Modeling of the Hydrochemical Response of High Elevation Forest Watersheds to Climate Change and Atmospheric Deposition Using a Biogeochemical Model (PnET-BGC)

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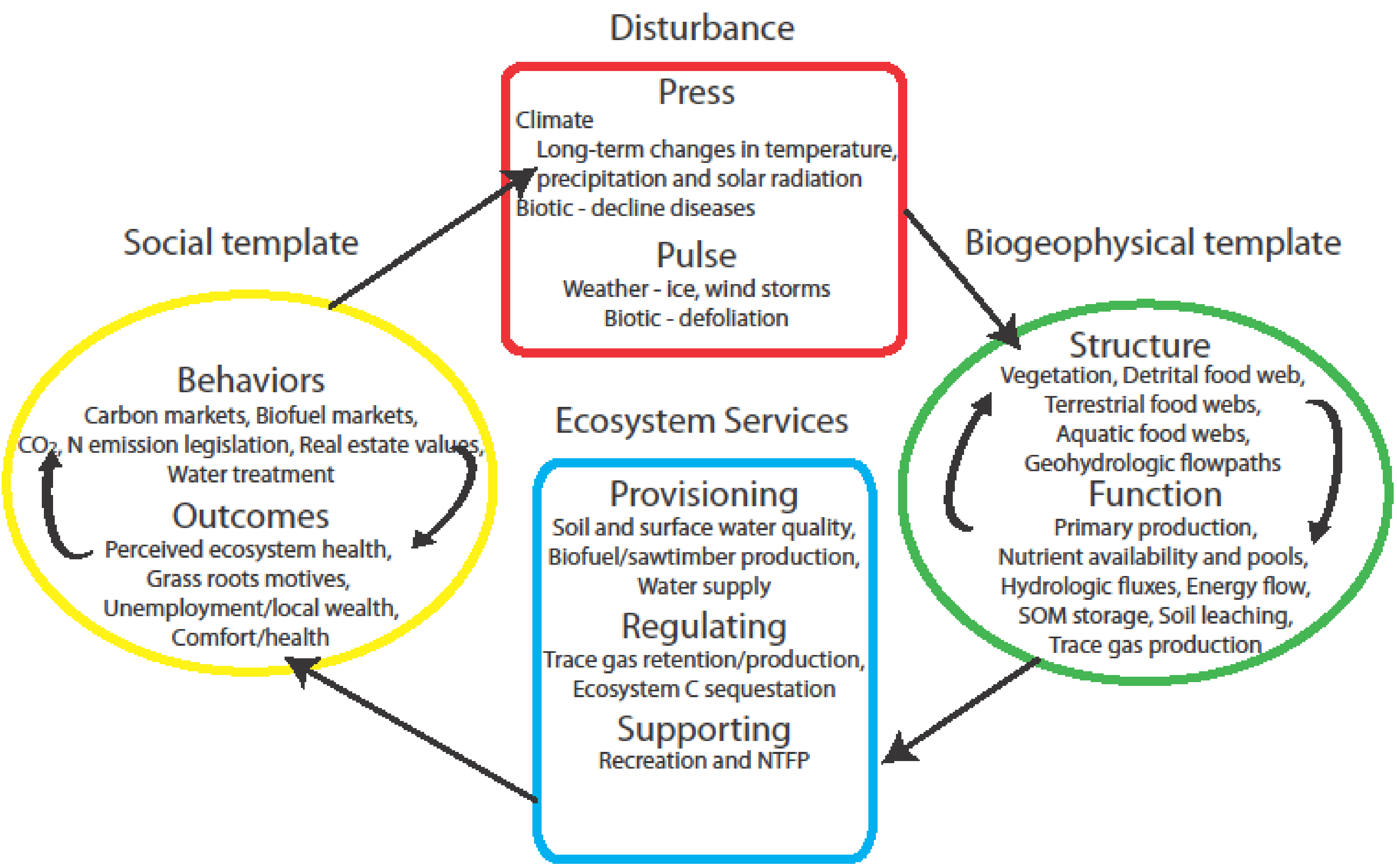
Outline

- Background and Rationale
- Project Goals and Hypotheses
- Approach
  - Study Sites
  - PnET-BGC
  - Future Scenarios
- Results
  - Hydrology
  - Stream Chemistry
  - Elemental Mass Balances
  - Cross Site Analysis
- Conclusion

Climate Change and Forest Ecosystems



Overarching Objective

To assess responses of headwater forested watersheds with a range of biophysical, climate and historical land disturbance (e.g. clear cut, fire, ice storm) characteristics across the U.S. to future climate change (21$^{st.}$ Century) using hydrochemical modeling.

Hypotheses

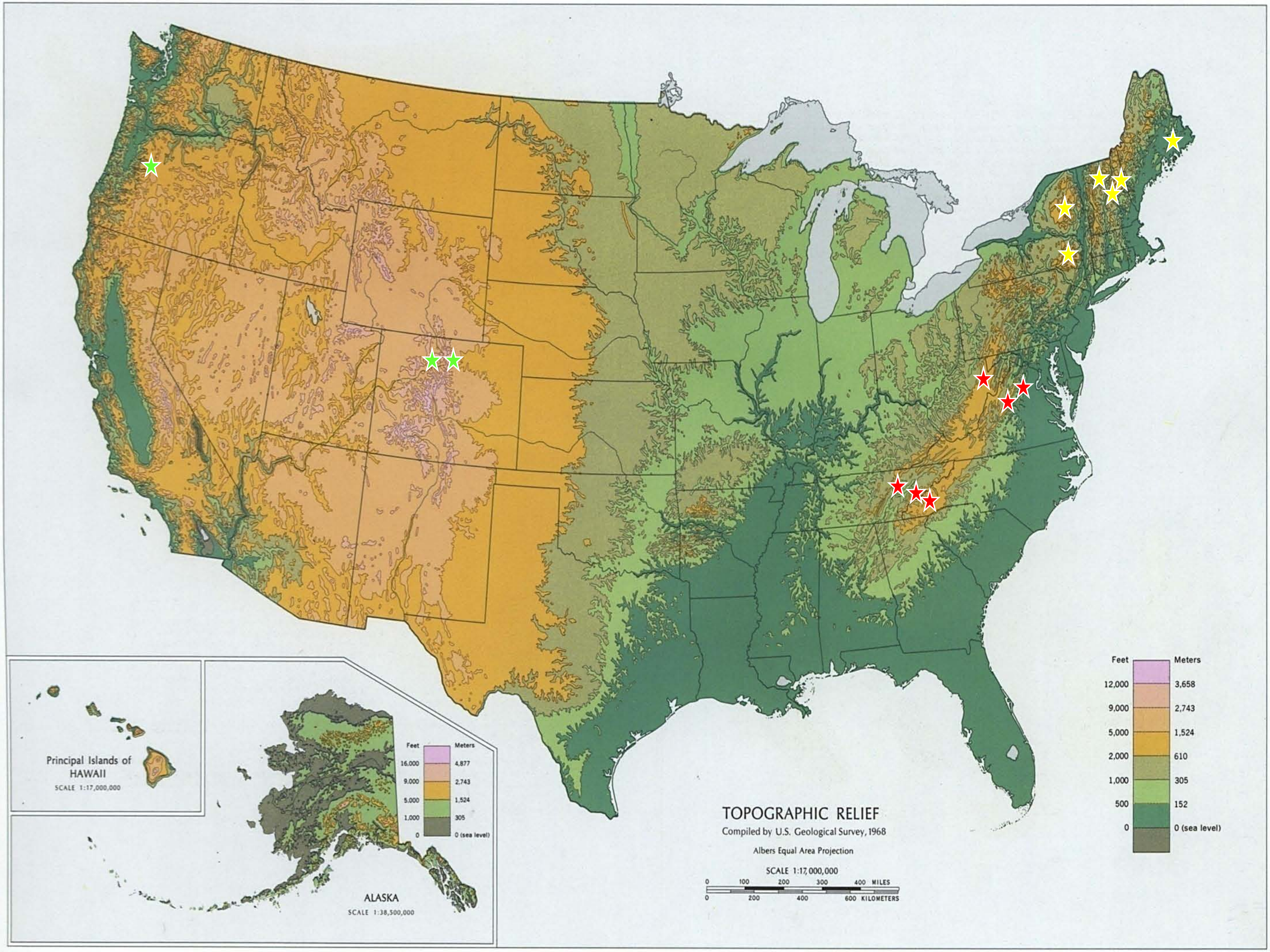
- **H1:** ***Climate change in high elevation watersheds will decrease the overall quantity of stream water and will alter the seasonal distribution of streamflow;***

- **H2:** ***Climate change will alter the overall quality of stream water, which will be compounded by direct and indirect effects of other global change processes such as air pollution, atmospheric CO_2, and historical land-disturbance; and***

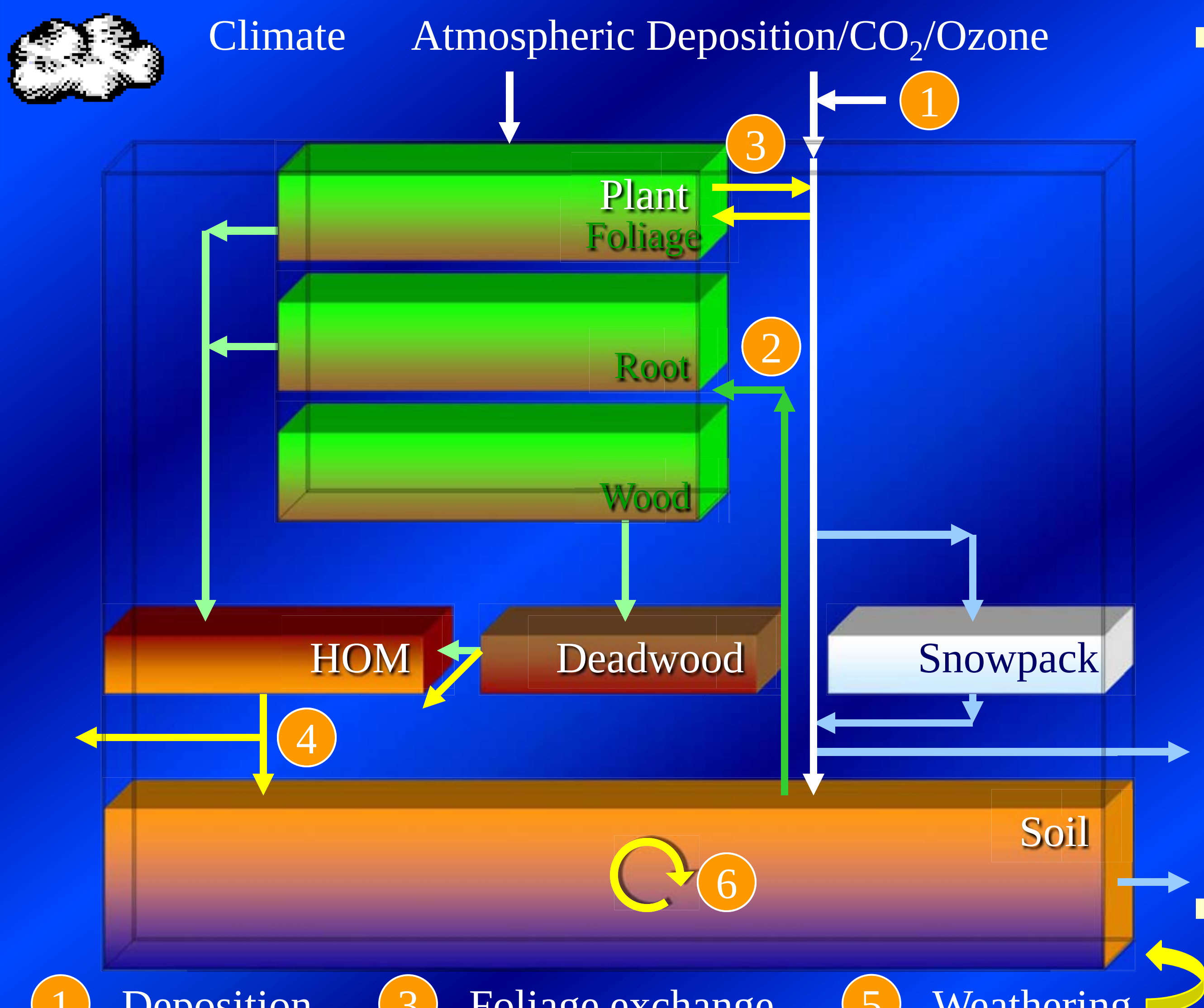
- **H3:** ***Stream water responses to climate change will vary across local, regional, and national geographic scales due to hydrometeorological, chemical and biological gradients.***

Study Sites

Site (Identifier, Region)	Stream	Lat., Long.	State	Record Length (yrs)	Elevation (m)	Vegetation Cover	Size (ha)	Annual Precipitation (mm)	Annual Discharge (mm)
Bear Brook (EBB; NE)	East Bear	44°52'N, 68°06'W	ME	20	265-475	Northern Hardwood	11	1250	920
Hubbard Brook (HBR; NE)	WS6	43°57'N, 71°44'W	NH	45	550-790	Northern Hardwood	13	1400	880
Cone Pond (CPW; NE)	Inlet	43°54'N, 71°36'W	NH	19	485-650	Spruce-Fir	33	1280	670
Sleepers River (SRW; NE)	W-9	44°29'N, 72°10'W	VT	18	520-680	Northern Hardwood	41	1320	740
Huntington Forest (HWF; NE)	Archer Creek	44°00'N, 74°13'W	NY	14	460-825	Northern Hardwood	135	1210	830
Biscuit Brook (BSB; NE)	Biscuit Brook	41°59'N, 74°30'W	NY	25	620-1125	Northern Hardwood	990	1520	970
Fernow (FEF; SE)	WS4	39°03'N, 79°41'W	WV	37	750-870	Central Hardwood	39	1460	710
White Oak Run (WOR; SE)	White Oak Run	38°09'N, 78°27'W	VA	29	480-968	Oak-chestnut	510	1000	500
Staunton Watershed (STR; SE)	Staunton River	38°15'N, 78°15'W	VA	16	335-1056	Oak-pine	1050	1780	765
Coweeta (CWT; SE)	WS2	35°4'N, 83°26'W	NC	35	710-1005	Oak-hickory	12	1760	810
Walker Branch (WBW; SE)	West Branch	35°58'N, 84°17'W	TN	19	265-350	Oak-hickory	38	1400	980
Noland Divide Watershed (NDW; SE)	Noland Creek	35°34'N, 83°29'W	TN	18	1680-1920	Spruce-Fir	17.4	1918	1714
Loch Vale (LVW; W)	Andrews Creek	40°17'N, 105°40'W	CO	17	3110-4190	Alpine	150	1230	1000
Niwot Ridge (NWT; W)	Green Lake Inlet	40°18'N, 105°22'W	CO	24	2591-3743	Alpine	225	1003	720
H.J.Andrews (AND; W)	WS9	44°16'N, 122°10'W	OR	40	425-700	Douglas-fir	9	2270	1260


TOPOGRAPHIC RELIEF
Compiled by U.S. Geological Survey, 1968
Albers Equal Area Projection
SCALE 1:17,000,000
0 100 200 300 400 MILES
0 200 400 600 KILOMETERS
Feet
Meters
12,000
3,658
9,000
2,743
5,000
1,524
2,000
610
1,000
305
500
152
0
0 (sea level)
Principal Islands of HAWAII
SCALE 1:17,000,000
ALASKA
SCALE 1:38,500,000
Feet
Meters
16,000
4,877
9,000
2,743
5,000
1,524
1,000
305
0
0 (sea level)

PnET-BGC in detail - Elements



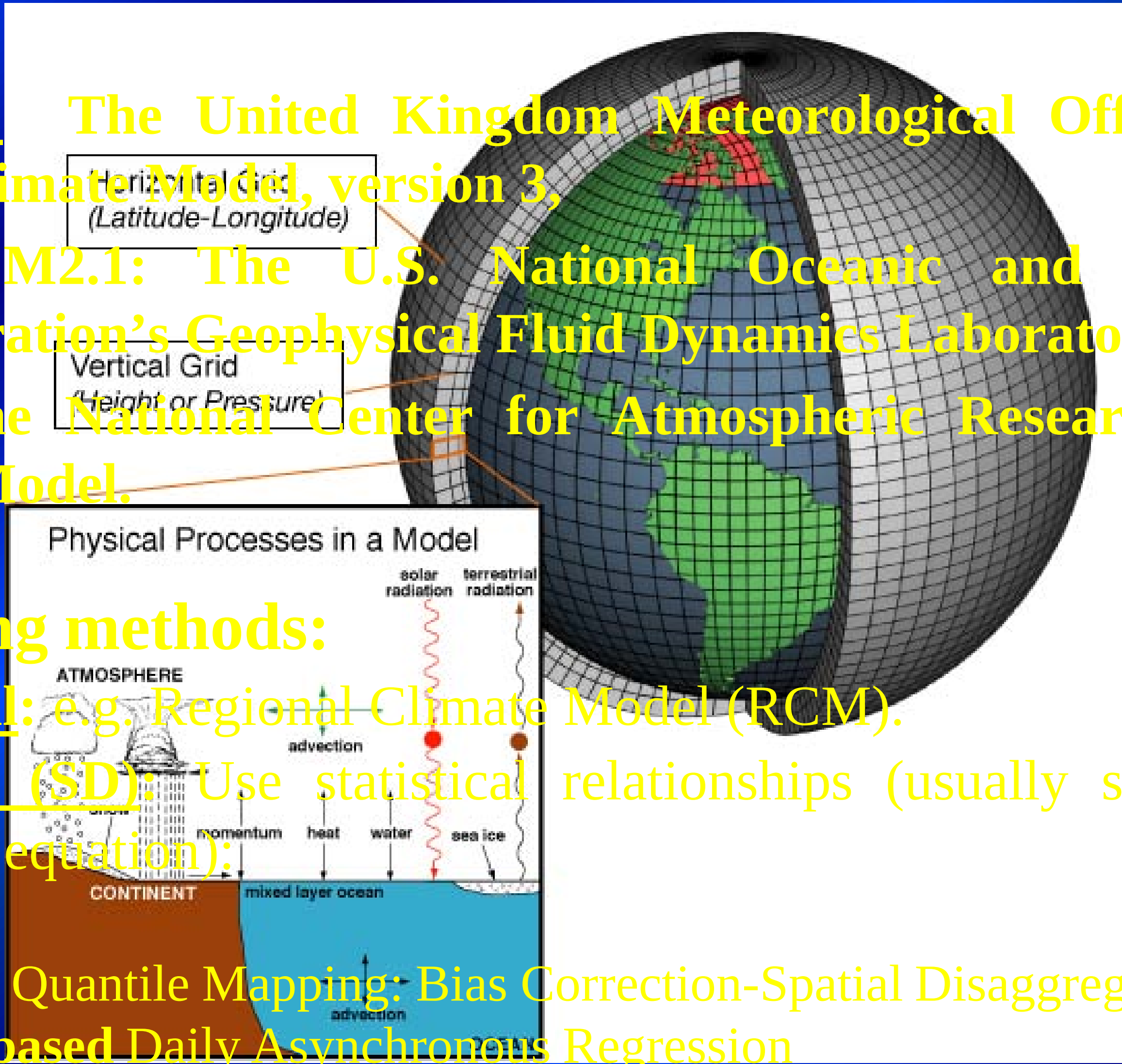
- Fluxes driven by
  - Climate
  - Atmospheric deposition
  - Atmospheric CO_2/Ozone
  - Water fluxes
  - Biomass and soil fluxes

$$S^{el}_{process} = \frac{m^{el}}{m^{pool}} \cdot S^{pool}_{process}$$

  - Transformation processes
- Pools with element composition

1 Deposition
2 Plant uptake
3 Foliage exchange
4 Mineralization
5 Weathering
6 Soil & soil solution interaction / nitrification

Global Climate Models (AOGCMs)

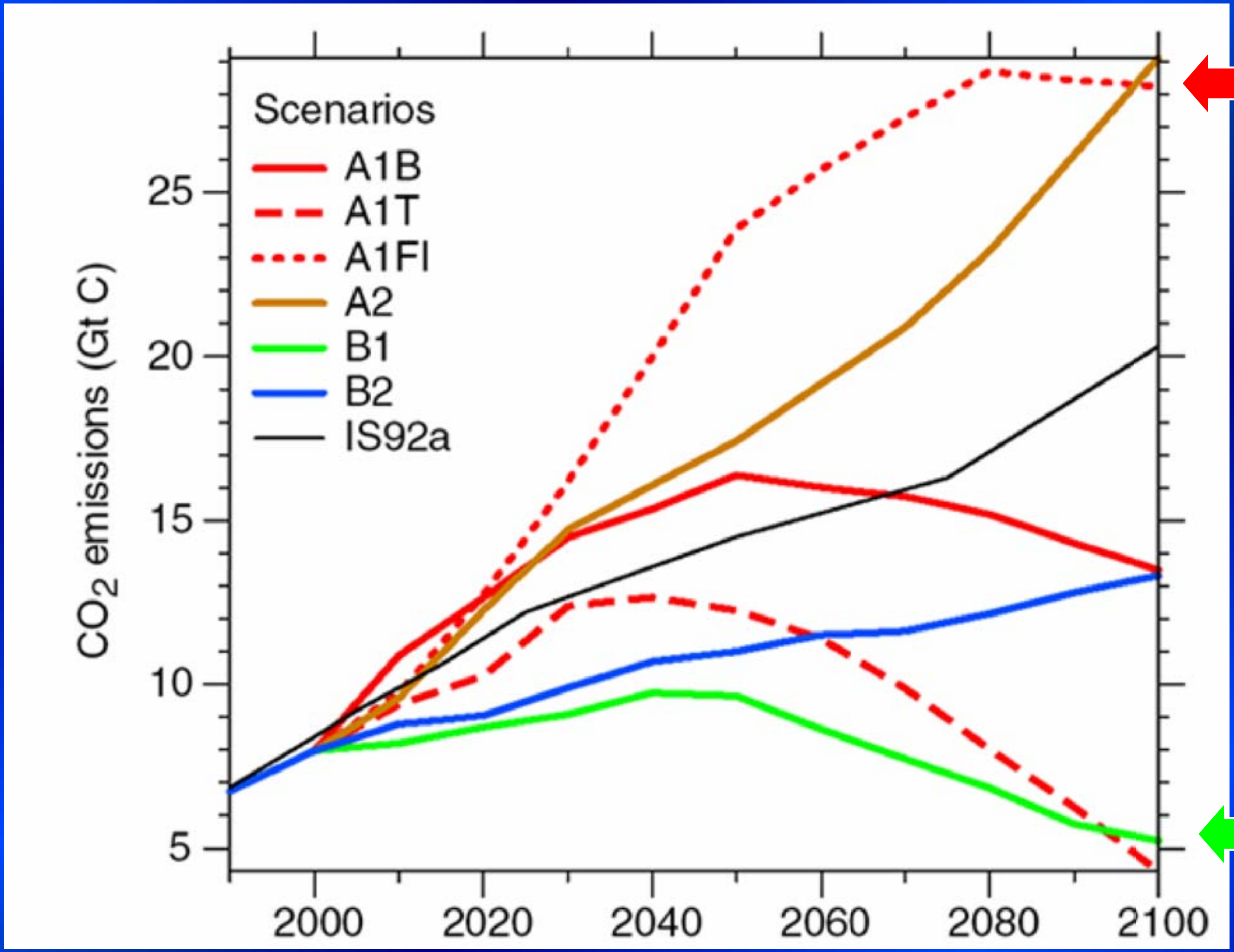


- **HadCM3:** The United Kingdom Meteorological Office's Hadley Centre Climate Model, version 3,
- **GFDL CM2.1:** The U.S. National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory, and
- **PCM:** The National Center for Atmospheric Research's Parallel Climate Model.

Downscaling methods:

- **Dynamical**: e.g. Regional Climate Model (RCM).
- **Statistical (SD)**: Use statistical relationships (usually some form of regression equation):
  - **Gridded** Quantile Mapping: Bias Correction-Spatial Disaggregation (BCSD)
  - **Station-based** Daily Asynchronous Regression

Future Scenarios



Source: NECIA/UCS, 2007 (see: www.climatechoices.org/ne/)

HIGHER

A1FI (970 ppm)

End-of-century concentrations range from ~double to triple pre-industrial levels

LOWER

B1 (550 ppm)

Source: IPCC 2001

Sensitivity Analysis to Climatic Drivers

Sensitivity analysis ➔ Testing the relative change in each state variable X values divided by the relative change in the value of the input (Input) tested.

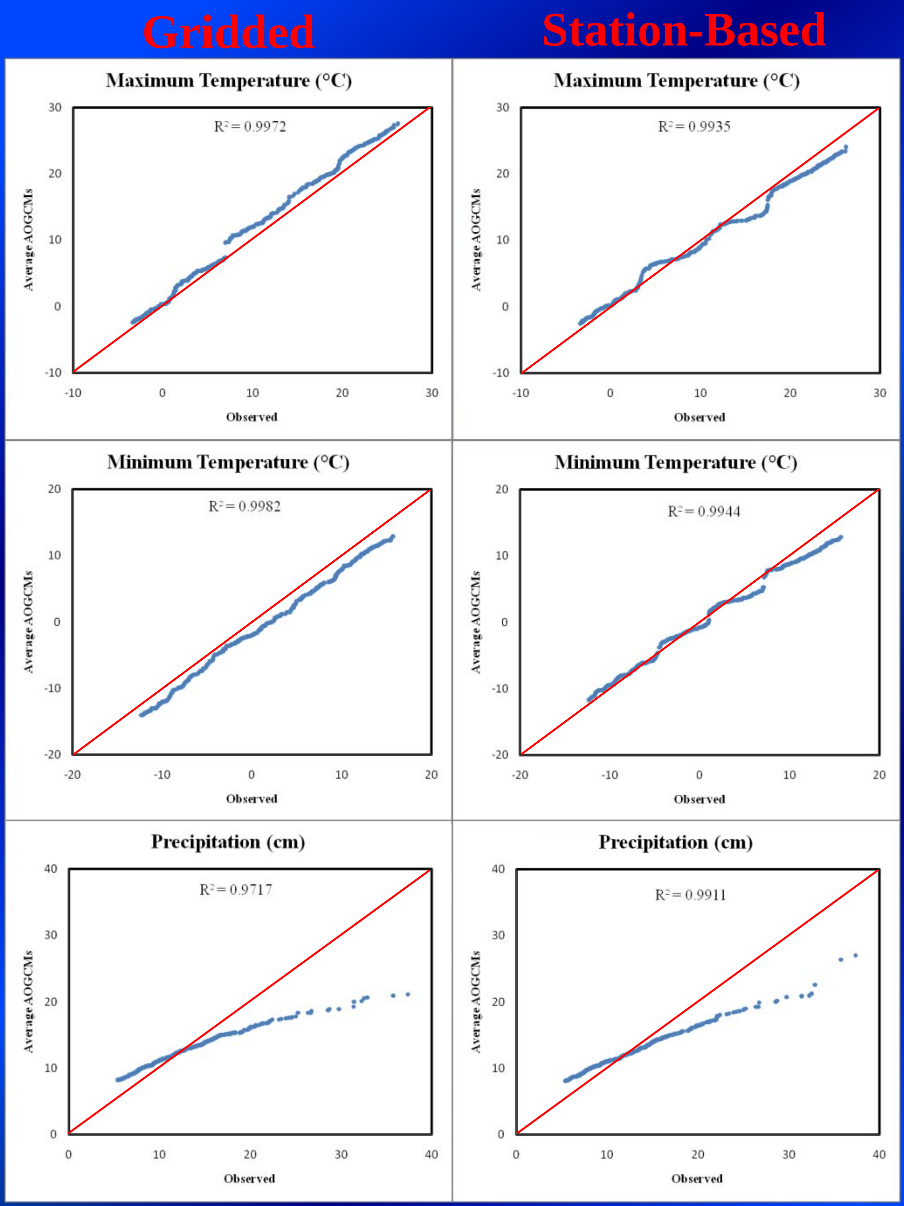
$$S_{Input,X} = \frac{\partial X / X}{\partial Input / Input}$$

Parameter	**Range**	$S^{Discharge}$	S^{NO3-}	S^{DOC}	S^{ANC}	$S^{\%BS}$
Temperature (°C)	4.46-7.22	-0.03	1.44	0.05	-1.29	-0.09
Precipitation (cm)	104.26-182.45	1.01	-0.51	-0.02	0.59	-0.02
PAR (mmol m^{-2} s^{-1})	456.15-629.99	-0.05	-1.43	0.04	1.25	0.24

•Positive number indicates positive correlation between the parameter and the state variable while negative number is an indication of negative correlation.

•Higher $S_{Input,\,X}$ values indicate that the model is more sensitive to that climate input type tested.

Downscaling Approaches:
Gridded Quantile Mapping vs. Station-Based



Gridded Quantile Mapping (BCSD):

- The most commonly-used for **monthly** downscaling
- Originally for GCM output ➔ Long-range streamflow forecasting.
- Compares favorably to **regional** climate models.

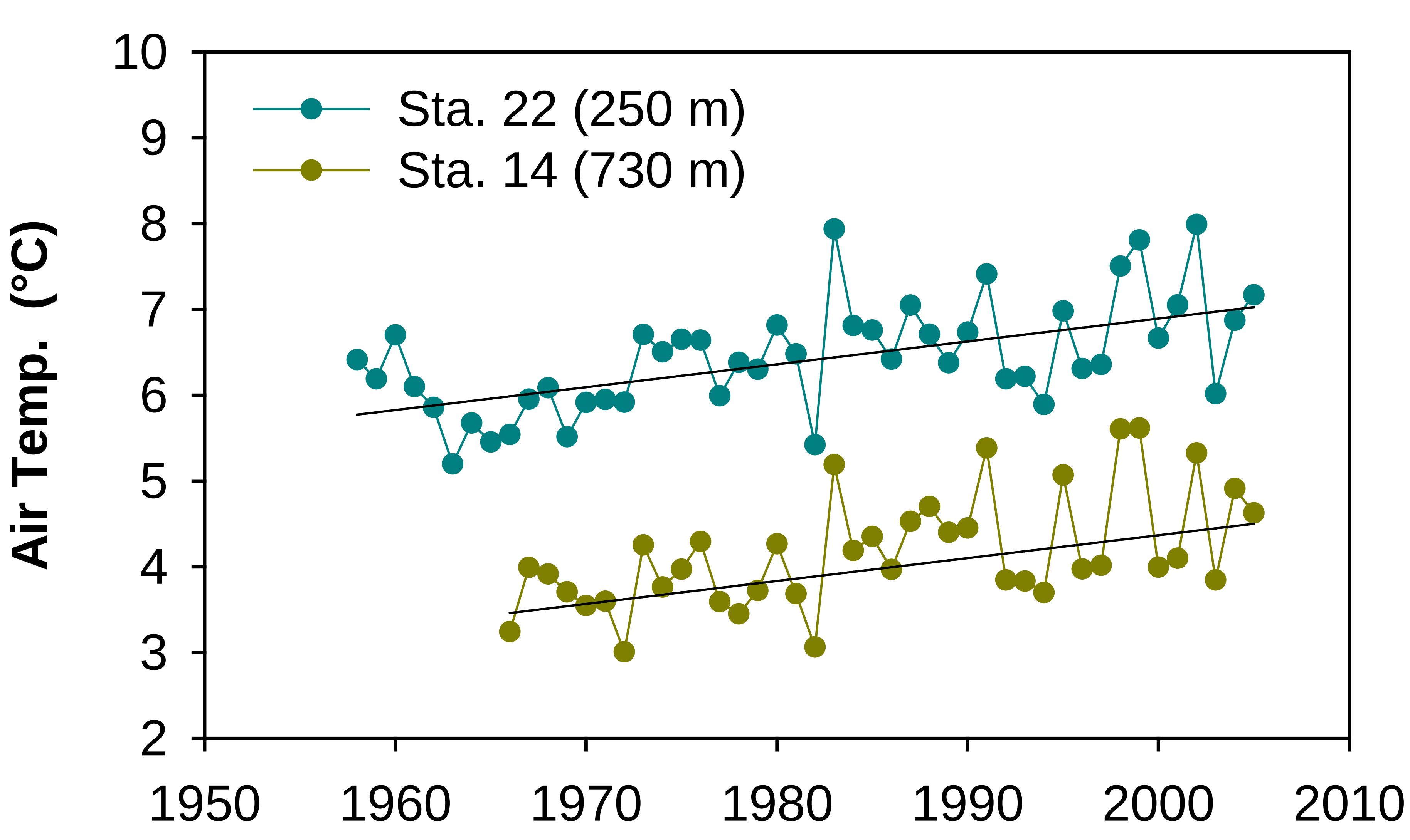
Station-based Daily Asynchronous Regression:

- More complex ➔ Between two quantities **without** temporal correspondence, but expected to have similar statistical properties (e.g. mean and variance).
- Uses all the GCM information; e.g. changes in **day-to-day** variability.
- Advantageous for extreme hot days projections (over 95ºF).

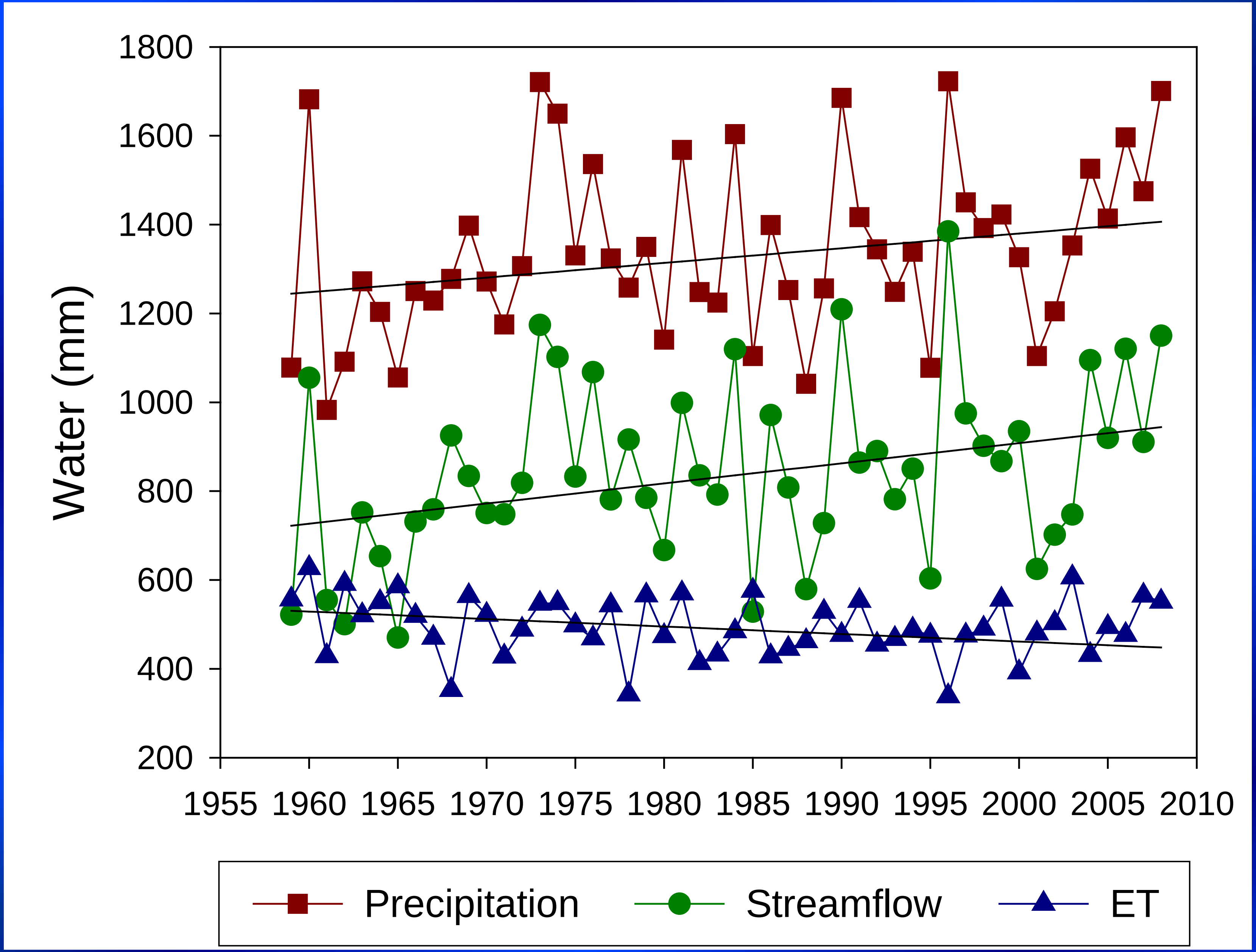
Hubbard Brook Climate

- Avg. air temperature: 19   C (Jul) to -8   C (Jan)
- Annual Precipitation: 1400 mm
- Avg. Max. Snowpack: 72 cm
- Avg. Max Soil frost: 6 cm

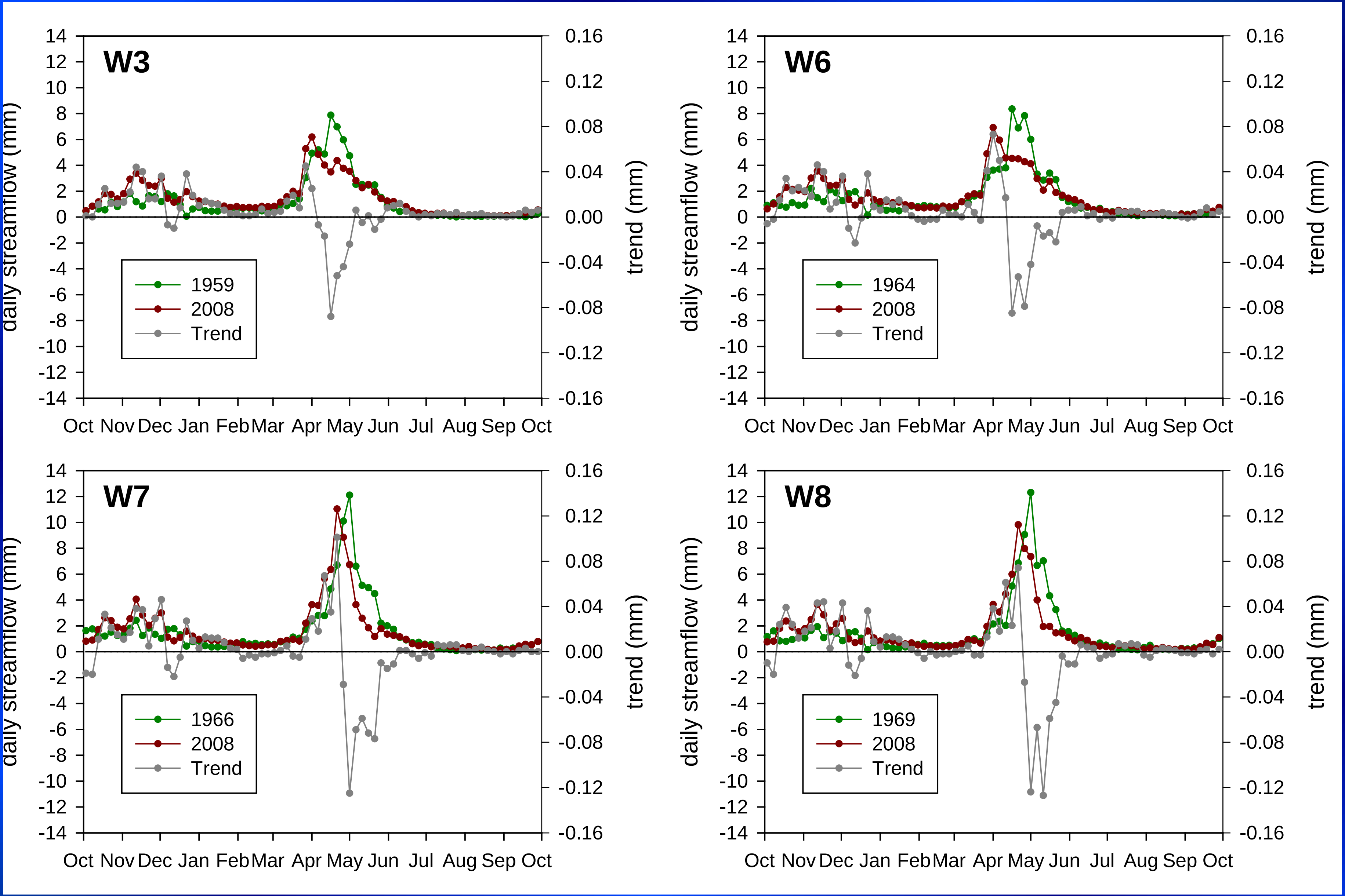
Long-term Air Temperature



Streamflow Quantity



Changes in Streamflow Timing



Climate Projections (HBEF)

	1970-1999	Mean Change 2070-2099					
		HadCM3		**PCM**		**GFDL**	
		A1 fi	B1	A1 fi	B1	A1 fi	B1
Temperature (°C)	5.7	+6.5	+3.1	+3.5	+1.7	+4.4	+2.0
Annual Precipitation (cm)	144	+31.7	+21.5	+3.9	+12.7	+20.2	+15.4
PAR (mmol m^{-2} s^{-1})	566	-4.6	+41.2	+104.7	+143.1	+17.2	-26.7

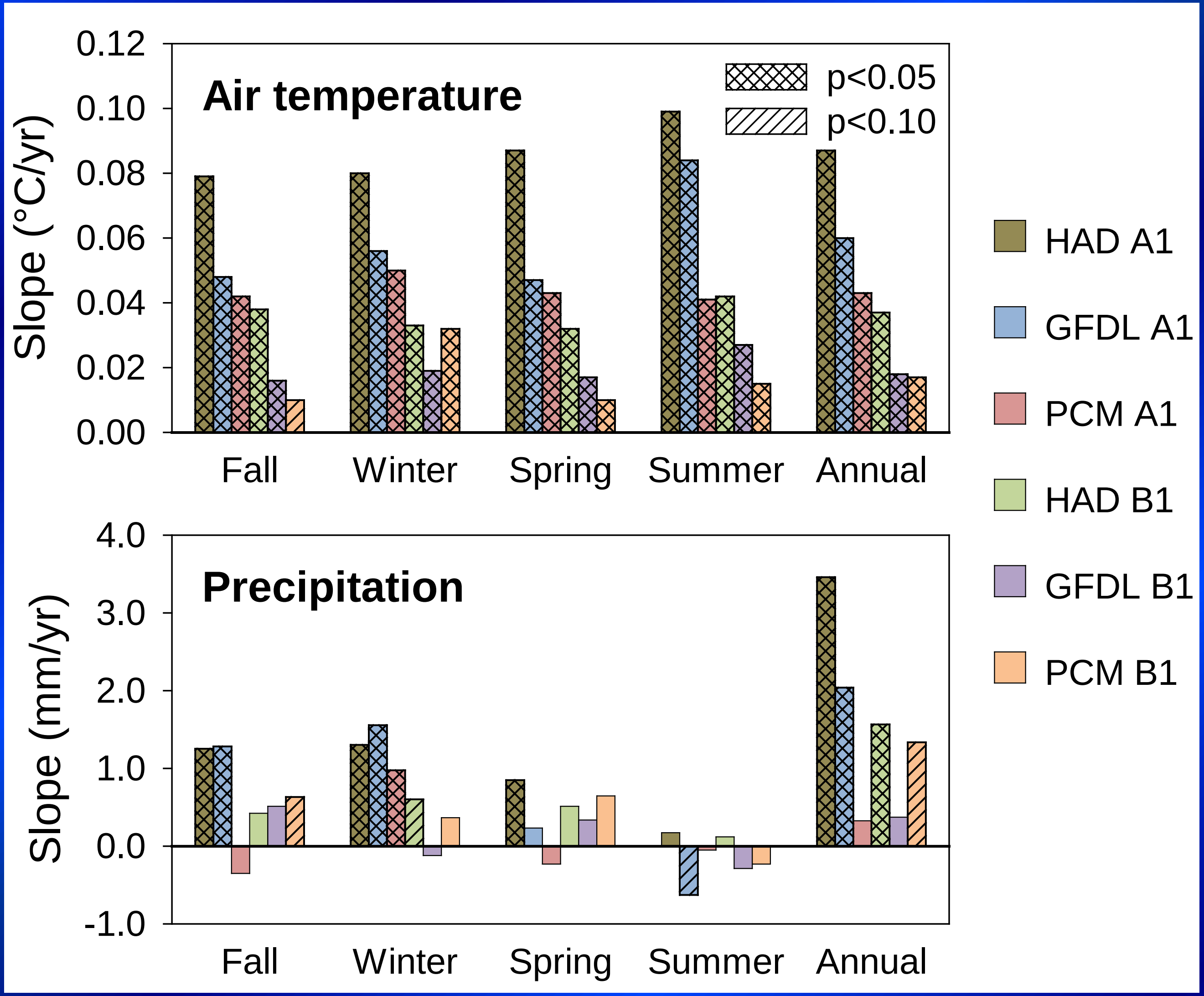
B1 (Low CO_2) = 550 ppm by 2100

A1 fi (High CO_2) = 970 ppm by 2100

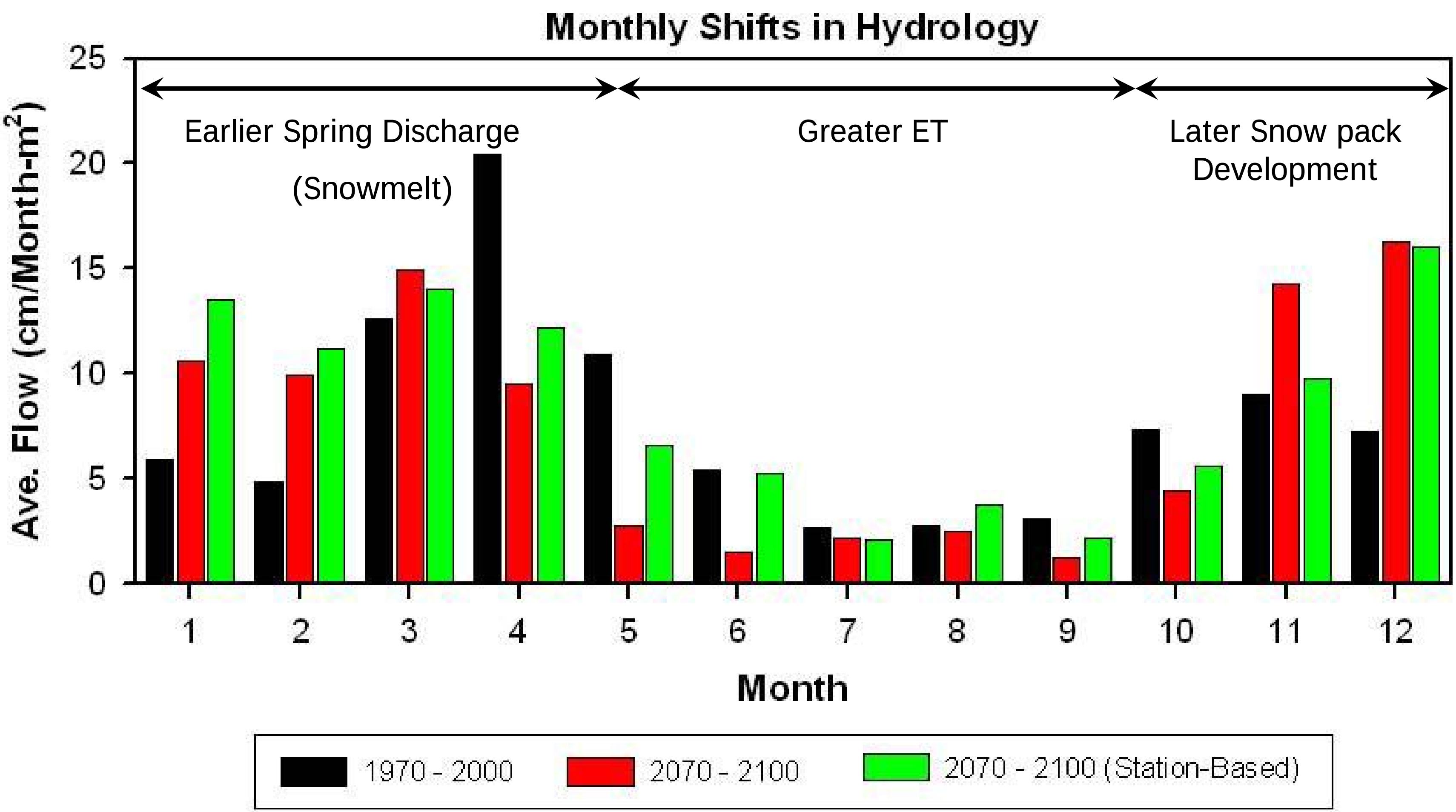
Current CO_2 = 390 ppm

In 1800 CO_2 = 280 ppm

Future Trends in Climate (2009-2099)



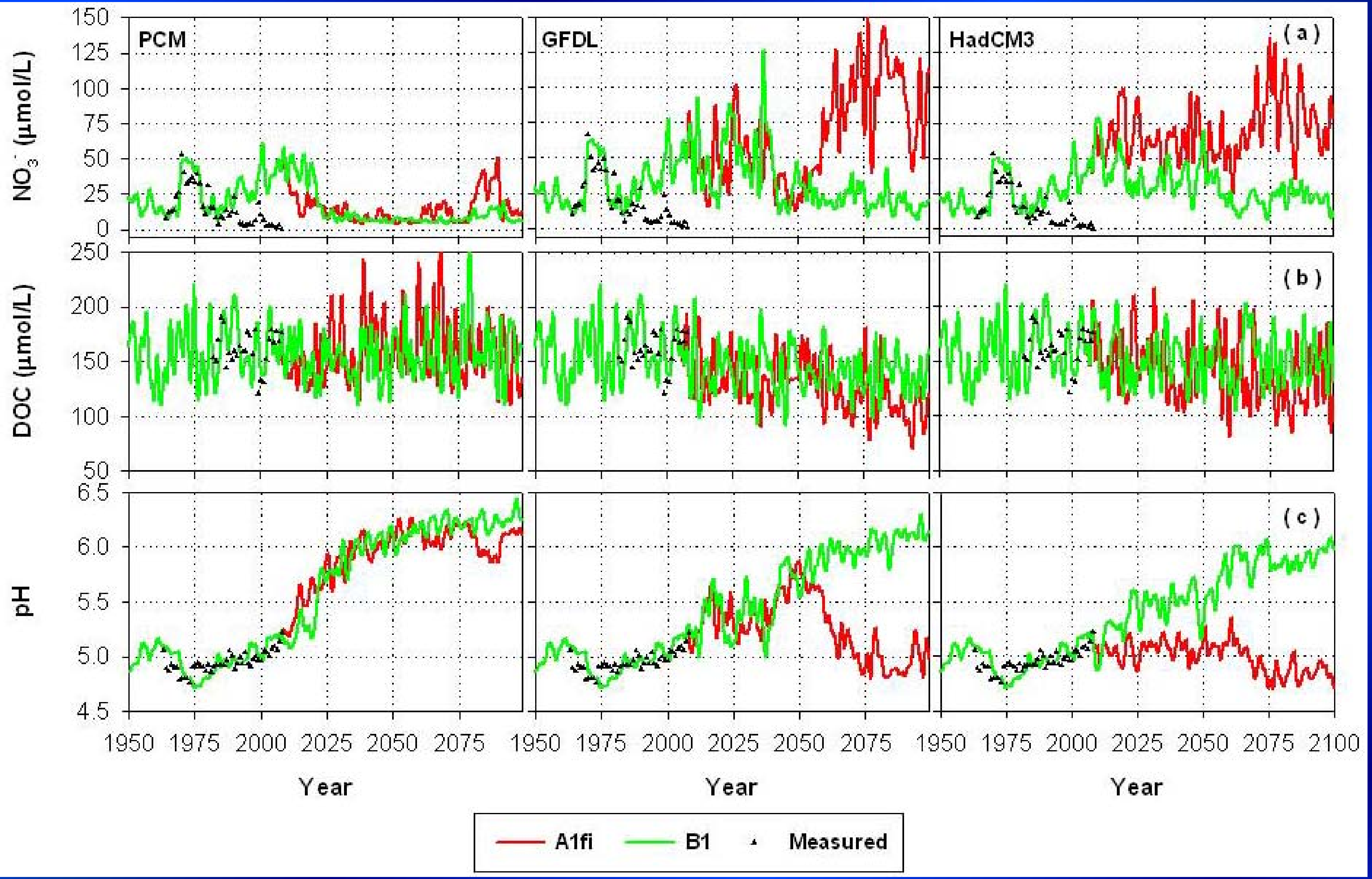
Stream Flow (HadCM3-A1 fi): Grid-Based vs. Station-Based



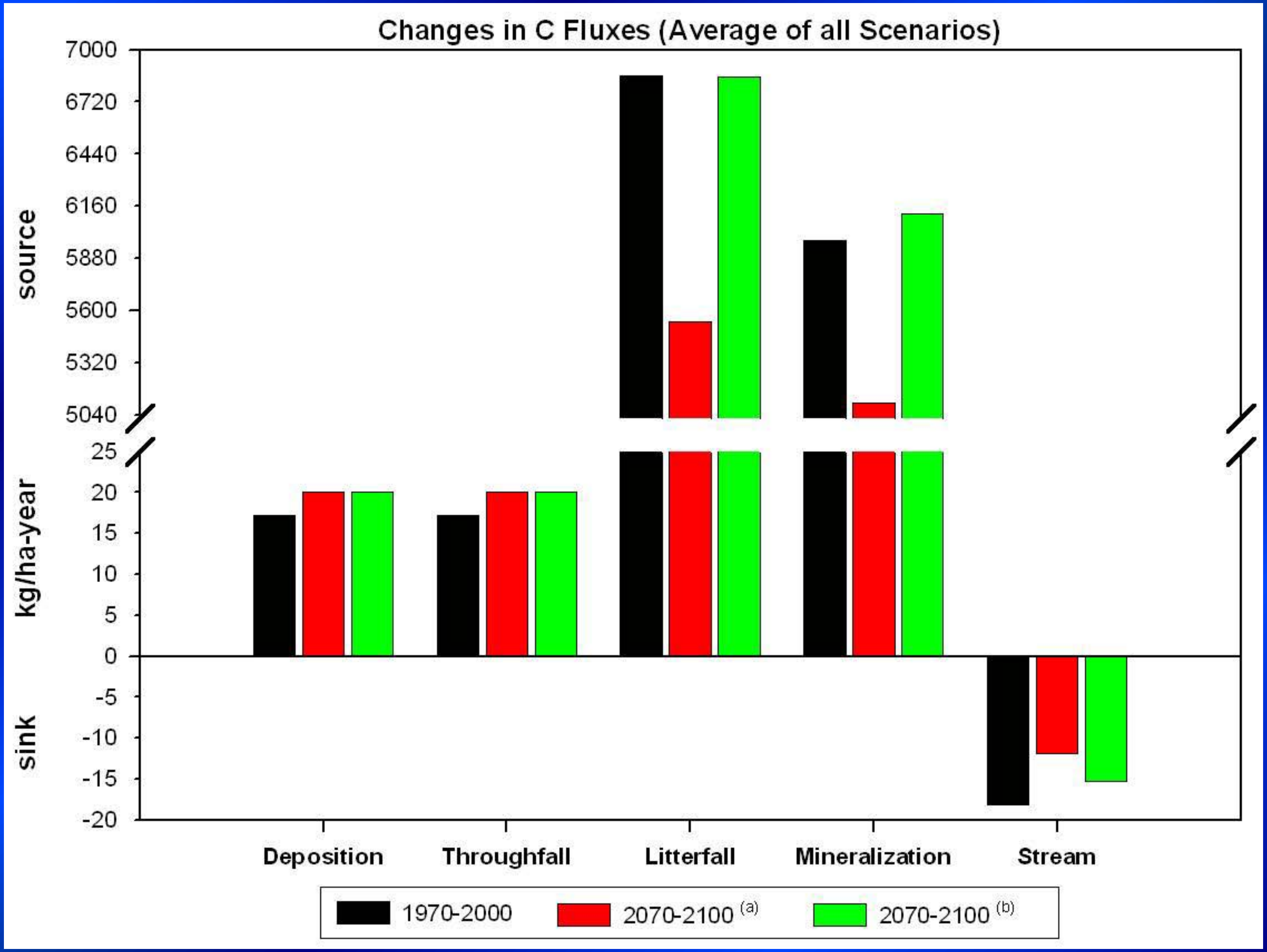
92.6 | 90.3 | 102.3

Streamwater Chemistry

With CO_2 Effect on Vegetation



Changes in *C* Fluxes under Climate Change

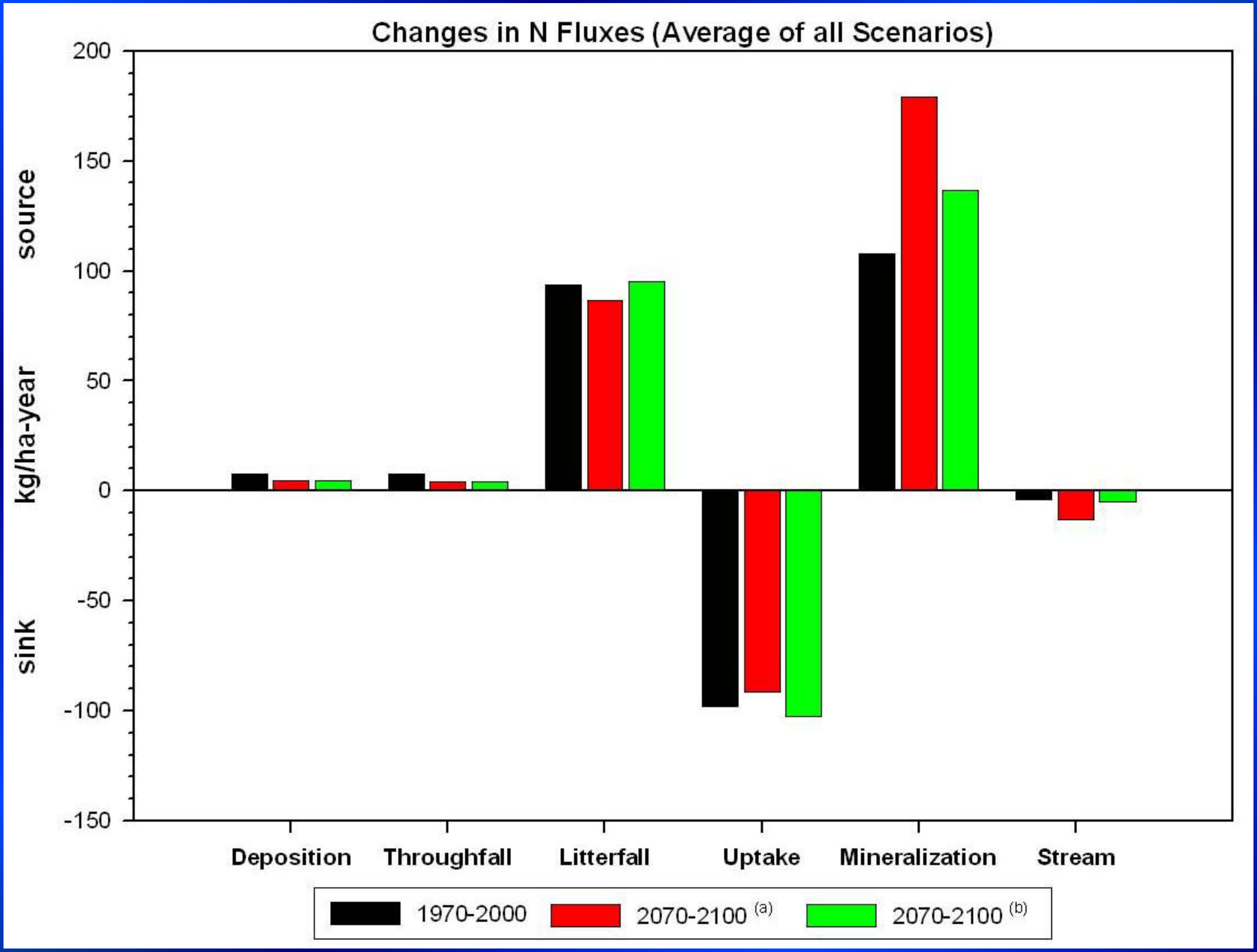


Note: Values for reference period (1970-2000) are simulated values from PnET-BGC. Future values are the average output of all six climate scenarios over the period of 2070-2100.

a Without CO_2 effects on vegetation

b With CO_2 effects on vegetation

Changes in *N* Fluxes under Climate Change

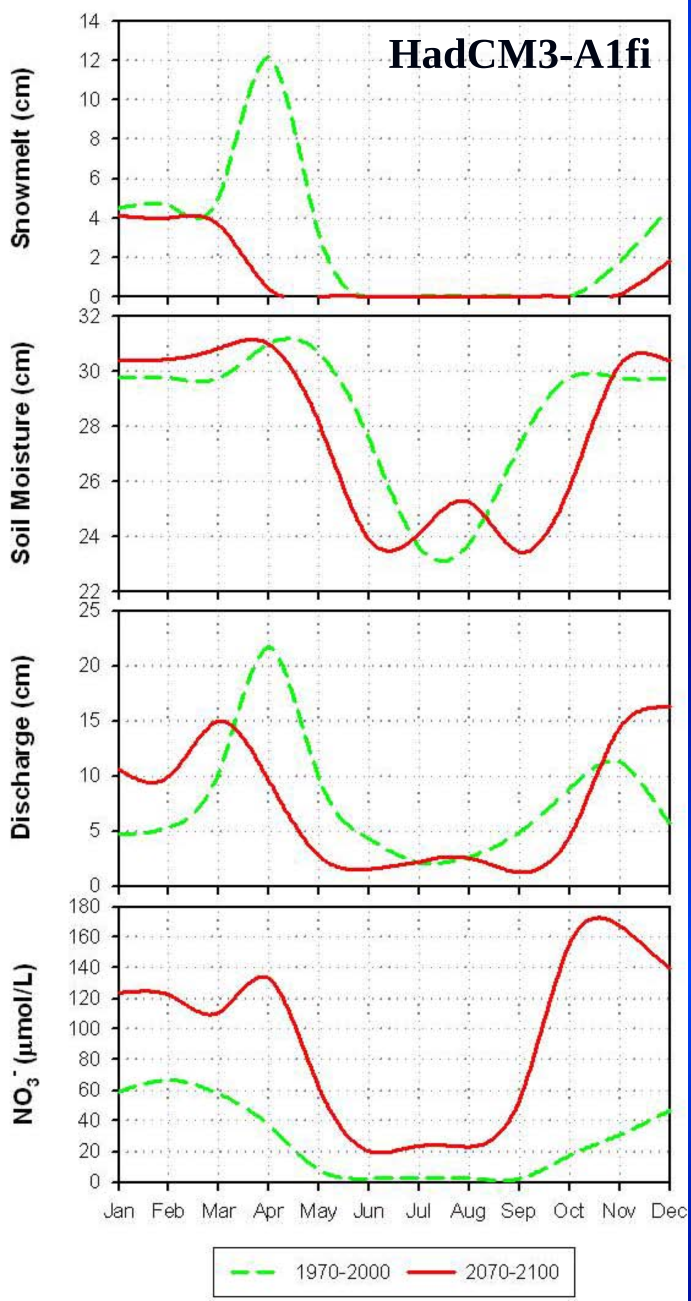


Note: Values for reference period (1970-2000) are simulated values from PnET-BGC. Future values are the average output of all six climate scenarios over the period of 2070-2100.

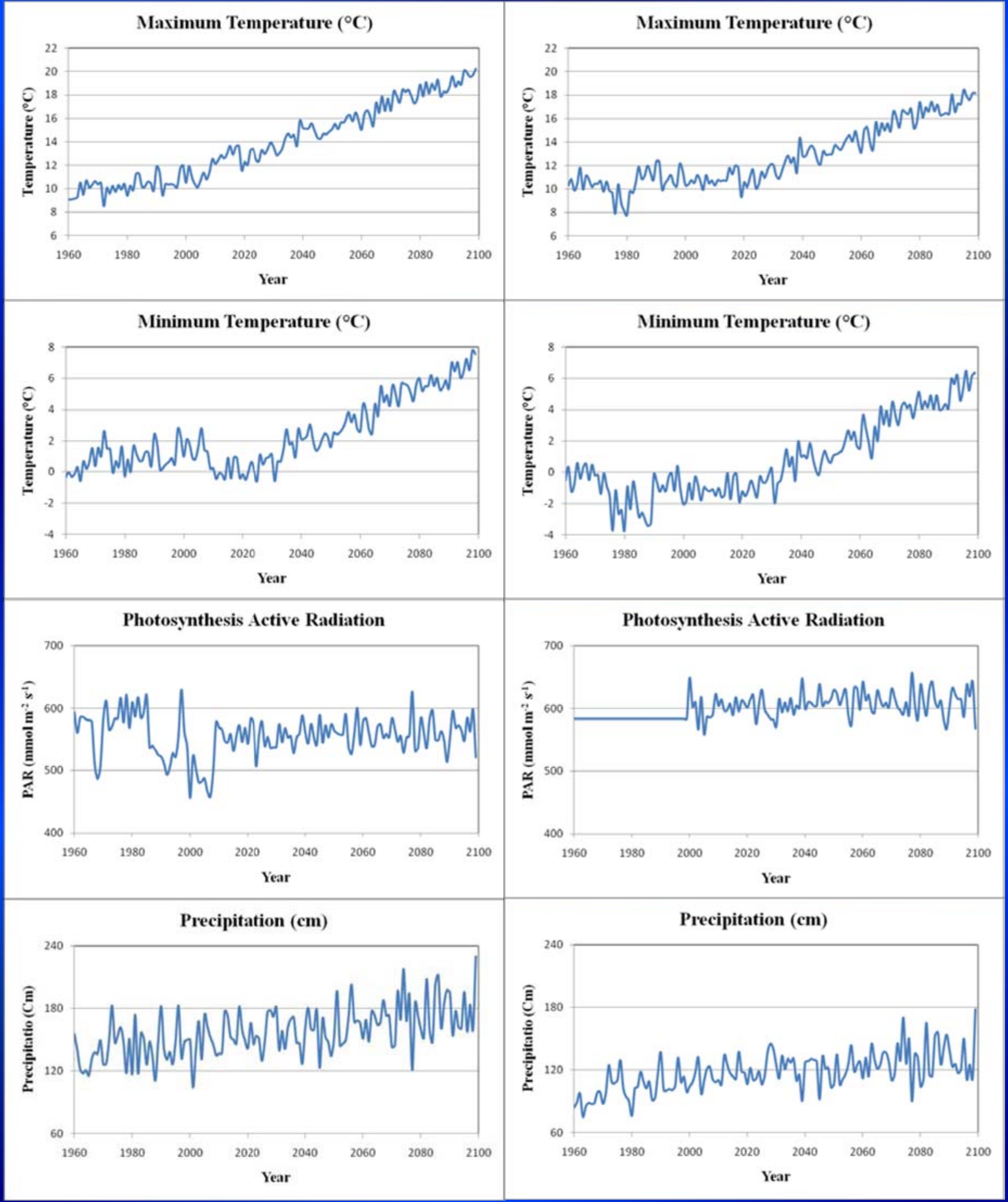
a Without CO_2 effects on vegetation

b With CO_2 effects on vegetation

Changes in Snowmelt, Soil Moisture, Discharge, and NO_3^-



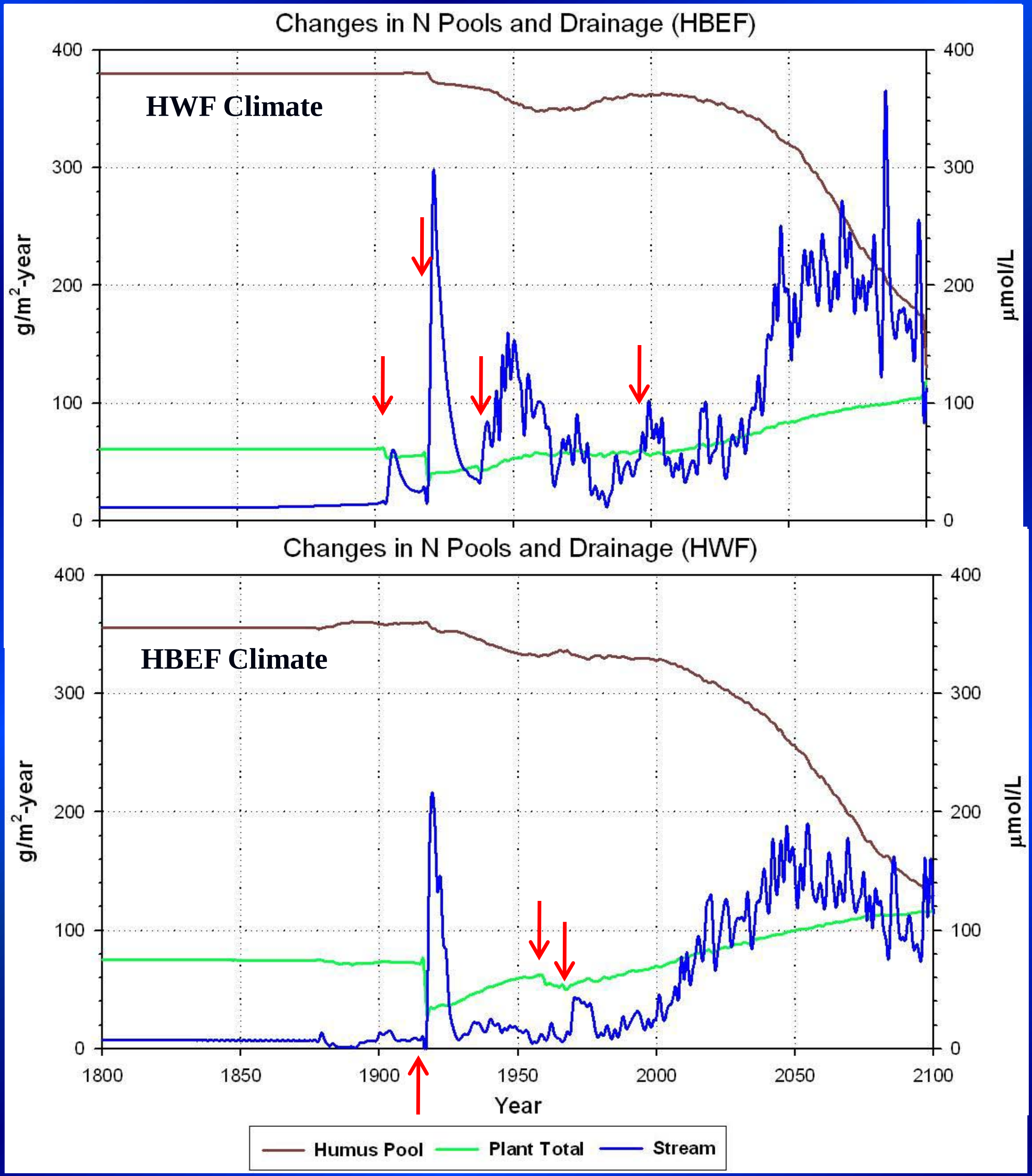
HBEF



Maximum Temperature (°C)
Temperature (°C)
Year
Maximum Temperature (°C)
Temperature (°C)
Year
Minimum Temperature (°C)
Temperature (°C)
Year
Minimum Temperature (°C)
Temperature (°C)
Year
Photosynthesis Active Radiation
PAR (mmol m-2 s-1)
Year
Photosynthesis Active Radiation
PAR (mmol m-2 s-1)
Year
Precipitation (cm)
Precipitatio (Cm)
Year
Precipitation (cm)
Precipitatio (Cm)
Year

HWF

Historical Land Disturbance (HBEF vs. HF)



Conclusions

- **Under future climate change, northern forest:**
  - **Hydrochemistry is sensitive to climatic drivers;**
  - **Hydrology changes due to later snow pack development, earlier spring discharge (snowmelt), and greater evapotranspiration;**
  - **Increases leaching losses of NO_3^- due to enhanced soil mineralization resulting in soil and stream water acidification.**
- **The effect of increasing atmospheric CO_2 on vegetation partially offsets NO_3^- loss by enhancing plant growth rates and nutrient uptake.**
- **Over the first half of the 21st century CO_2 is the dominant driver of watershed responses to climate change while it shifts to temperature over the second half.**

Future Work

- Additional cross site analysis examining latitude, elevation, climate, vegetation, land disturbance and atmospheric deposition history
- Interactions of climate, land disturbance, and air pollution
- Examination of grid based vs station based downscaling
- Publications

Publications/Presentation

- **Pourmokhtarian, A., Driscoll, C. T., Campbell, J. L., Hayhoe, K., (2011)** ***'Modeling Potential Hydrochemical Responses to Climate Change and Rising CO_2 at the Hubbard Brook Experimental Forest Using a Dynamic Biogeochemical Model (PnET-BGC)'*** **Water Resources Research (in review)**

- **Campbell, J. L., Driscoll, C. T., Pourmokhtarian, A., Hayhoe, K., (2010)** ***'Streamflow Responses to Past and Projected Future Changes in Climate at the Hubbard Brook Experimental Forest, New Hampshire, USA'*** **Water Resources Research**

- **Tominaga, K., Aherne, J., Watmough, S. A., Alveteg, M., Cosby, B. J., Driscoll, C. T., Posch, M., Pourmokhtarian, A., (2010)** ***'Predicting Acidification Recovery at the Hubbard Brook Experimental Forest, New Hampshire: Evaluation of Four Models*'** **Environmental Science & Technology**

- **18 presentation at professional meetings**

Acknowledgements

- US EPA STAR program
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- NSF LTER program
- US EPA LTM program
- Site monitoring support

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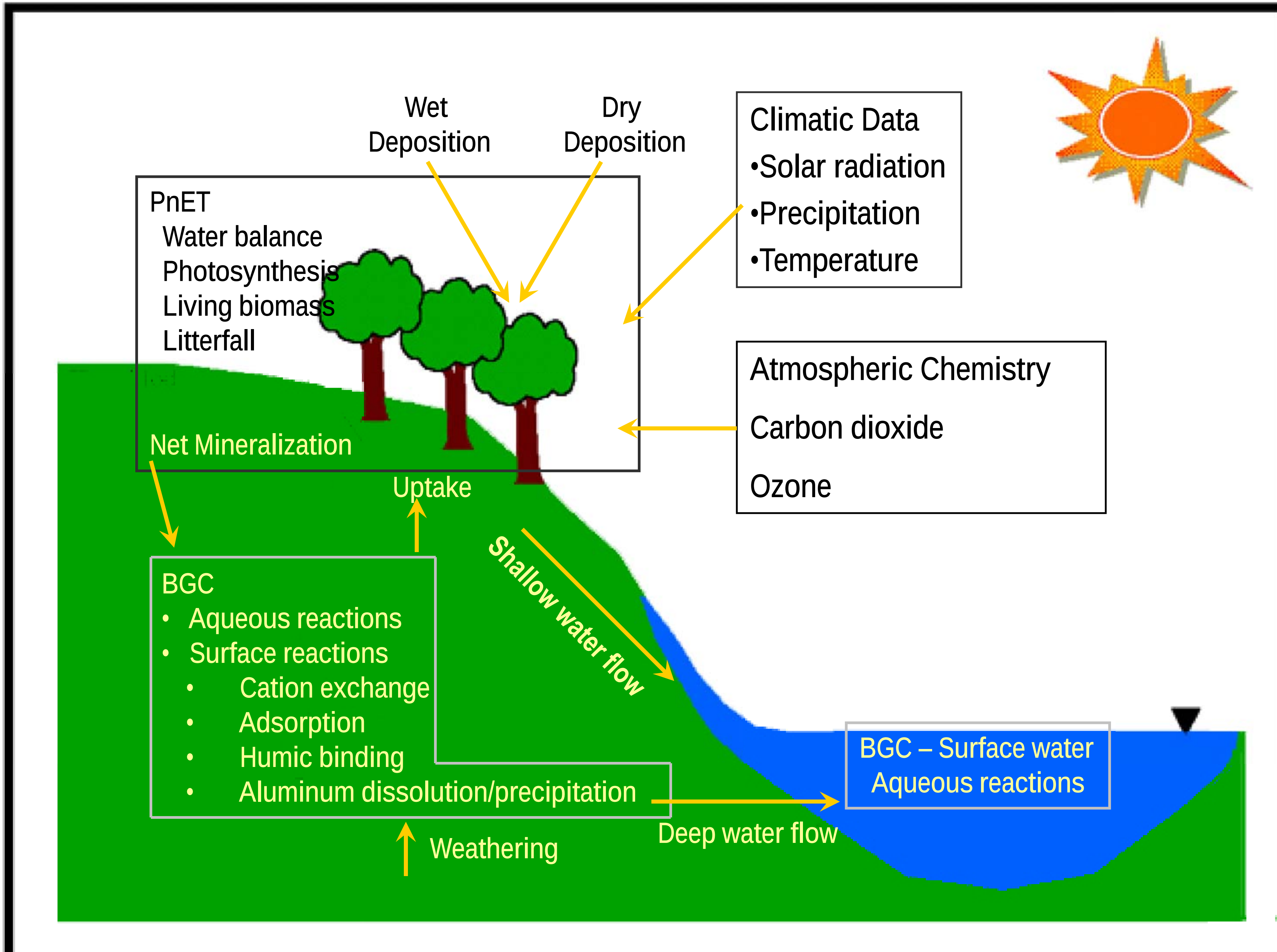

Wet
Deposition
Dry
Deposition
Climatic Data
•Solar radiation
•Precipitation
•Temperature
PnET
Water balance
Photosynthesis
Living biomass
Litterfall
Atmospheric Chemistry
Carbon dioxide
Ozone
Net Mineralization
Uptake
Shallow water flow
BGC
• Aqueous reactions
• Surface reactions
• Cation exchange
• Adsorption
• Humic binding
• Aluminum dissolution/precipitation
BGC – Surface water
Aqueous reactions
Deep water flow
Weathering

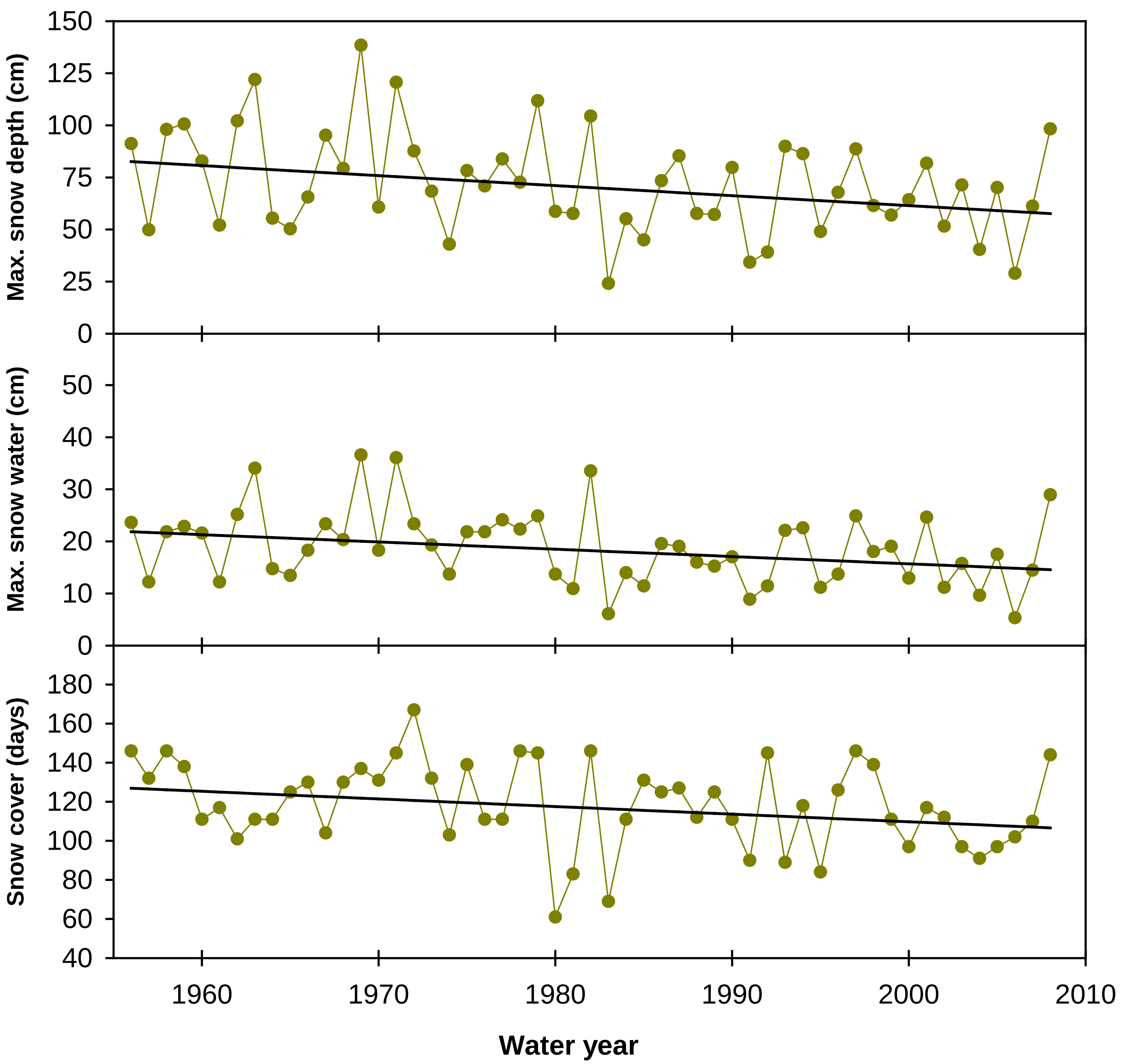
Downscaling Approaches:
Gridded Quantile Mapping vs. Station-Based

Gridded Quantile Mapping:

- The most commonly-used method for monthly downscaling is the Bias Correction-Spatial Disaggregation (BCSD) approach.
- Originally developed for adjusting global-scale model output for long-range streamflow forecasting.
- More recently, it has been adapted for use in studies examining the hydrologic impacts of climate change including Sierra Nevada snowpack and water resources in the U.S. Northeast.
- The resulting time series reproduces changes in both the mean and variability of monthly observations as simulated by the GCM outputs, and compares favorably to regional climate model simulations.

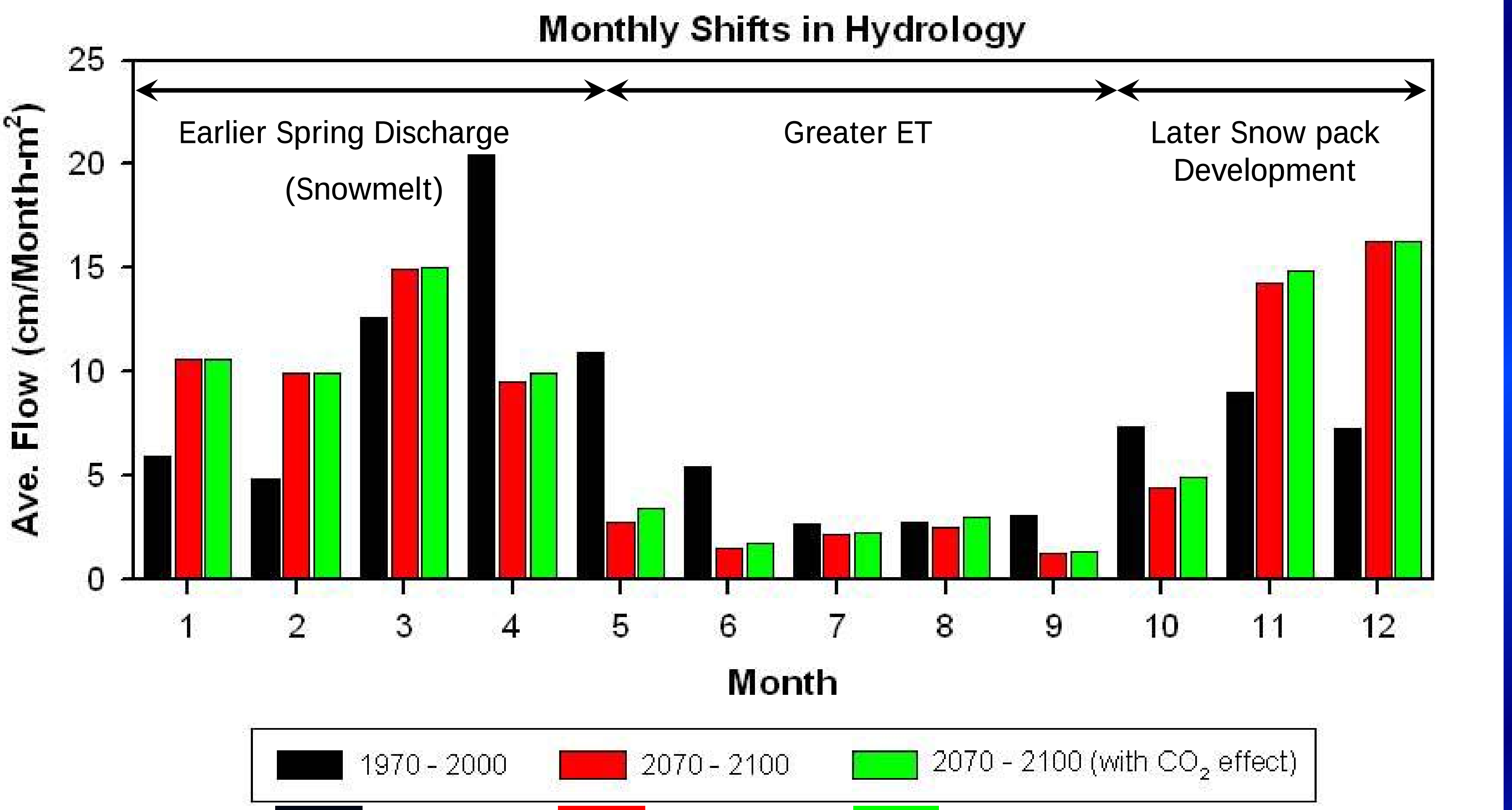
Station-based Daily Asynchronous Regression:

- More complex statistical method that uses quantile regression to determine relationships between two quantities that do not have temporal correspondence, but that are expected to have similar statistical properties such as mean and variance. A regression relationship is determined between two independent time series using only their probability distributions.
- This approach uses all the information provided by the global climate model regarding how day-to-day variability might change. It allows the shape of the probability distribution to change over time, including shifts in the mean, the variance, and even the skewness (symmetry) of the distribution.
- Asynchronous regression-based projections for changes in the tail of the distribution, such as the number of days per year over 95^{o}F or 36^{o}C, can be significantly different from other downscaling methods that do not include daily global climate model inputs



Max. snow depth (cm)
150
125
100
75
50
25
0
Max. snow water (cm)
50
40
30
20
10
0
Snow cover (days)
180
160
140
120
100
80
60
40
1960
1970
1980
1990
2000
2010
Water year

Stream Flow (HadCM3-A1 fi)



92.6 90.3 93.5

Changes in *C* Fluxes under Climate Change

Fluxes/Pools	C/DOC		
Period	1970-2000	2070-2100[a]	2070-2100[b]
Deposition	17.2	20.0	20.0
Throughfall	17.2	20.0	20.0
Litterfall	6860.8	5543.0	6855.8
Weathering	0.0	0.0	0.0
Uptake	0.0	0.0	0.0
Mineralization	5975.6	5109.1	6117.5
Nitrification	0.0	0.0	0.0
Plant total	228778.5	296834.6	460706.0
Humus	119713.0	79138.2	91331.8
Soil Exchangeable pools	0.0	0.0	0.0
Drainage Losses	-18.1	-11.9	-15.2

Note: Values for reference period (1970-2000) are simulated values from PnET-BGC. Future values are the average output of all six climate scenarios over the period of 2070-2100. Positive fluxes indicate an increase in soil solution concentration.

a Without CO_2 effects on vegetation

b With CO_2 effects on vegetation

Changes in *N* Fluxes under Climate Change

Fluxes/Pools	NH_4-N			NO_3-N		
Period	1970-2000	2070-2100[a]	2070-2100[b]	1970-2000	2070-2100[a]	2070-2100[b]
Deposition	2.4	2.0	2.0	5.6	2.5	2.5
Throughfall	2.0	1.6	1.6	5.6	2.5	2.5
Litterfall	93.6	86.8	95.1	0.0	0.0	0.0
Weathering	0.0	0.0	0.0	0.0	0.0	0.0
Uptake	-82.5	-22.2	-71.9	-15.5	-69.0	-30.9
Mineralization	94.2	99.9	103.5	13.7	79.3	33.2
Nitrification	-13.7	-79.3	-33.2	13.7	79.3	33.2
Plant total	681.9	1035.5	1309.8	0.0	0.0	0.0
Humus	3372.2	2388.0	2619.8	0.0	0.0	0.0
Soil Exchangeable pools	0.0	0.0	0.0	0.0	0.0	0.0
Drainage Losses	0.0	0.0	0.0	-3.8	-12.8	-4.8

Note: Values for reference period (1970-2000) are simulated values from PnET-BGC. Future values are the average output of all six climate scenarios over the period of 2070-2100. Positive fluxes indicate an increase in soil solution concentration.

a Without CO_2 effects on vegetation

b With CO_2 effects on vegetation

Stream Flow (HadCM3-A1 fi): Grid-Based vs. Station-Based