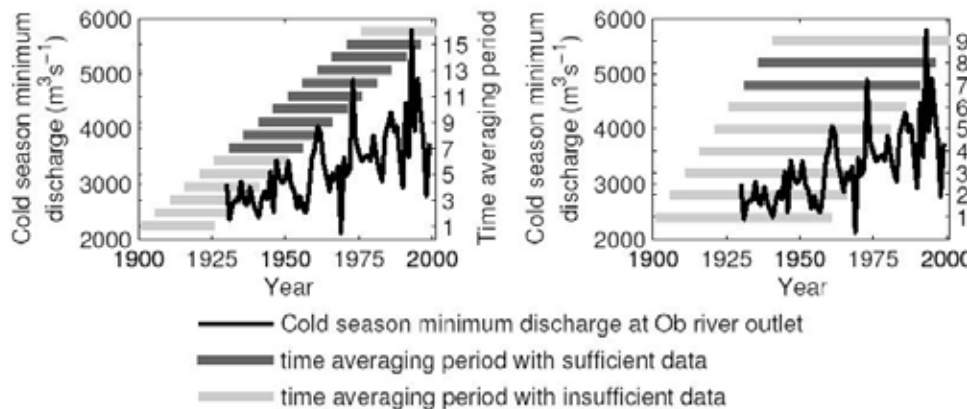
*Peterson et al. 2002, Science*



*Rennermalm et al. 2006*

# Trends in Cold Season Low Flows

- Cold-season low flows are increasing across Northern Eurasia at large time scales (60 years) with conflicting results over smaller trend periods.
- Consistent trends between natural and managed basins
- Ob River shows pronounced increases in low flows



# Extents of lakes and peatlands are changing

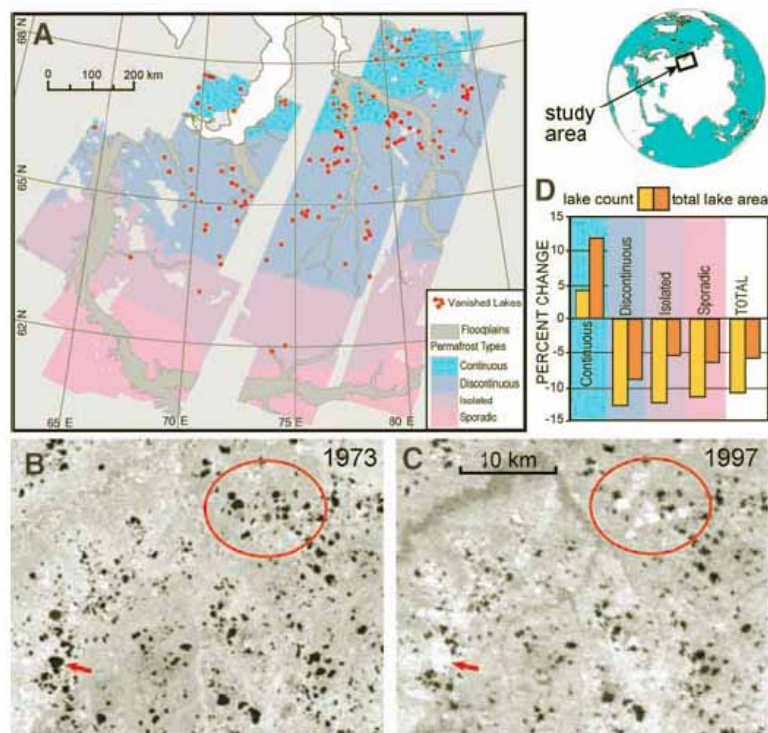


Fig. 1. (A) Locations of Siberian lake inventories, permafrost distribution, and vanished lakes. Total lake abundance and inundation area have declined since 1973 (B), including (C) permanent drainage and revegetation of former lakebeds (the arrow and oval show representative areas). (D) Net increases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

## Continuous Permafrost

- Melt of near surface ground ice leads to thermokarst and ground subsidence
- Surface depressions fill with water

## Discontinuous Permafrost

- Sub-lake talik formation breaches the thinner permafrost
- Lakes develop subsurface outlet and decrease in extent

# Conflicting Explanations for Discharge Trends

Increased northward atmospheric moisture transport	Nijssen et al. (2001), Wu et al. (2005), McClelland et al. (2004)
Human effects (reservoir construction)	Yang et al. (2004), Ye et al. (2003), Adam et al. (2008)
Release of water from permafrost degradation	Frauenfeld 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)

# Modeling terrestrial hydrology: the basic water budget equation

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

Soil moisture,  
Drainage,  
Baseflow

Lakes,  
Rivers.  
Snowpack

River discharge  
Groundwater fluxes

Evapotranspiration

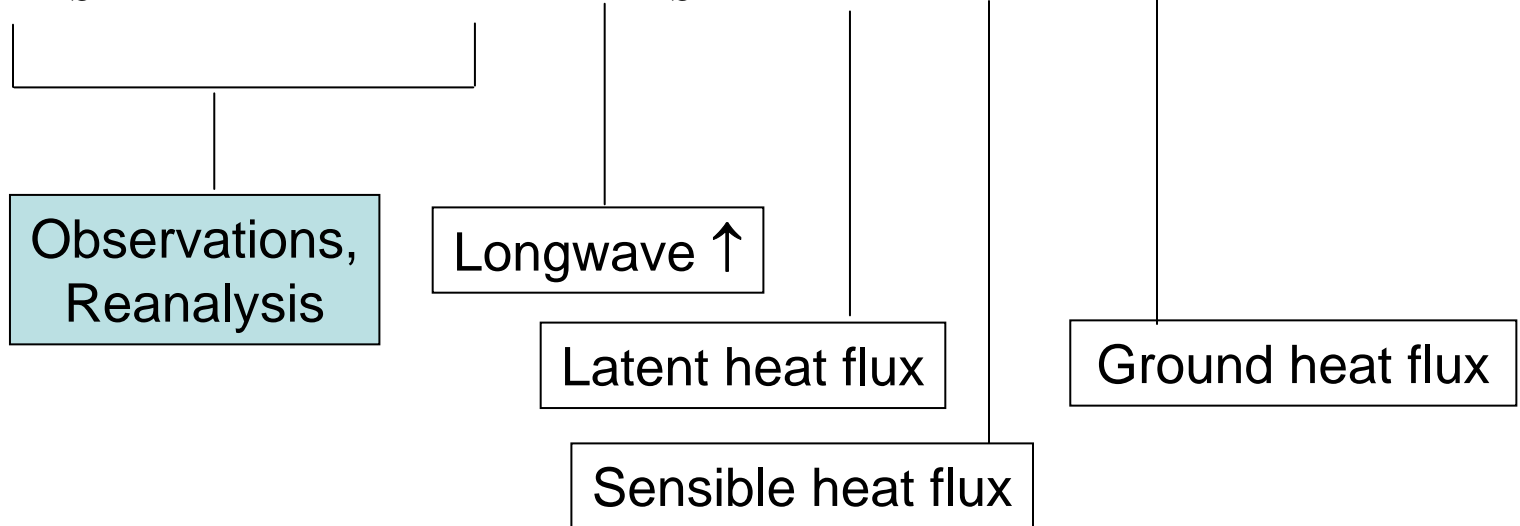
Observations

Observed,  
Reanalysis

Parameterized

# Modeling terrestrial hydrology: the basic energy budget equation

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



Observations

Parameterized

# A terrestrial hydrology observation-modeling strategy

Development of a coupled water-energy, hydrologically-based SVAT that is developed at small scales, and applied and validated across a range of scales.

<b>Modeling/ observations</b>	<b>Scale (sq. km)</b>	<b>Research focus</b>	<b>Research Objective</b>	<b>Data set/ experiment</b>
<b>Small Scale</b>	$10^2$ - $10^3$	<b>Process modeling</b>	<b>Land-atmospheric processes and interactions</b>	<b>BOREAS Tower Data, Small basins</b>
<b>Medium Scale</b>	$10^4$ - $10^5$	<b>Coupled models</b> <b>Remote sensing</b>	<b>Scaling</b> <b>Test Algorithms</b>	<b>BOREAS region, medium-scale basins</b>
<b>Large scale</b>	$10^5$ - $10^6$	<b>Budget analysis</b>	<b>Continental scale variability</b>	<b>Princeton 50-yr Forcing data</b>

# Data Needs for Land Surface Modeling

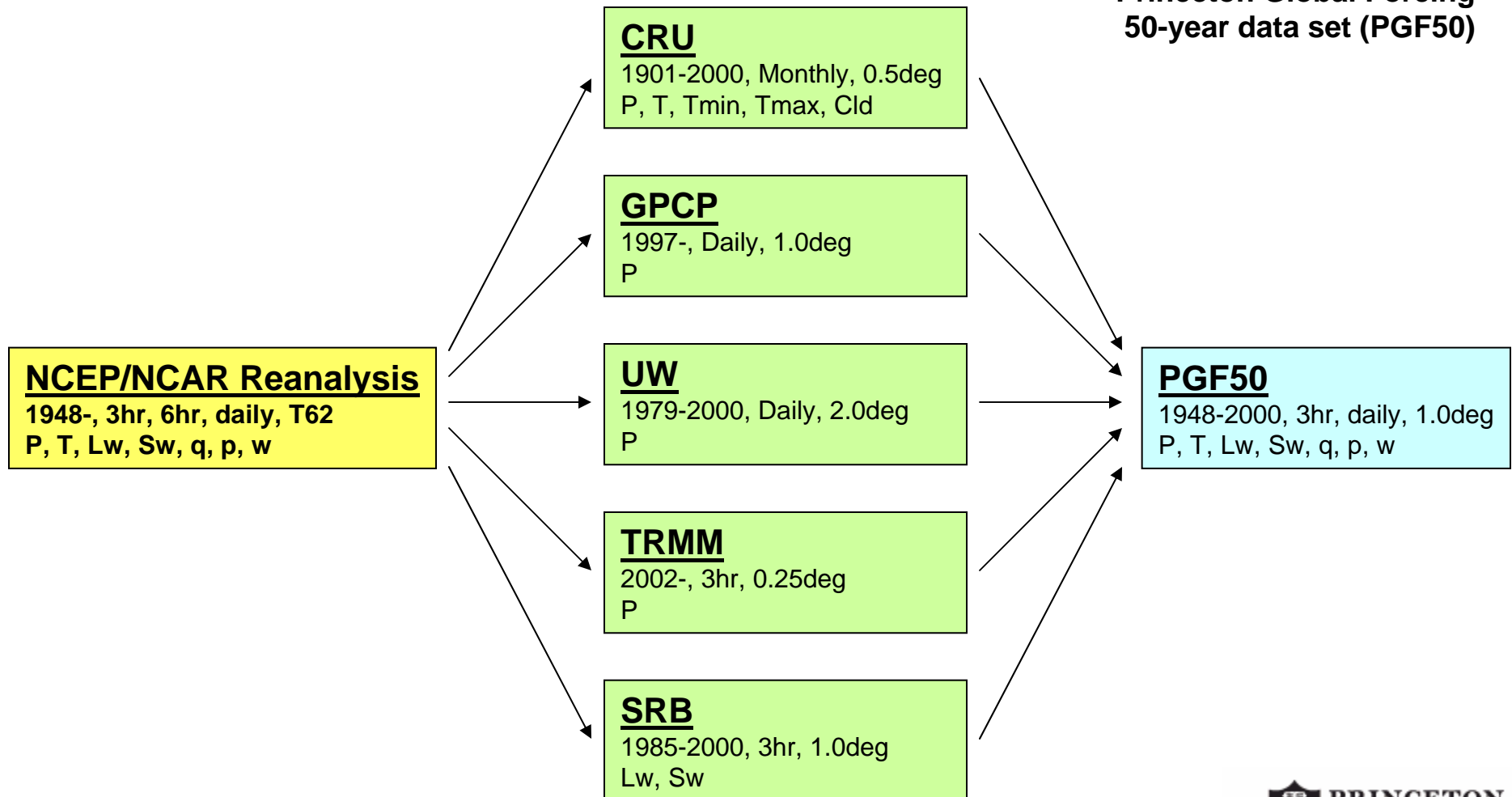
- **Forcing data**
  - Surface meteorology & radiation
- **Input data for process parameterizations**
  - Land cover and vegetation properties
  - Soil data (hydraulic and thermal properties)
  - Topography
- **Validation data**
  - River discharge, snow cover extent, snow water equivalence, lake area/levels, soil moisture, water table depth, soil temperature, evapotranspiration measurements, active layer depth

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

**Reanalysis**  
High temporal/low  
spatial resolution

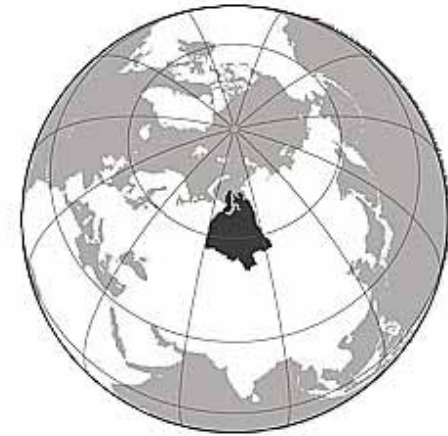
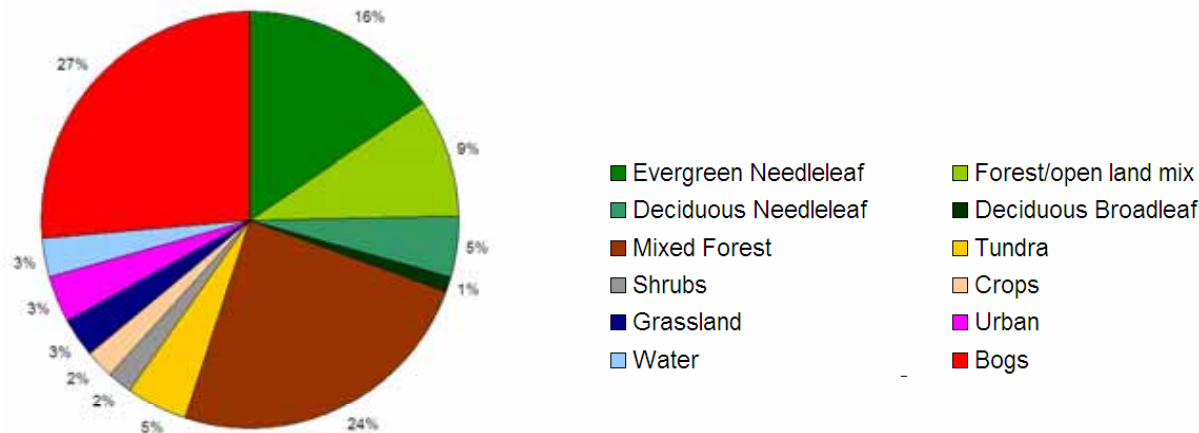
**Observations**  
Generally low temporal/high  
spatial resolution

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



# Do land cover products have sufficient accuracy?

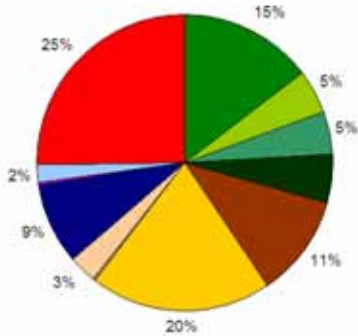
Observations  
Frey et al. (2007)



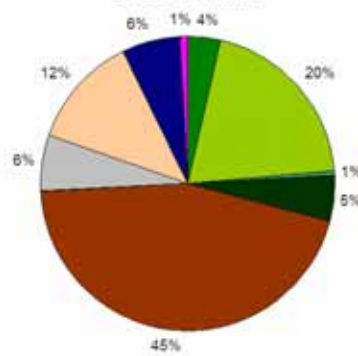
Source: Frey et al., 2007

Remote Sensing Products

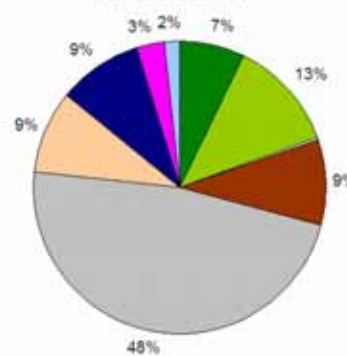
Bartalev et al. (2003)



GLCC-AVHRR

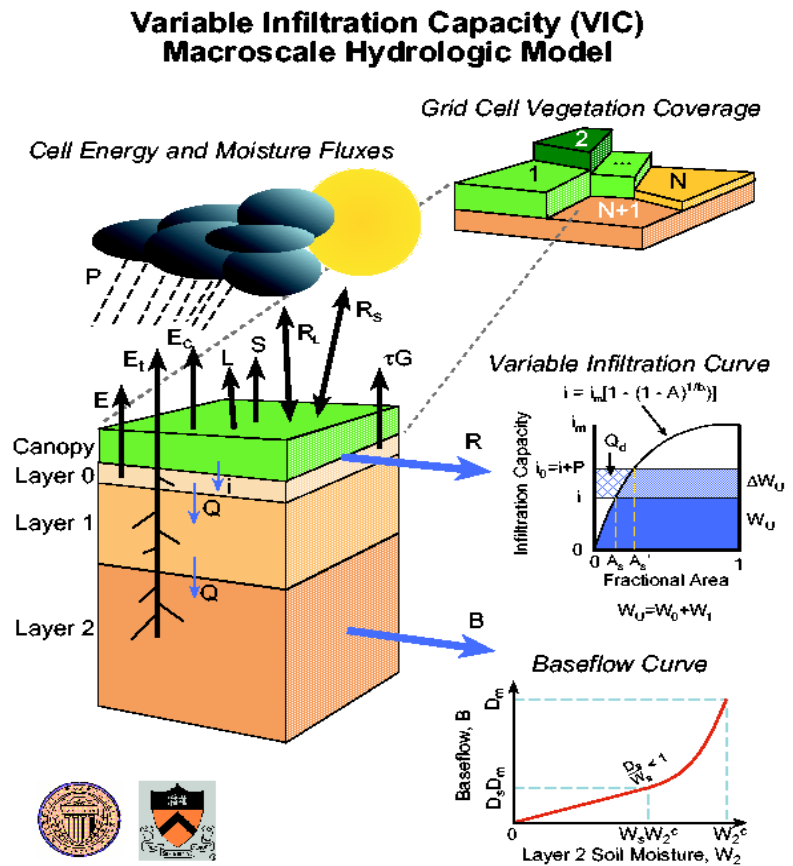


GLCC-MODIS

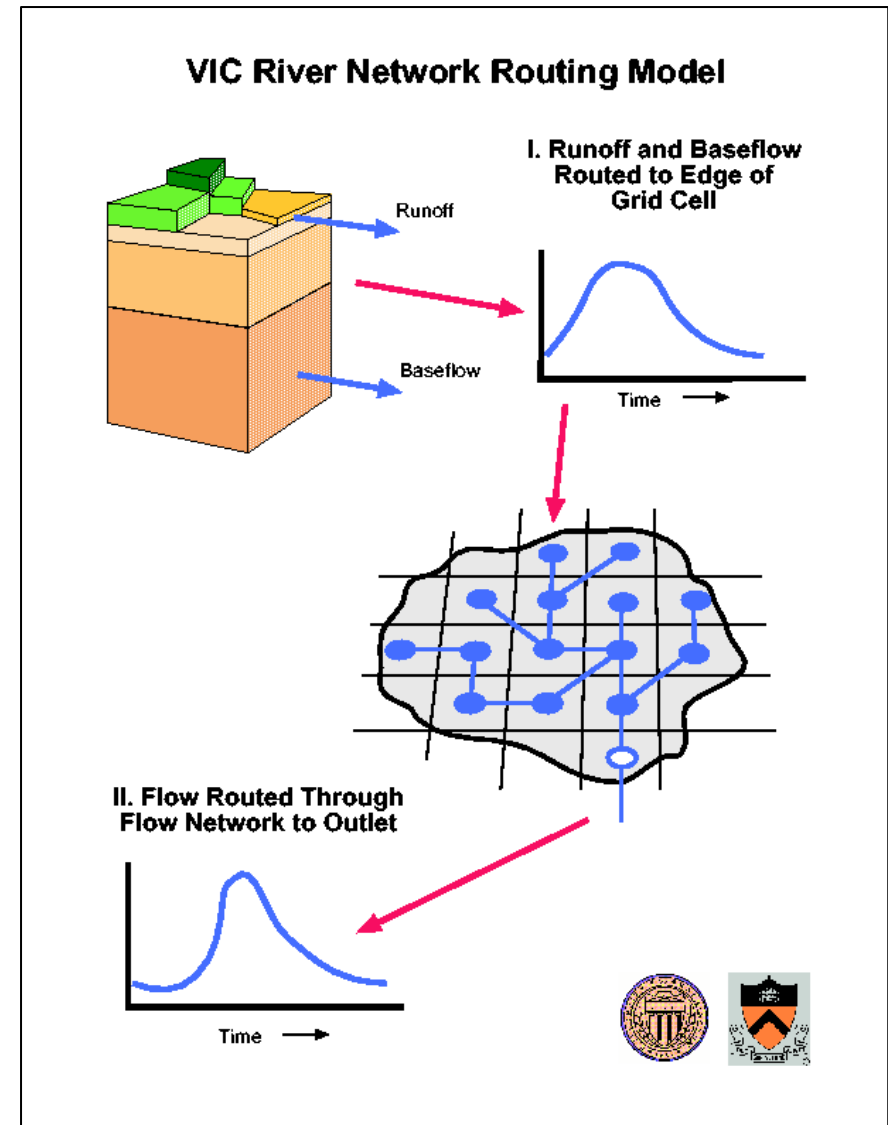
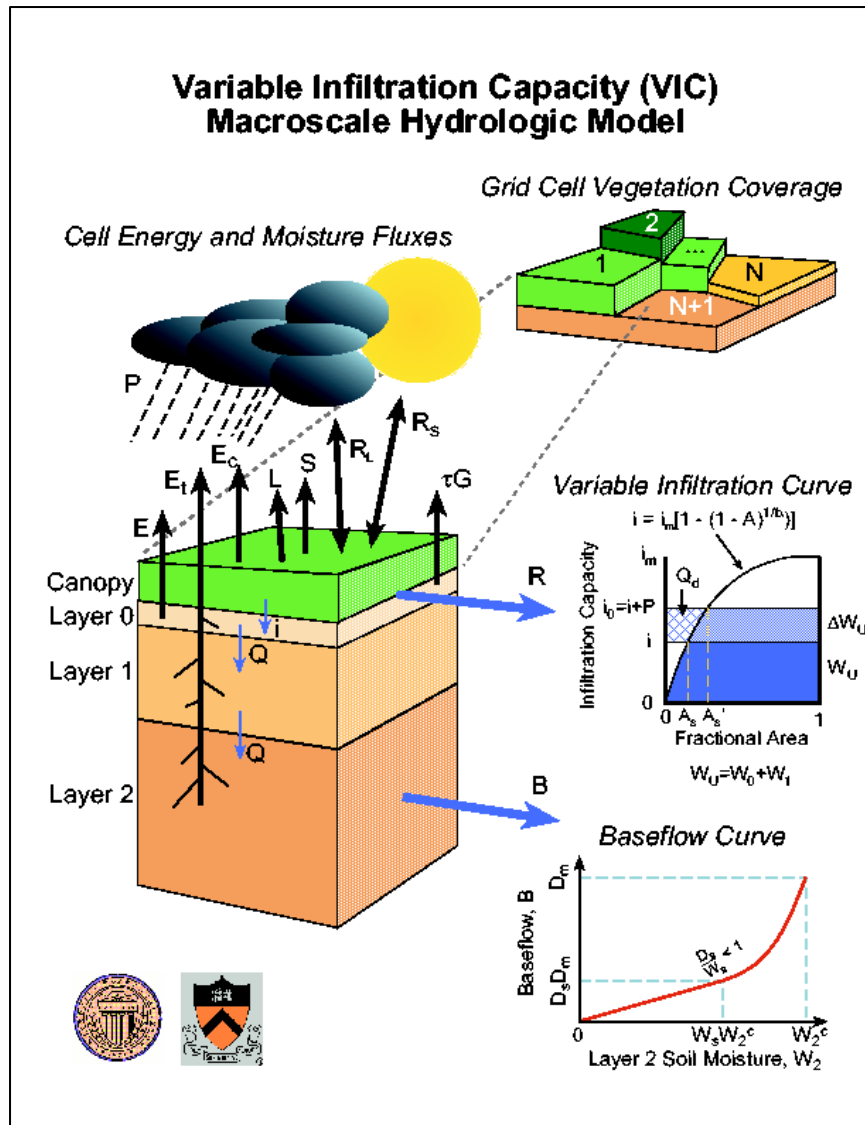


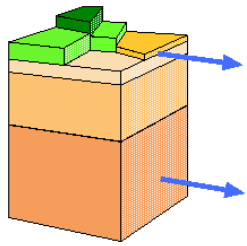
# Typical Land Surface Modeling Framework

- 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

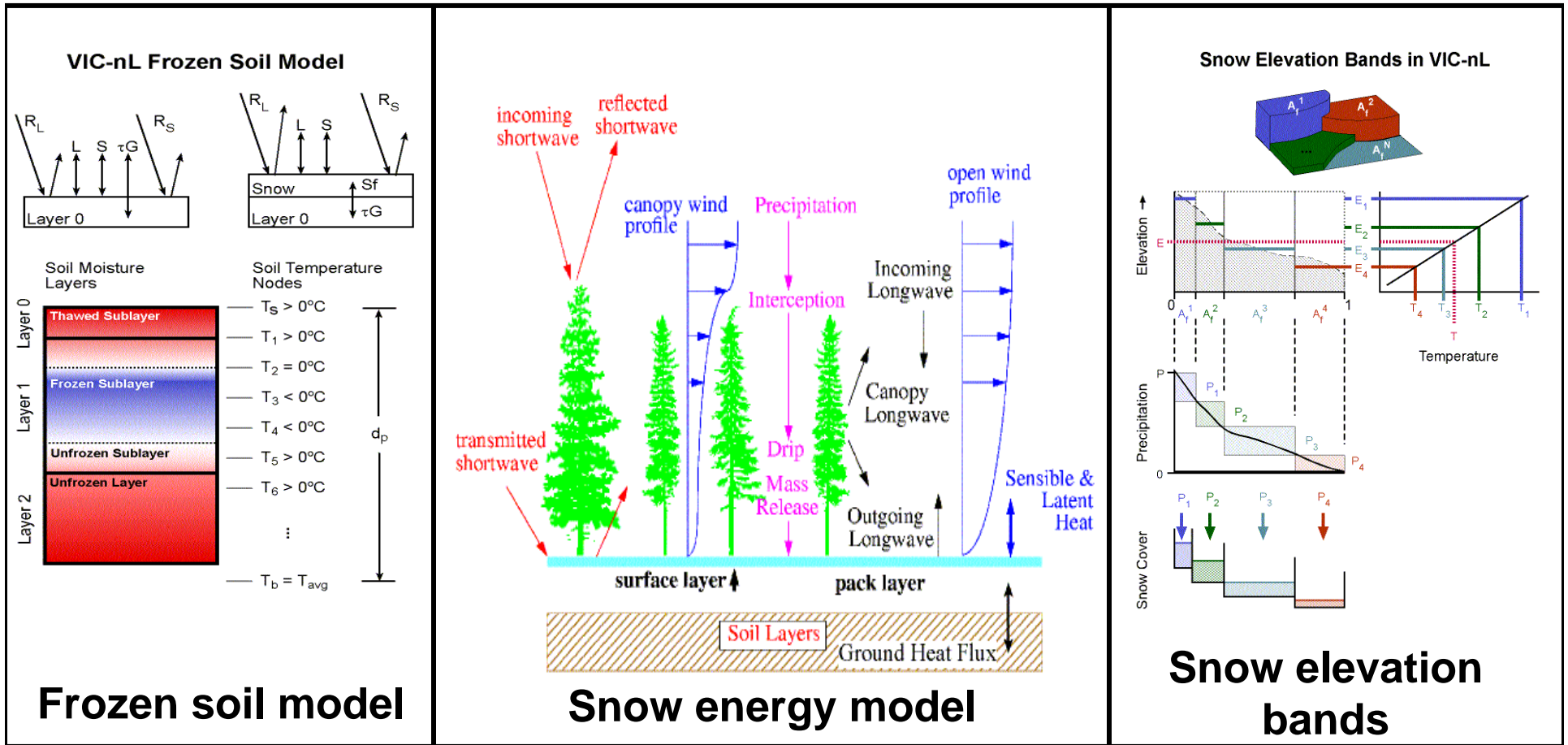


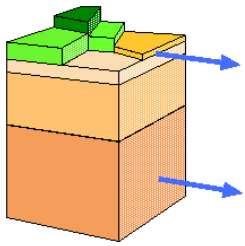
# Variable Infiltration Capacity (VIC) Model





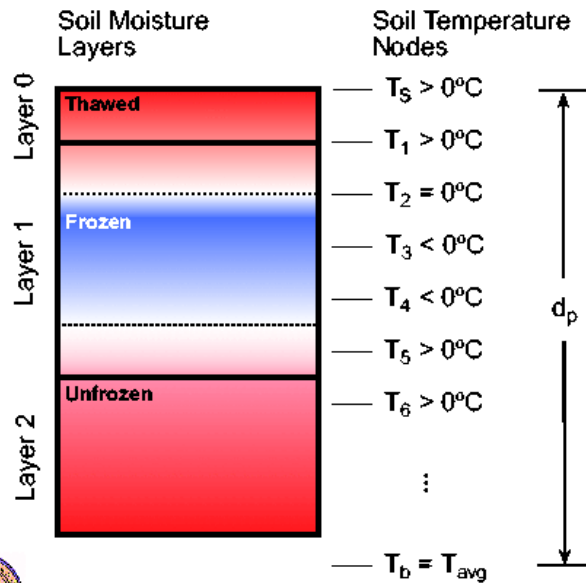
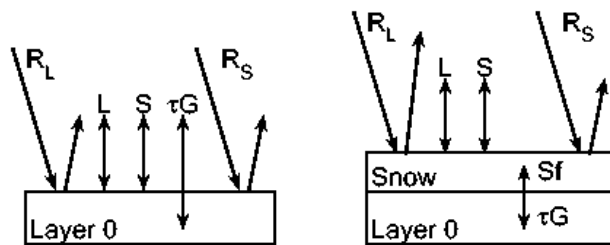
# VIC Cold Season Processes



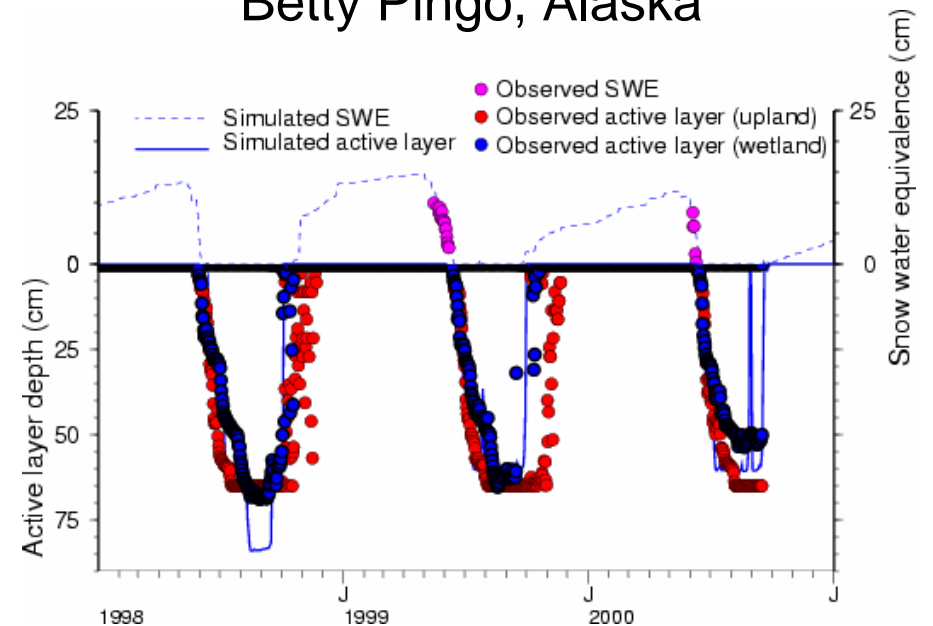


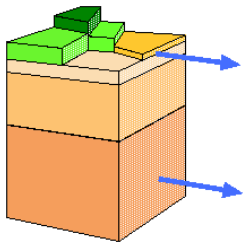
# Frozen Soil Modeling

## VIC Frozen Soil Algorithm

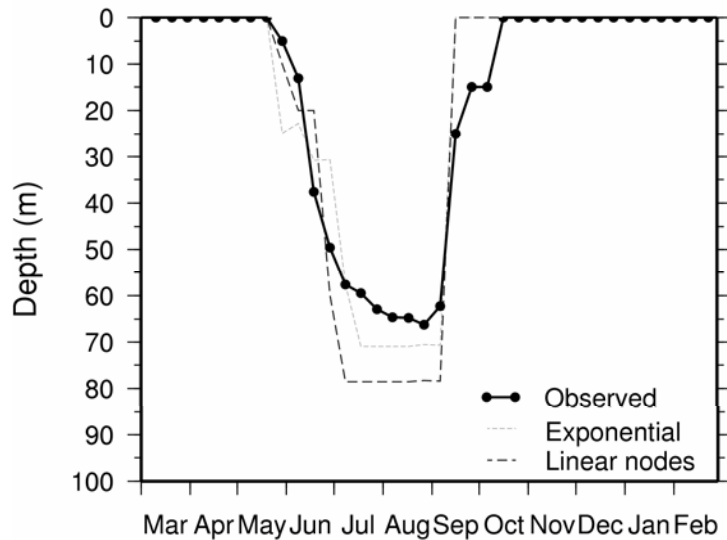
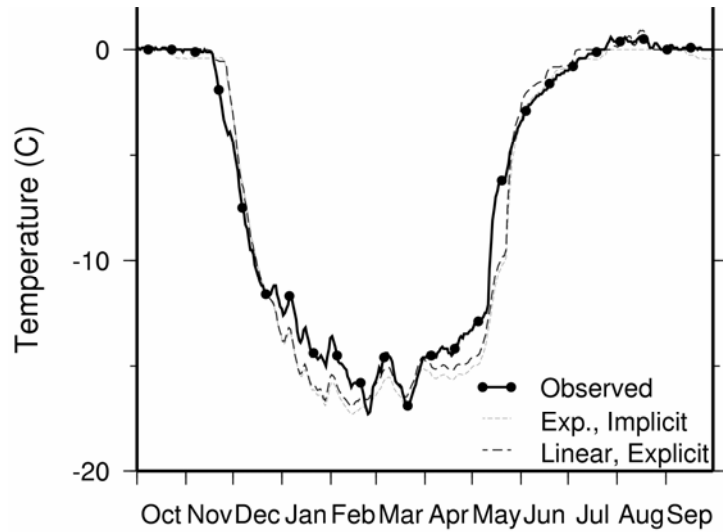


## Betty Pingo, Alaska



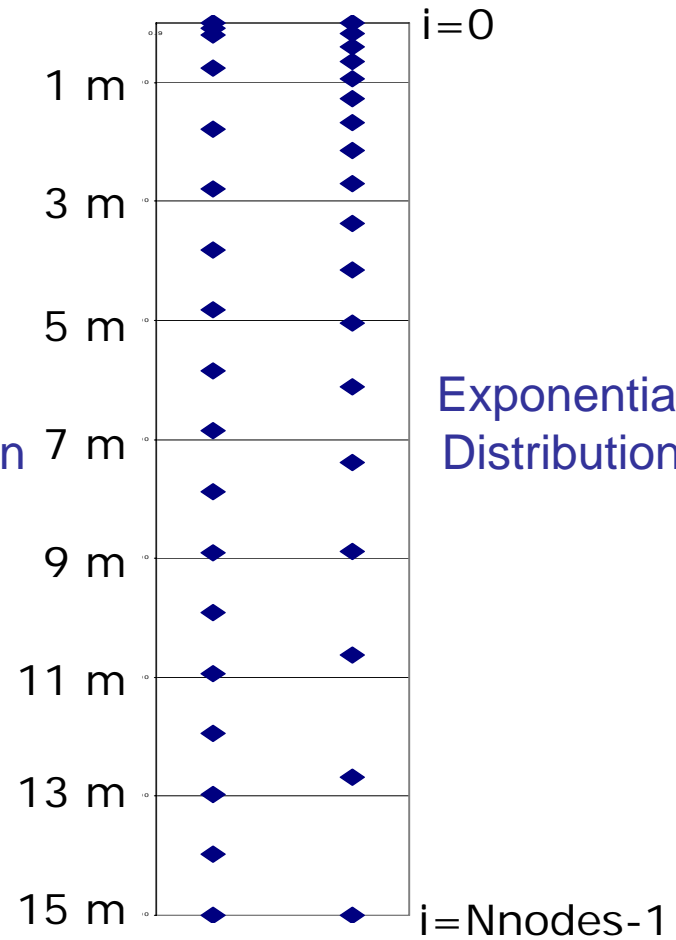


# Frozen Soils Improvements



Linear  
Distribution

Exponential  
Distribution



# Snow (Re)Distribution

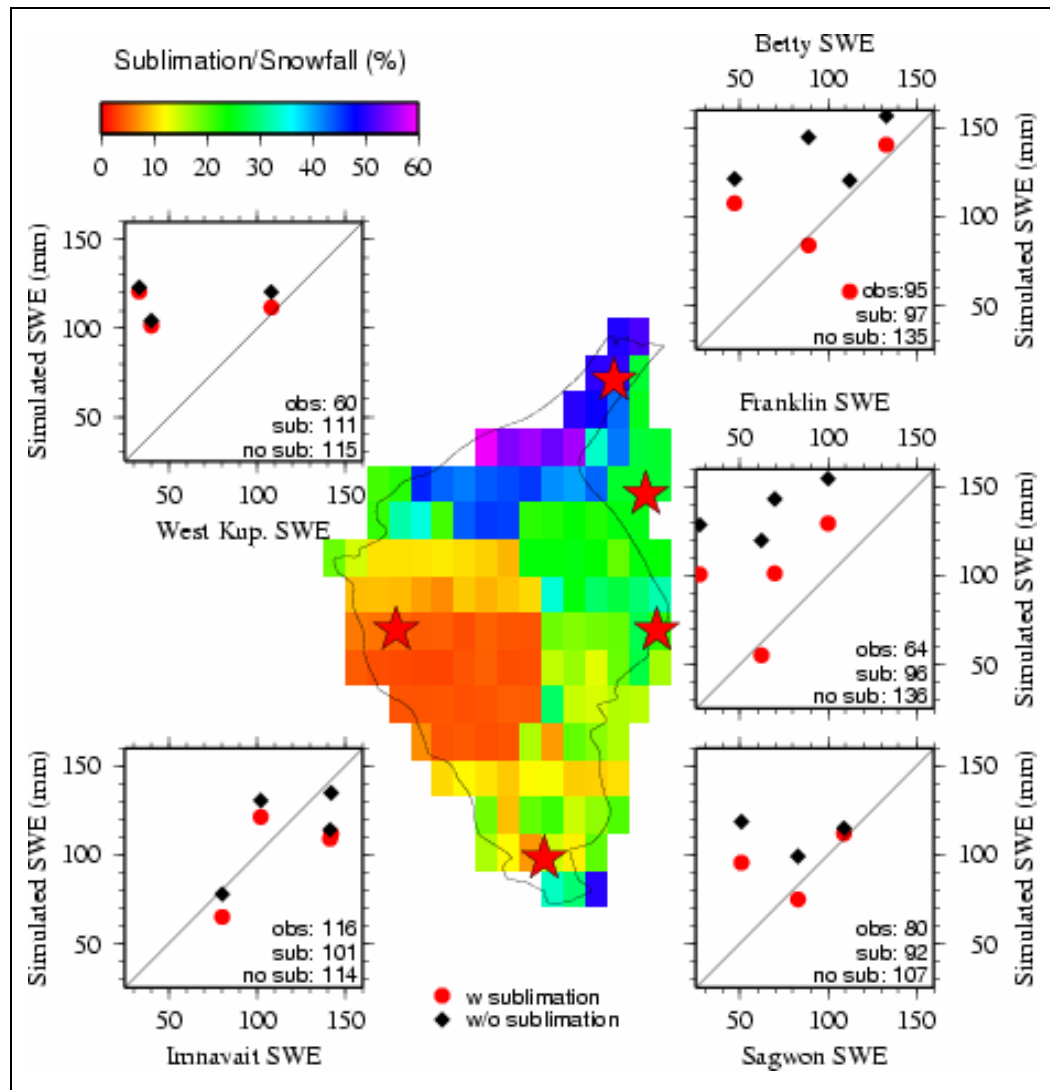


- Sublimation during blowing snow
  - Increase in winter latent heat
  - Decrease in snow available for melt

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



# Sublimation from transported snow



# Lakes and wetlands



*Source: San Diego State University Global Change Research Group*

# 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

# Non-Permafrost Wetlands

## Bogs and peatlands

- Underlain by carbon-rich soil: peat
  - Extremely porous
  - High hydraulic conductivity
- Shallow water table
- Some areas never covered by water
- Found in flat, poorly-drained areas



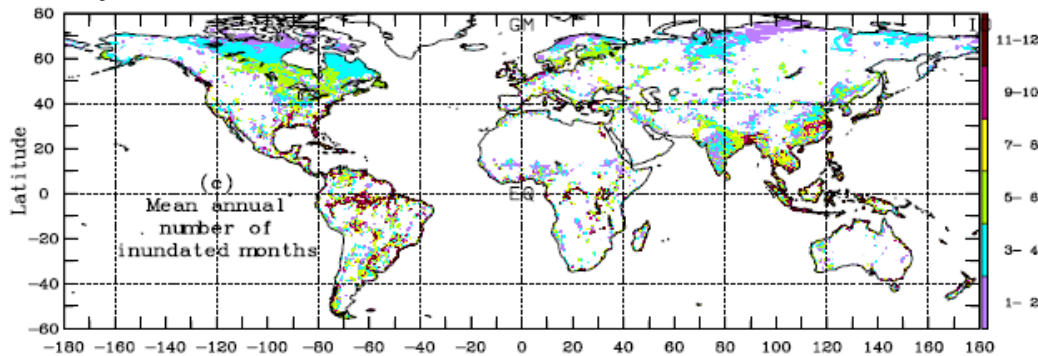
## Bog Pools

- Found in large bogs; peat soils
- Smaller catchments (topographic highs)
- Can occupy up to 25% of bog area
- Extent changes seasonally
- Expand with age

*Photos: J. Shuman, UVA*

# How do 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

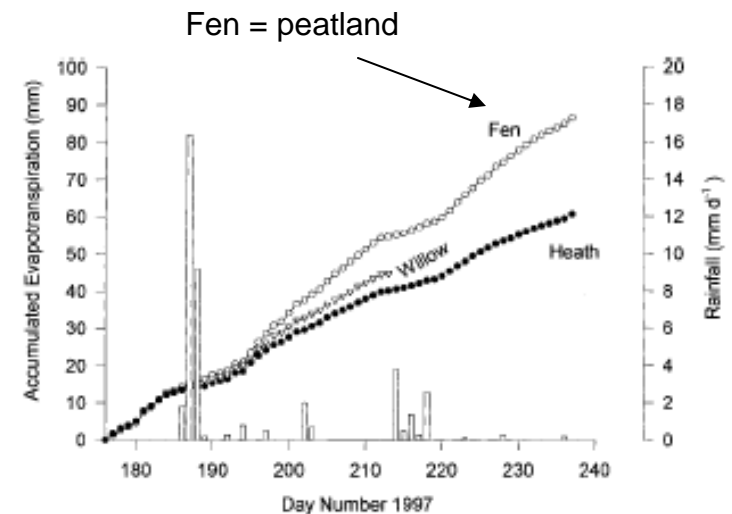
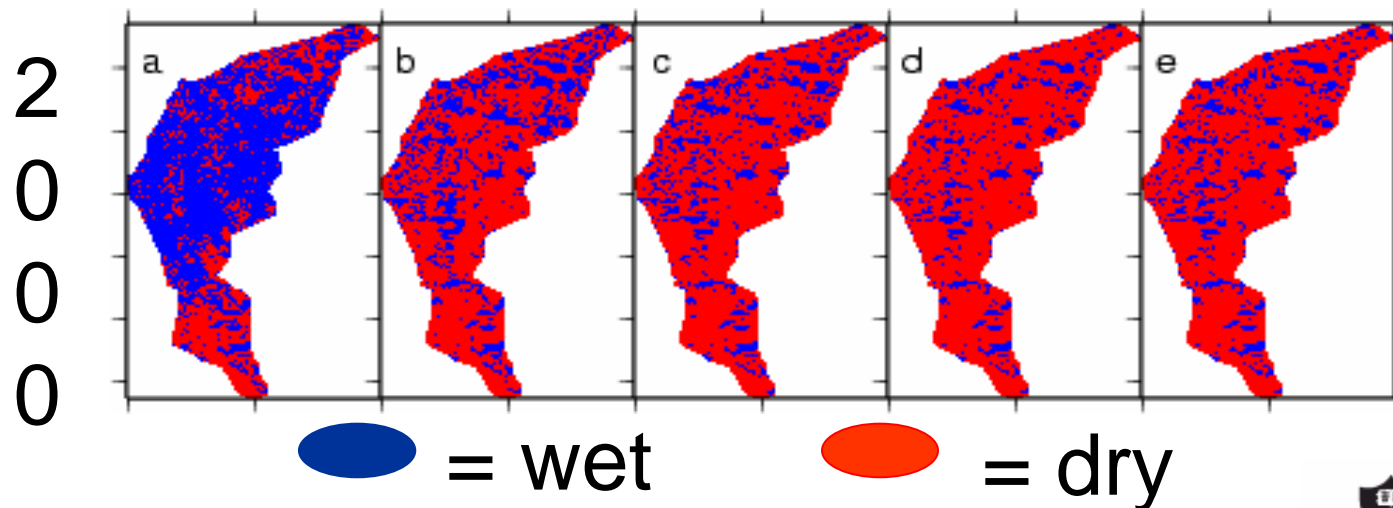


Fig. 4. Daily rainfall and accumulated evapotranspiration from three ecosystems throughout the 1997 growing season

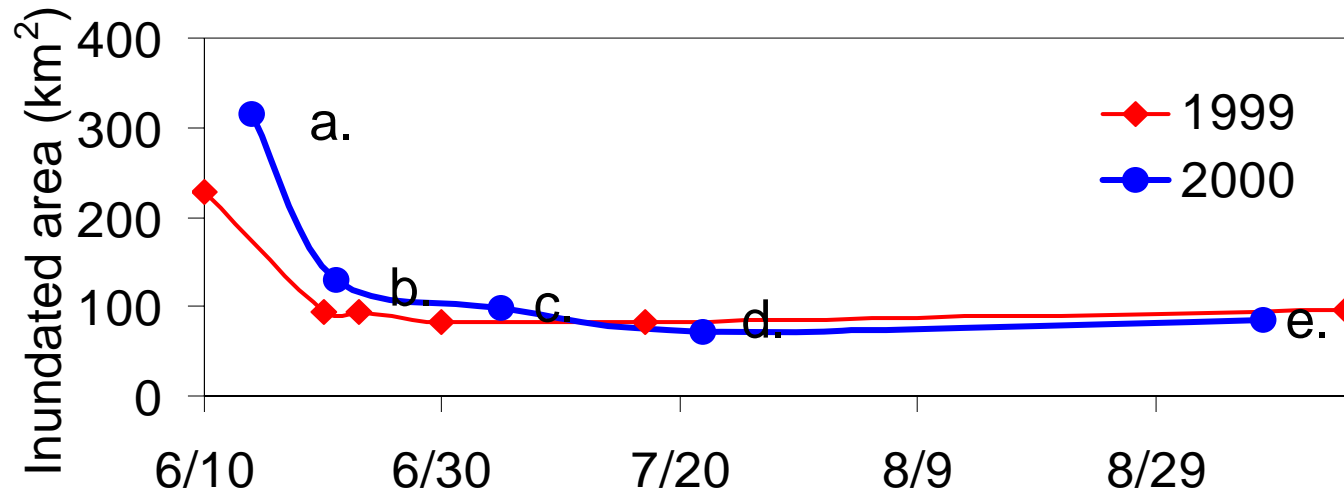
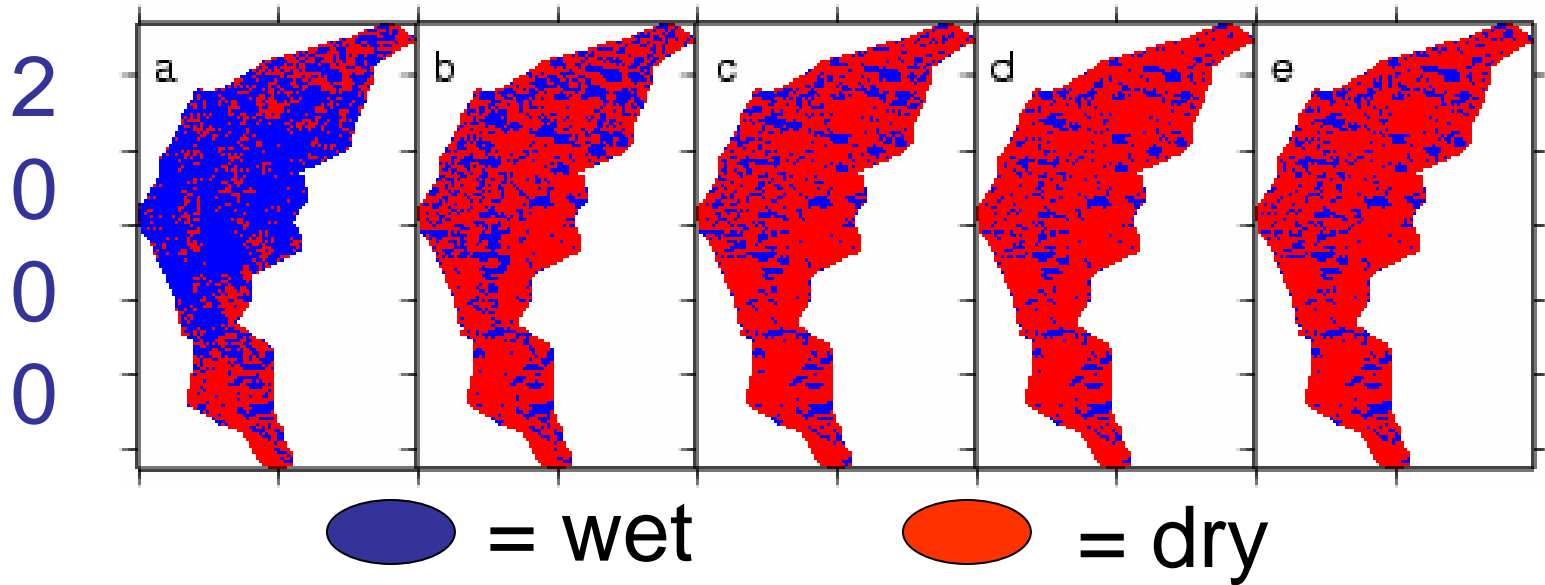
Soegaard, H., et al. (2001), Surface energy- and water balance in a high-arctic environment in NE Greenland, *Theoretical and Applied Climatology*, 70, 35-51.

# Permafrost wetland complexes and thaw ponds

- Low-gradient wetland complexes illustrate dramatic seasonal flooding and short term water storage on the surface
- Ice-rich frost inhibits percolation of snow meltwater and little subsurface storage capacity
- Ponds provide interannual storage



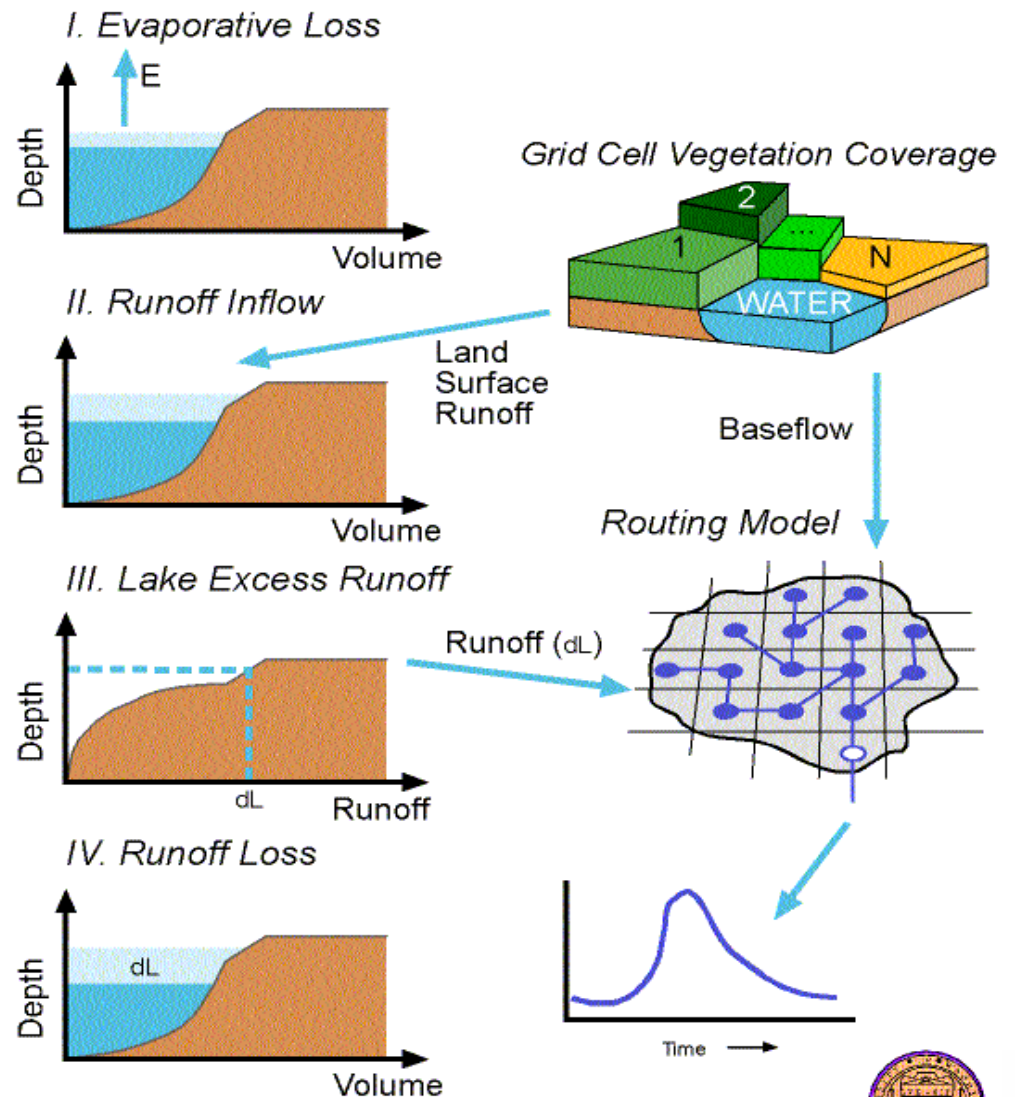
# Saturated extent 1999 and 2000



# Predicting the effects of lakes and wetlands

## VIC Lake Algorithm

- Lake energy balance based on:
  - Hostetler and Bartlein (1990)
  - Hostetler (1991)
- Assumptions:
  - One “effective” lake for each grid cell;
  - Laterally-averaged temperatures; and

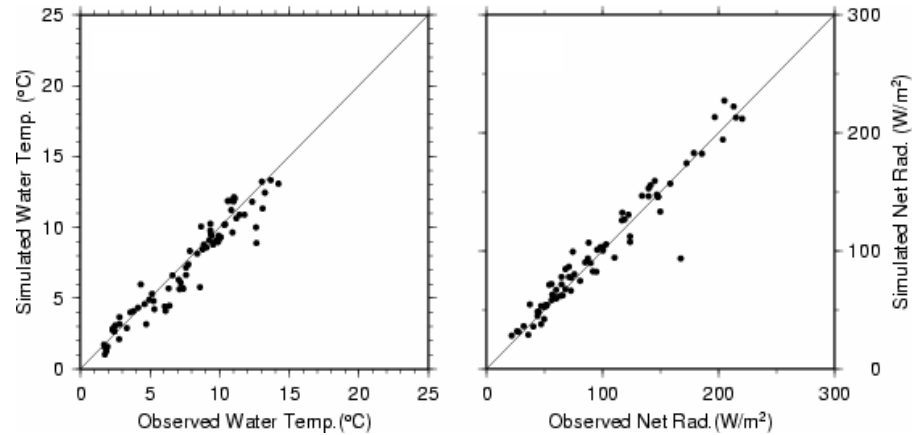


# Lake Surface Energy Balance

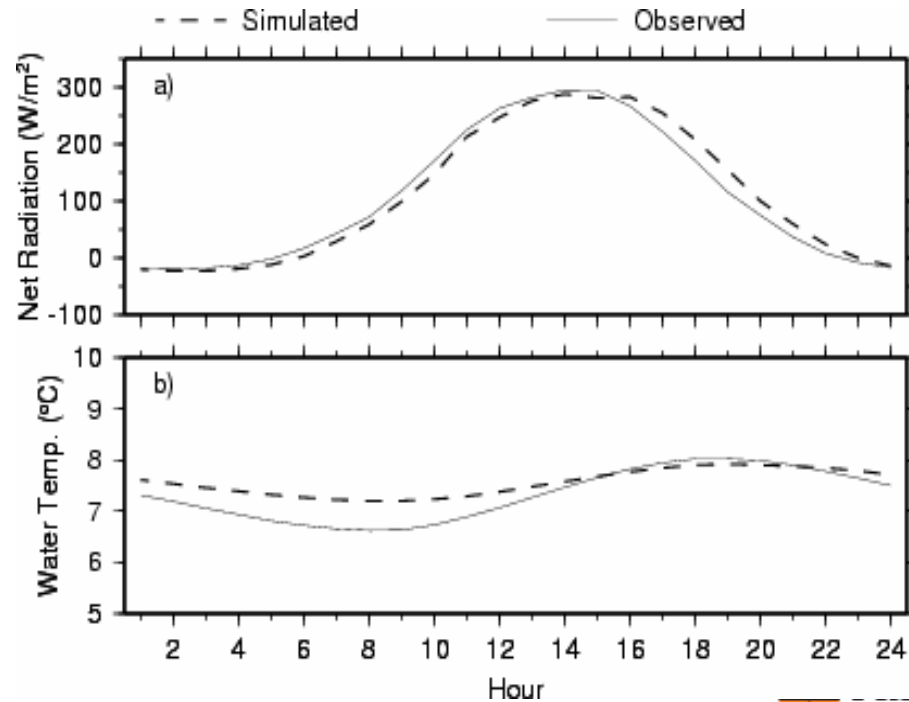
'Lake 1', Arctic Coastal Plain, Alaska



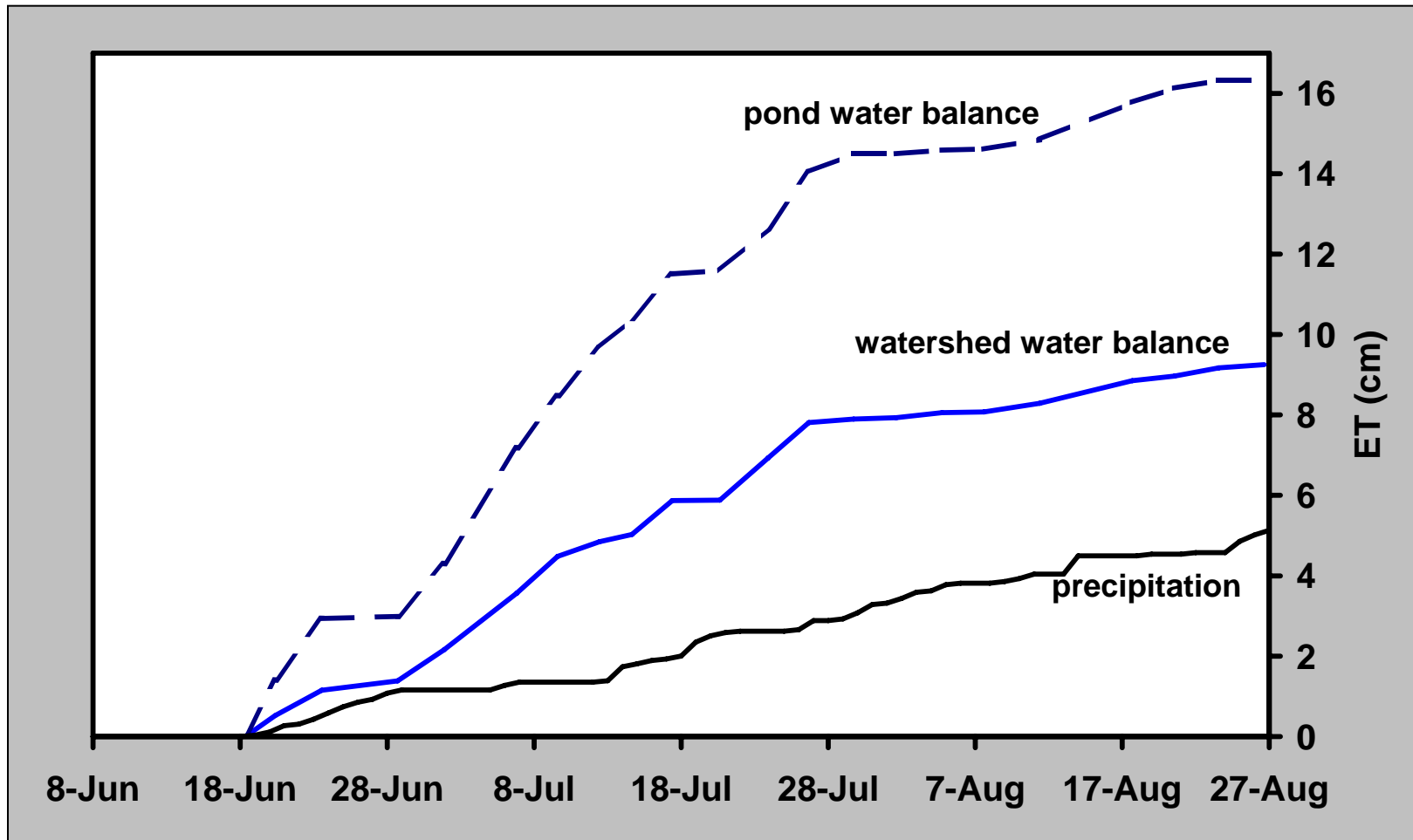
Mean daily values, June-August 2000



Mean diurnal values, June-August 2000



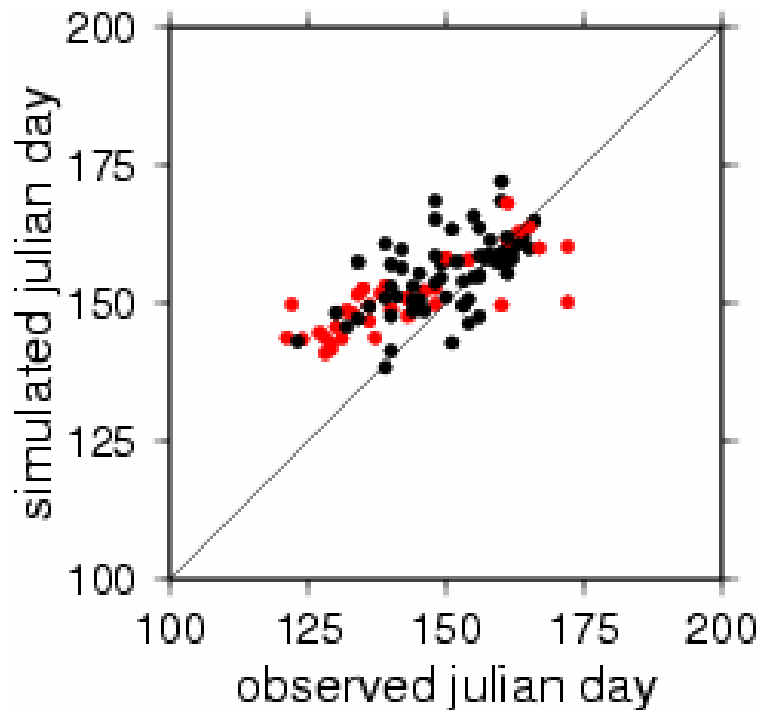
# Cumulative wetland complex evapotranspiration, Summer 1996



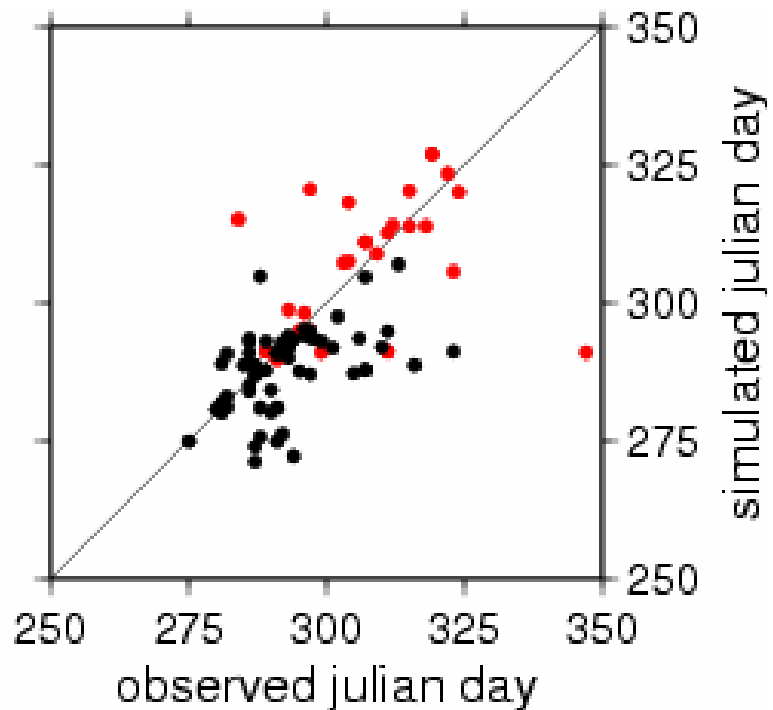
# Lake ice formation and break-up

## Torne River, Sweden

ice break-up



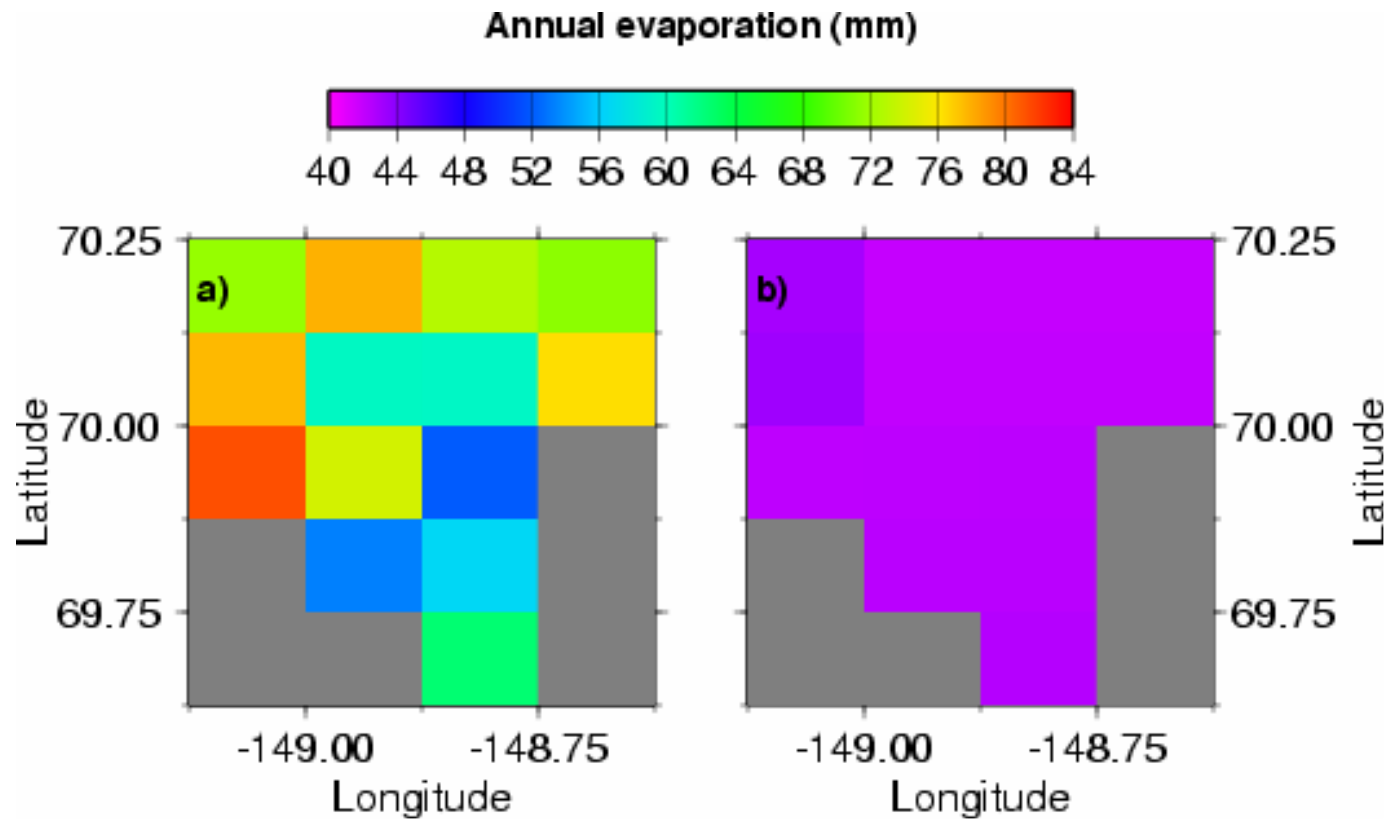
ice formation



● = area > 20 km<sup>2</sup>

● = area < 20 km<sup>2</sup>

# Simulated mean annual evaporation

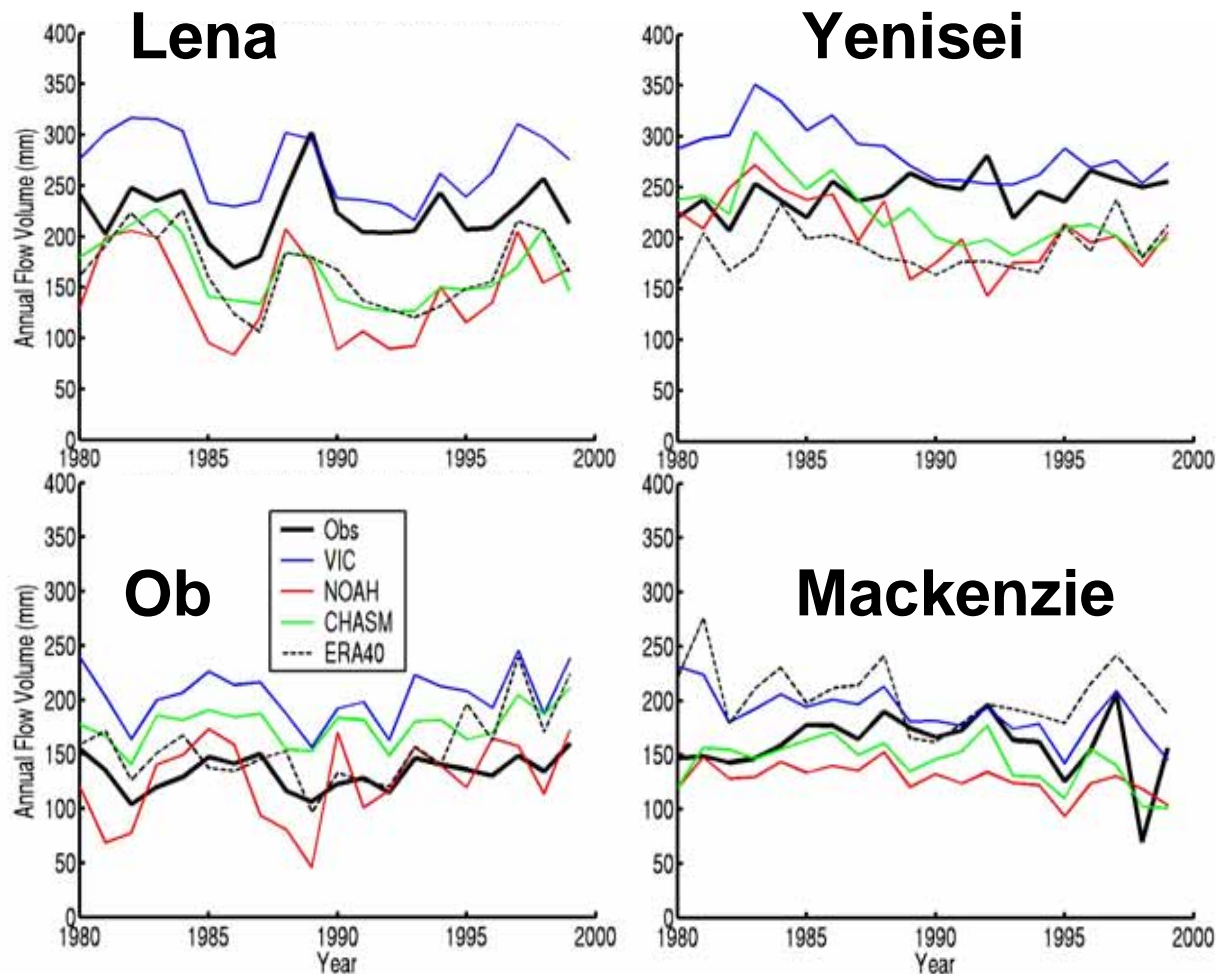


with lake algorithm    without lake algorithm

- Simulated annual evaporation increases by 60%

# Multi-model runoff across the pan-Arctic

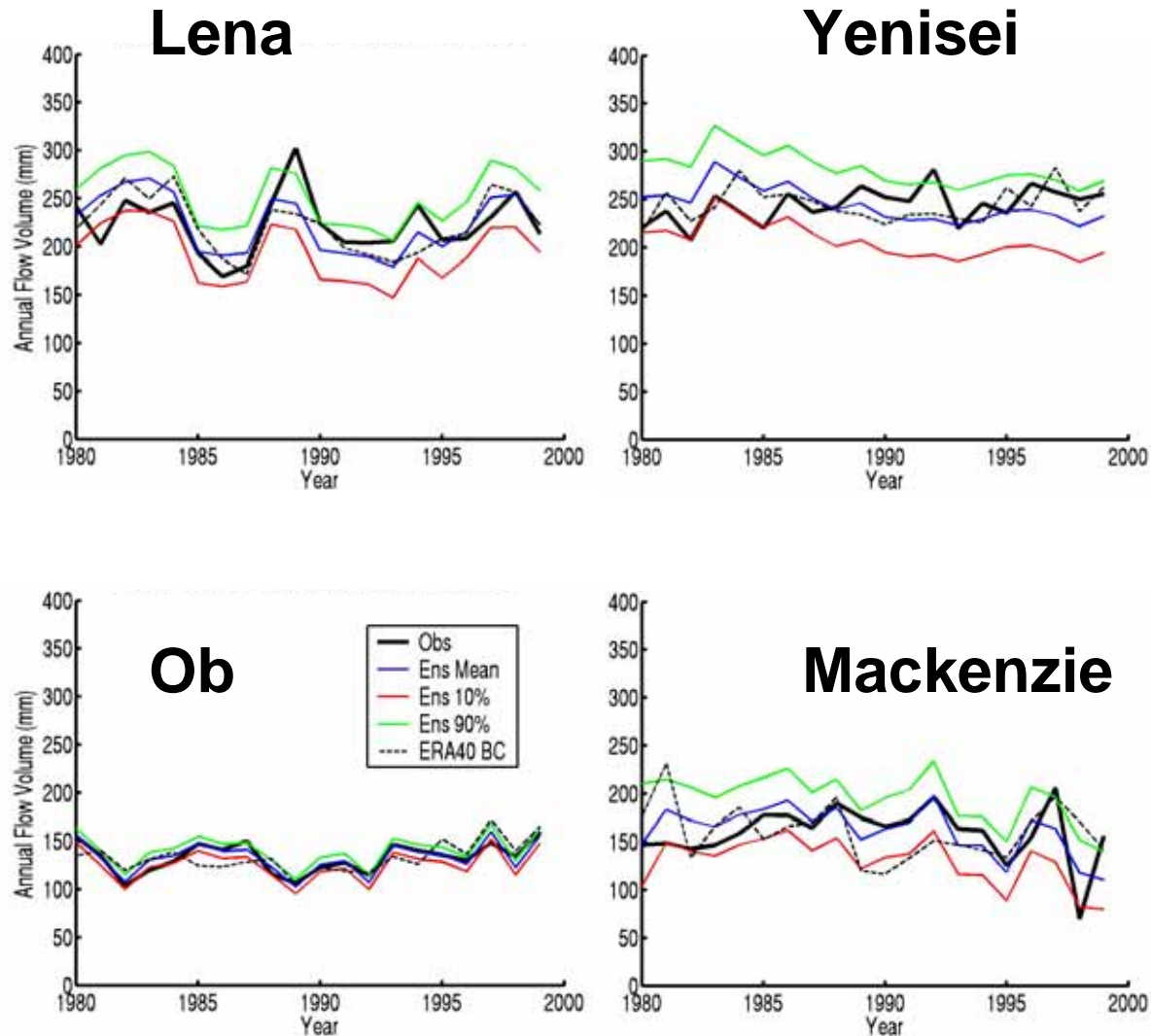
## Raw Annual Discharge, 1980-1999



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

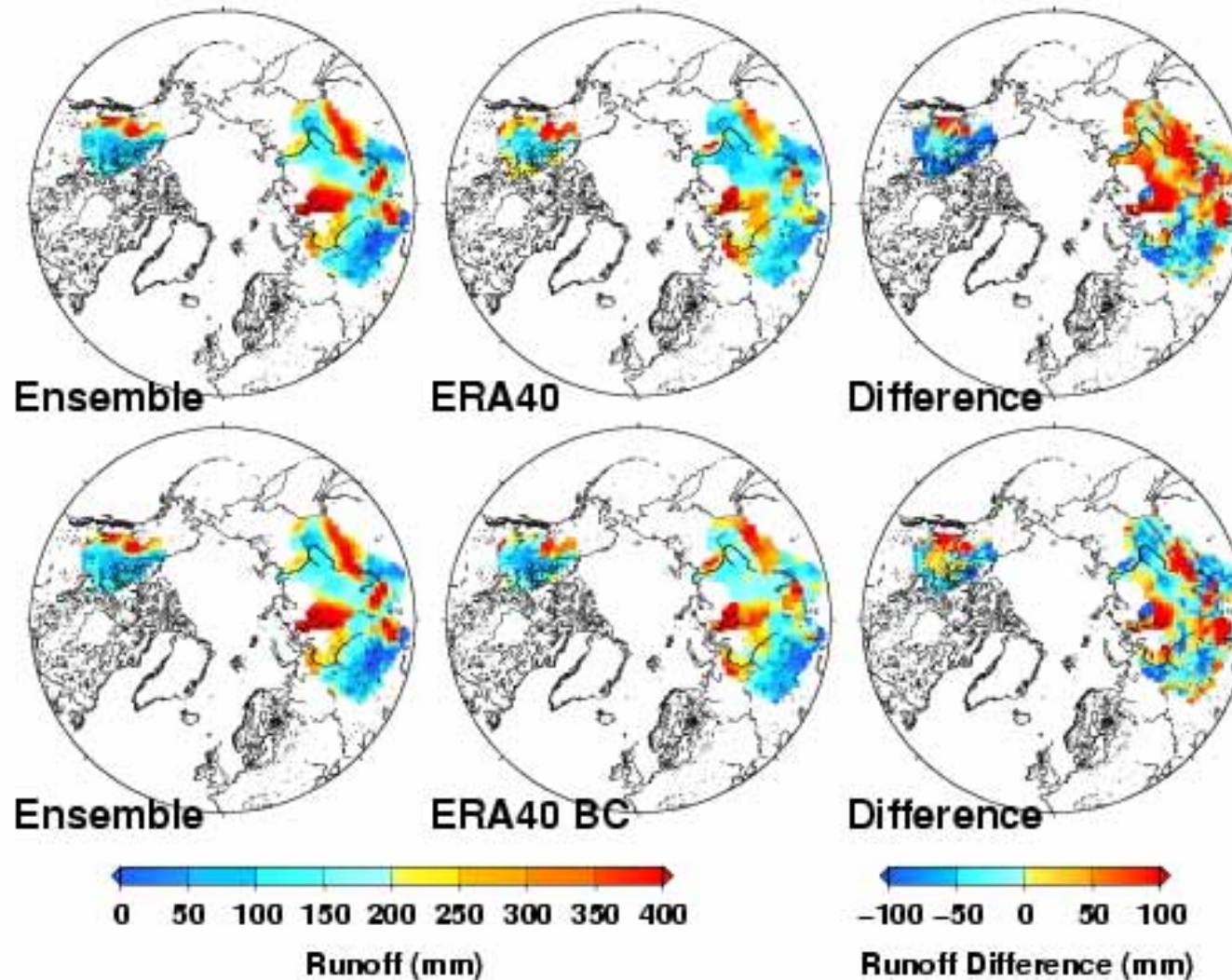
# Multi-model Runoff Across the Pan-Arctic

## Ensemble Discharge, 1980-1999



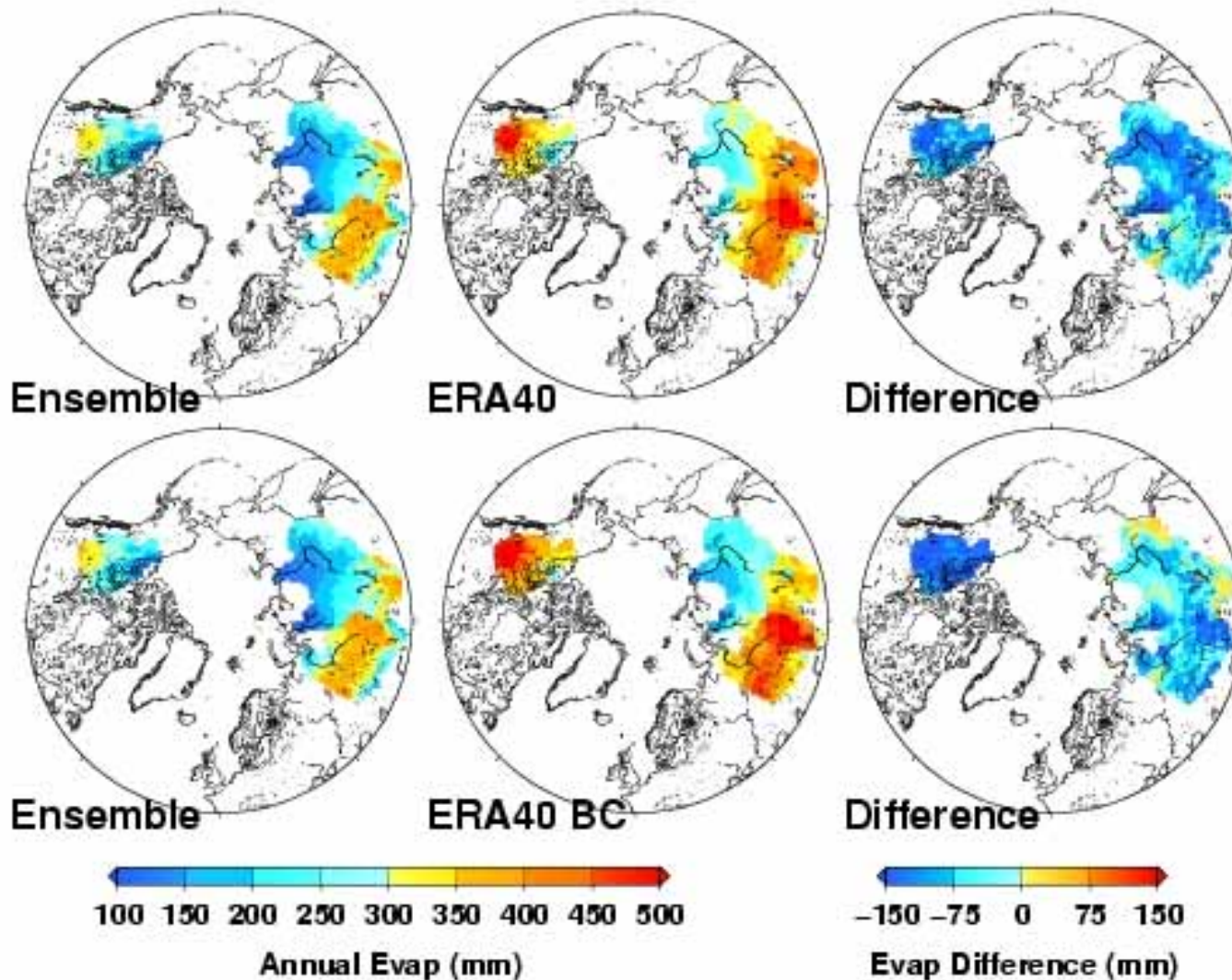
From Bohn et al. 2005 (Multi-model estimates of Arctic land surface conditions, AGU Dec 2005)

# Annual Runoff Across Pan-Arctic



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

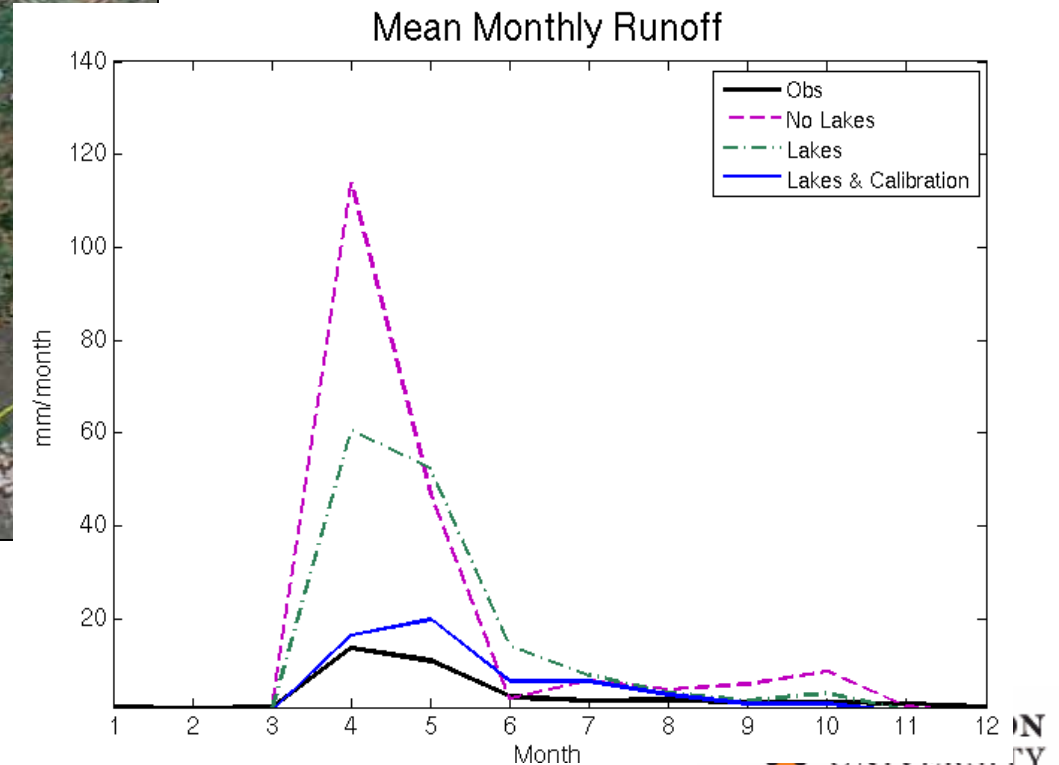
# Annual Evapotranspiration Across the Pan-Arctic



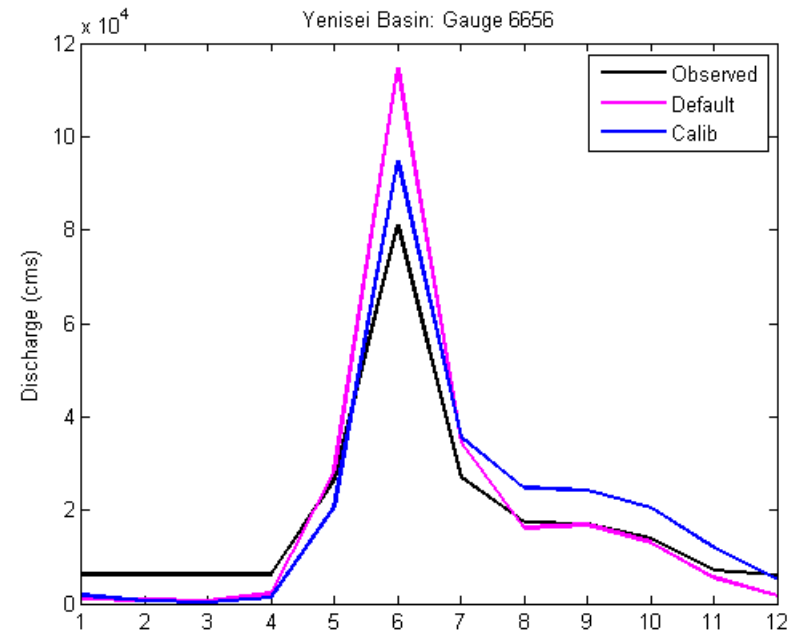
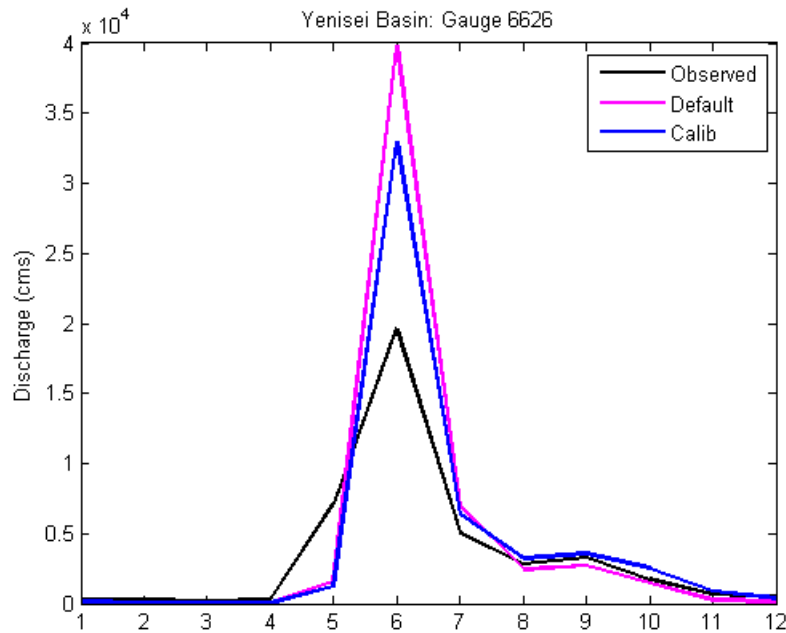
From Bohn et al. 2005 (Multi-model estimates of Arctic land surface conditions, AGU Dec 2005)

# Initial Calibration Work

- Isit River (Gauge 7185) in Ob Basin in region characterized by flat landscape and lakes (drainage area: 56,000 km<sup>2</sup>)



# Current Calibration Work



- 5 soil parameters, 2 lake parameters
- Tests indicate that can improve results with additional soil parameters to increase winter baseflow generation

# Where do we go from here?

## 1. Improved Parameterizations

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

- Need for continued improvements, especially for cold season processes
- Inclusion of a water table for deep soil layers
- Peatlands – significant in the NEESPI region with links to carbon cycle
- 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

# Where do we go from here?

## 2. Improved observations.

(Are the in-situ observations sufficient to capture the temporal and spatial dynamics of energy and water cycle dynamics across the NEESPI domain?)

- Is there a scale disconnect between modeling and observations – are there ways to bridge this?
- Can we better utilize remote sensing to further our understanding of the hydrologic cycle across NEESPI?

# Where do we go from here?

3. Intercomparison of LSM parameterizations and predictions
  - Need to validate specific process parameterizations. Princeton may host a workshop in late 2008 – early 2009 on permafrost and active layer modeling.
  - Can multi-model ensemble predictions offer a better assessment of the terrestrial hydrology across NEESPI?
  
4. Test the ability of LSM to evaluate anthropogenic influences and test attribution hypotheses

Thank You