Anomaly Propagation and Trend Detection of Land-atmosphere Hydrologic Cycle Changes

November 2, 2010

Presented at the International Workshop of Water Vulnerability & Adaptive Governance under the Climate Change & Development, Beijing, China

Pat Yeh, M. Yuan and Taikan Oki

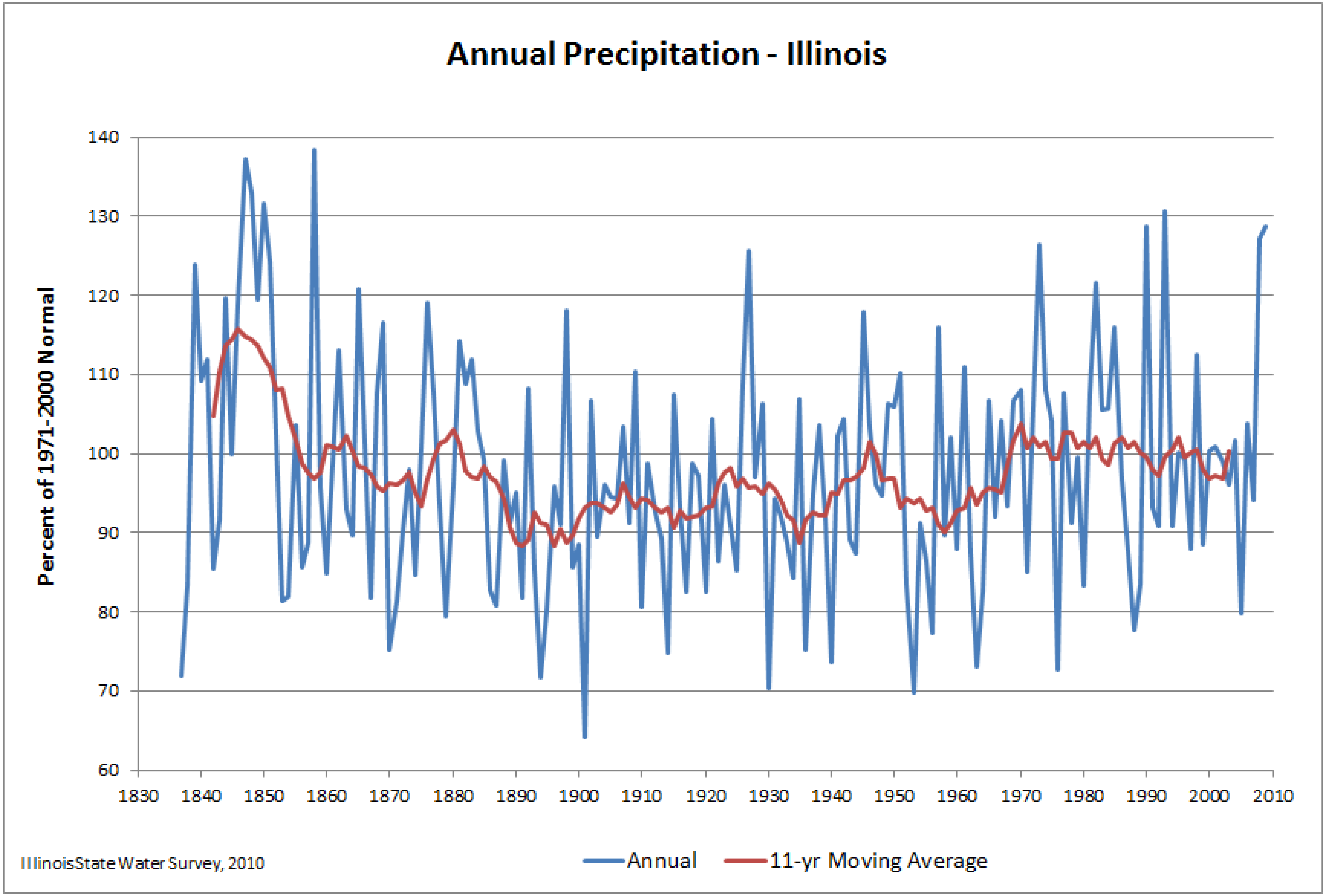
OKI Laboratory, Institute of Industrial Science, University of Tokyo, Japan

Outline of the Talk

- Combined Land–atmosphere water balance and hydrologic cycles
- Study Region – Illinois and Data
- Characteristics and Anomaly propagation through the combined Land-atmosphere hydrological cycle
- Mann-Kendall test to identify the annual and monthly trend of Hydro-climatic Variables (1970 -2009)
- Conclusions

Motivation: Warming vs. Hydrologic Cycle Intensification

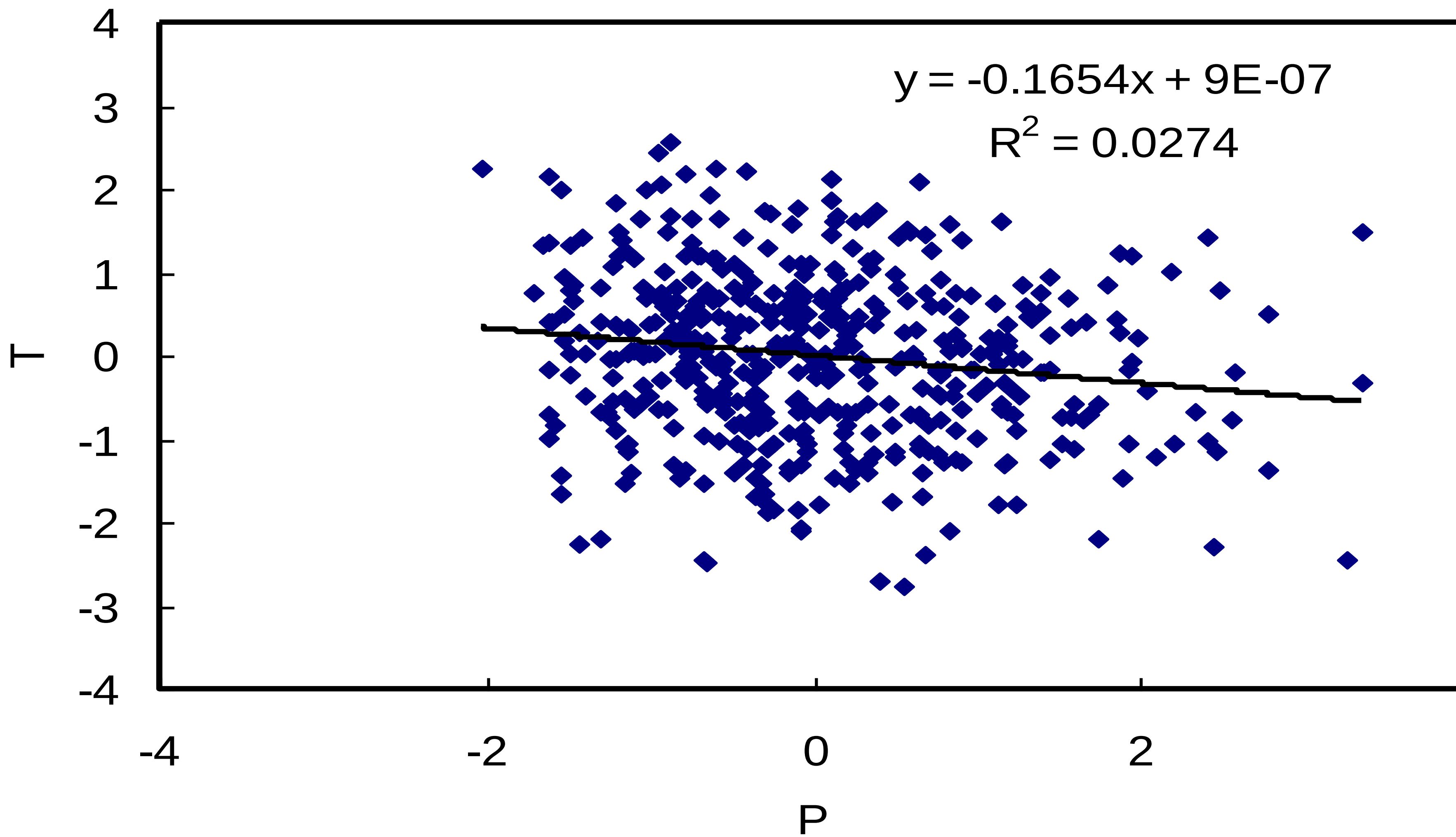
- Clasius-Clapeyron relation for P-T relationship? Thermodynamic vs. Dynamic contribution ?
- Water-resources sustainability ??
- IPCC AR4 - more storms, floods, droughts, heat waves in the 21st century??
- However, empirical evidence on the intensification of hydrological cycle are not well established; Regional analyses are variables and sometimes contradictory
- Existing empirical evidence does not yet support an increase in the frequency or intensity of floods and droughts
- **Numerous trend detection studies have been performed with respect to the records of past temperature, precip. and streamflow (*trend direction, magnitude, mechanism*??). To our knowledge, none or very little have considered most water balance components in the combined land-atmospheric hydrologic cycles. Therefore, the whole picture of hydrological signatures as a result of climate/environemntal change cannot be revealed.**



(Courtesy of ISWS)

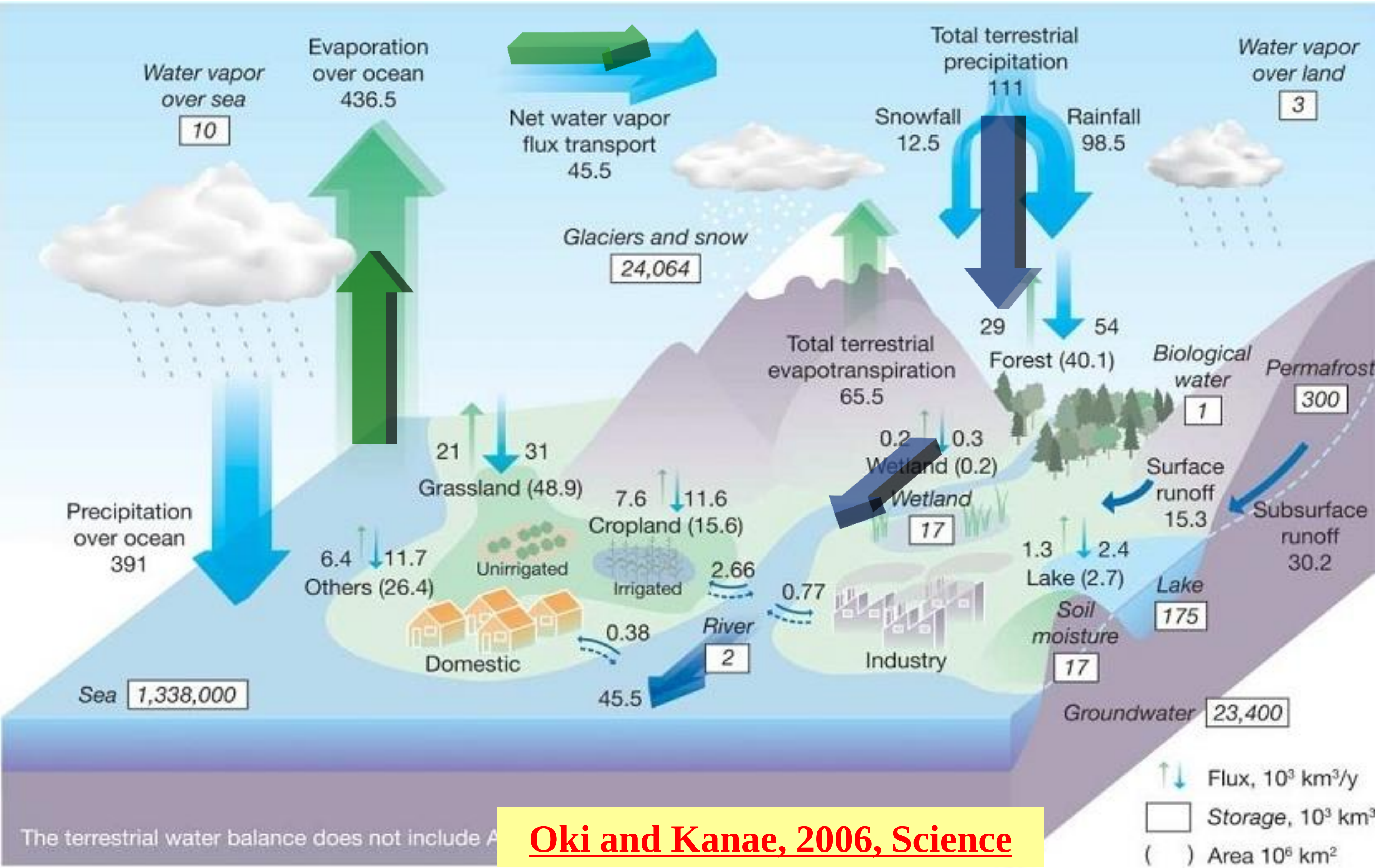
1970-2009 Illinois Monthly Precip. vs. Temp. Standardized Anomalies

P



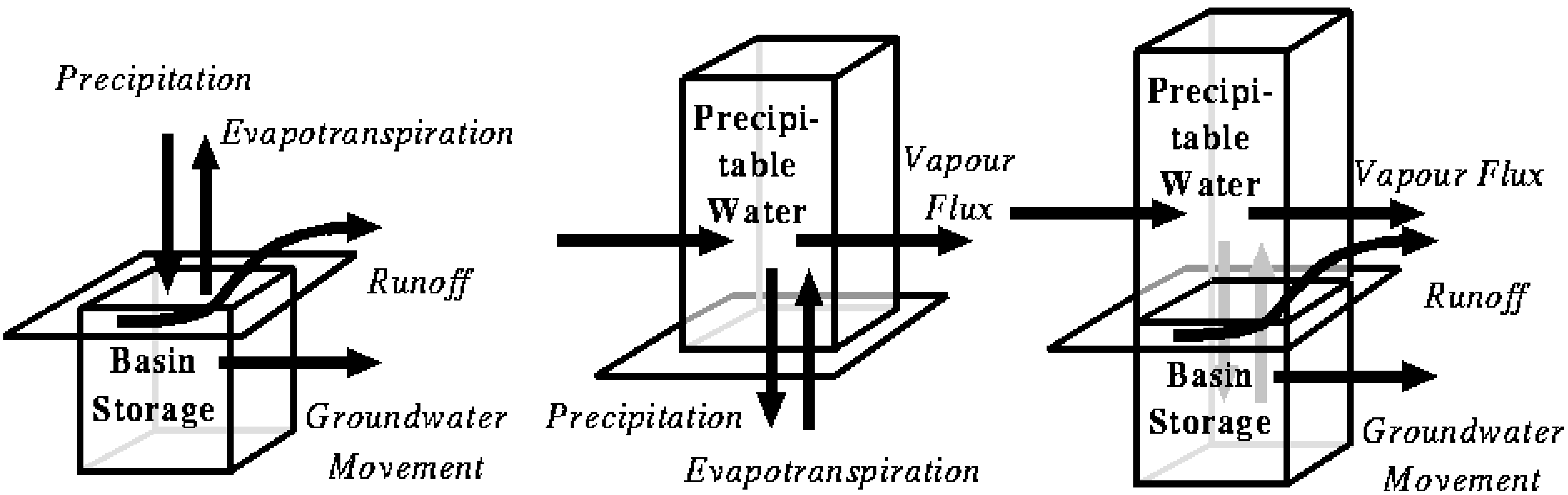
T

Global Water Cycle: Storages and Fluxes



Oki and Kanae, 2006, Science

Combined Land surface-Atmospheric Water Balance



(a) Water balance in the basin

(b) Water balance in the atmosphere

(c) Combined water balance

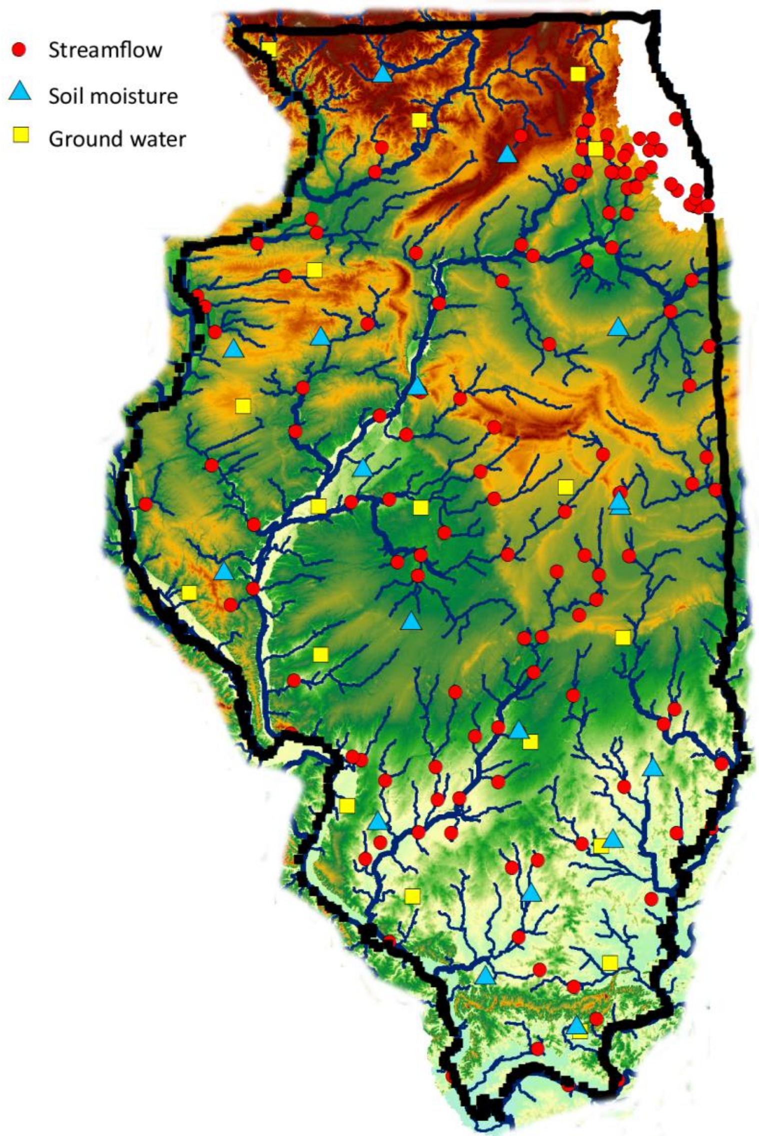
$$\frac{\partial S}{\partial t} = P - E - R_o - R_u$$

$$\frac{\partial W}{\partial t} = Q + (E - P)$$

$$\frac{\partial S}{\partial t} = -\frac{\partial W}{\partial t} + Q - R_o$$

Change in total *terrestrial water storage* can be estimated from water vapor convergence and river discharge data based on combined water balance

Illinois Long-term Hydrometeorology Network



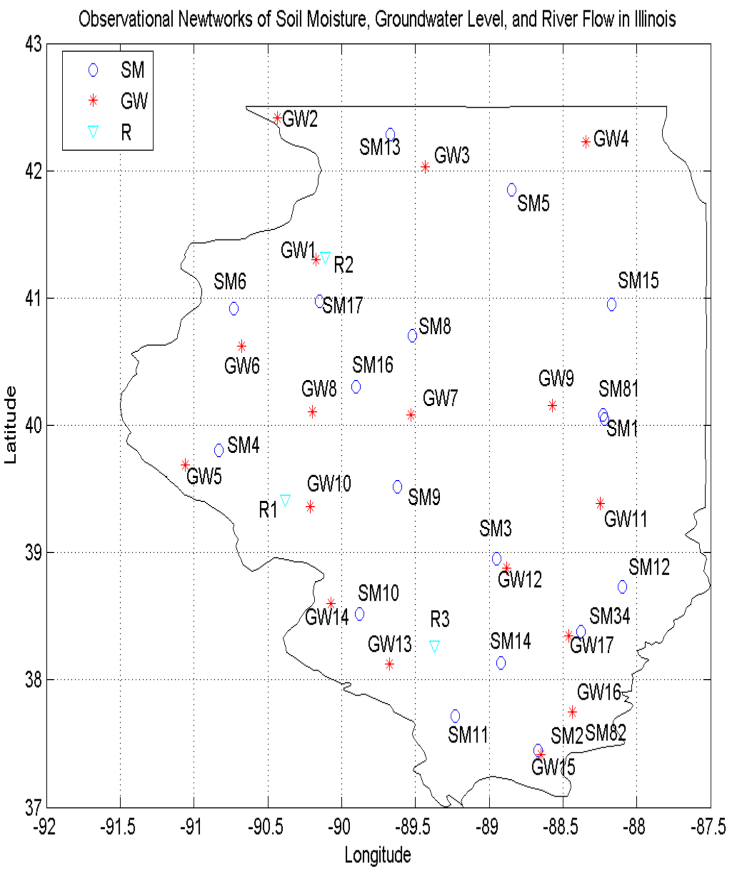
- *One of the very few regions with almost the entire set of long-term (from 1970s or 1980s on) observations for most water balance components*

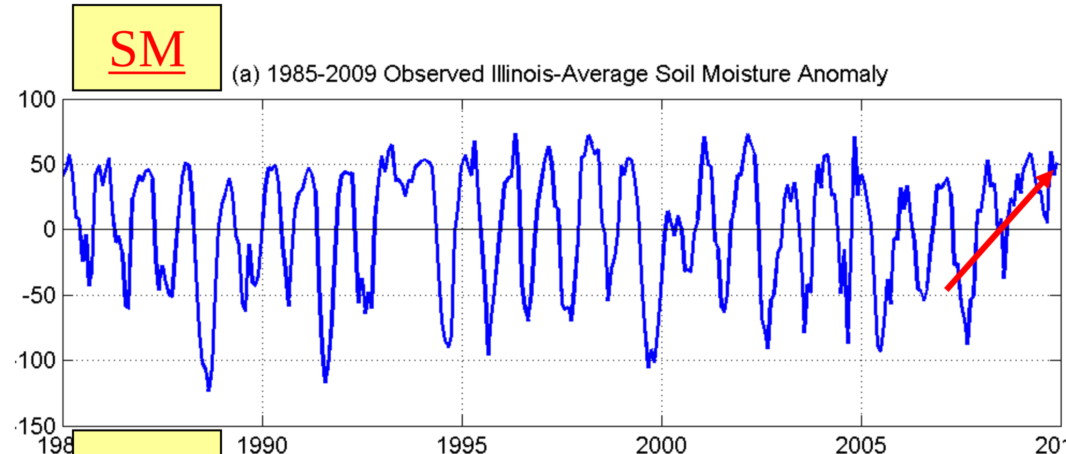
- *Humidity and Atmospheric Vapour Convergence based on NCEP/DOE R2 Reanalysis Data*

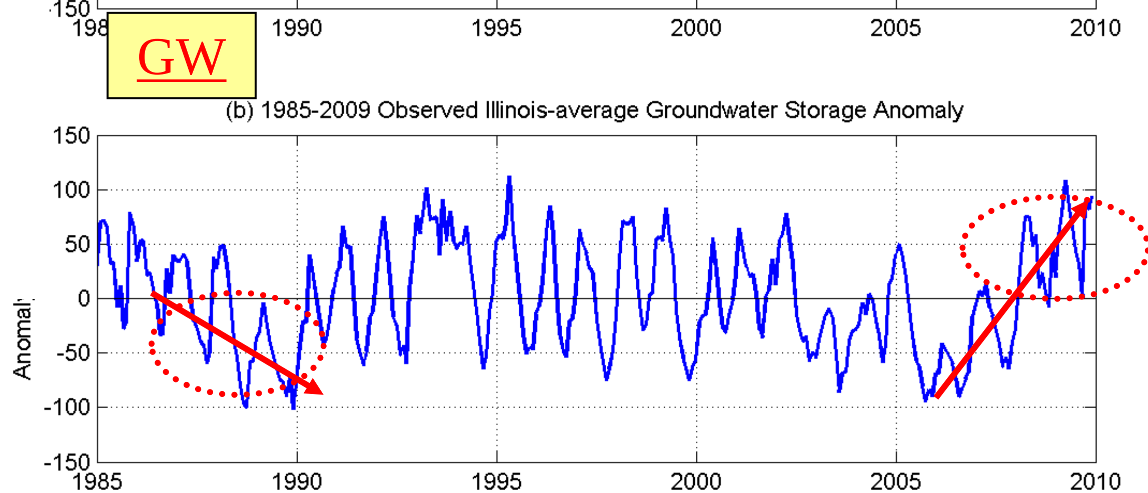
- *Using terrestrial and atmospheric water balance computations to estimate ET respectively.*

http://hydro.iis.u-tokyo.ac.jp/

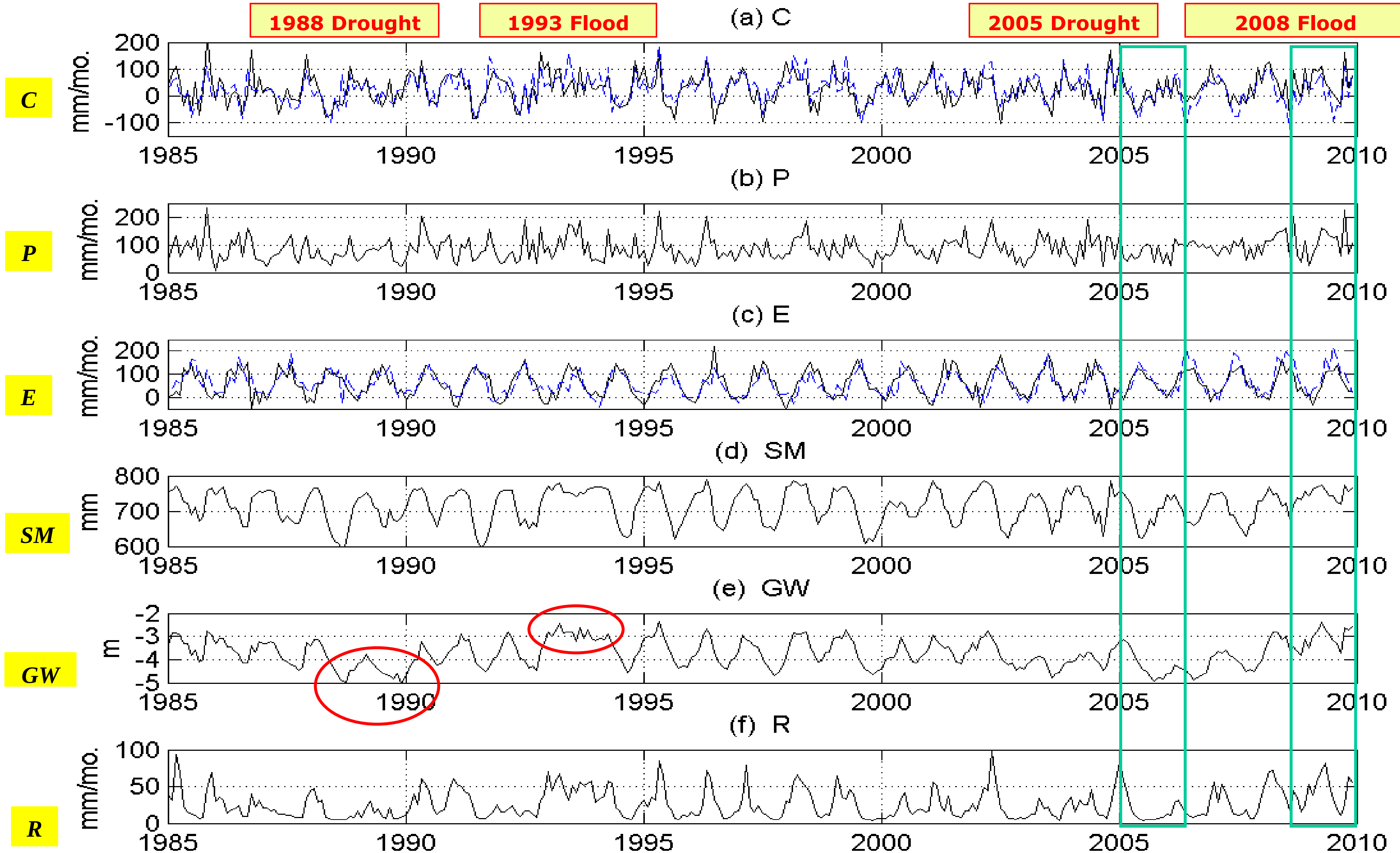
Data	Station #	Resolution	Sources
Precip. / Snow	129	daily	MRCC
Soil Moisture	19	bi-weekly	ISWS
Water Table Depth	19	monthly	ISWS
Streamflow	3	daily	USGS





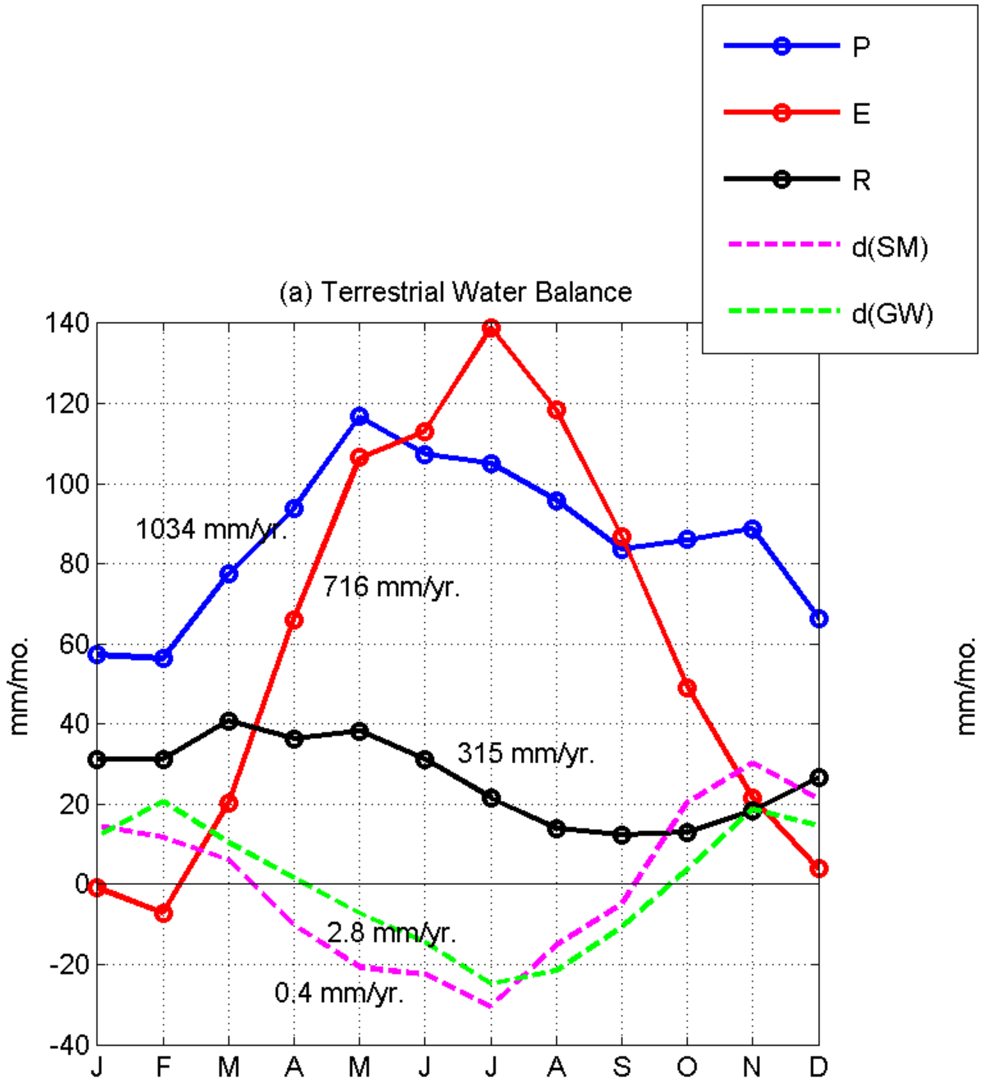


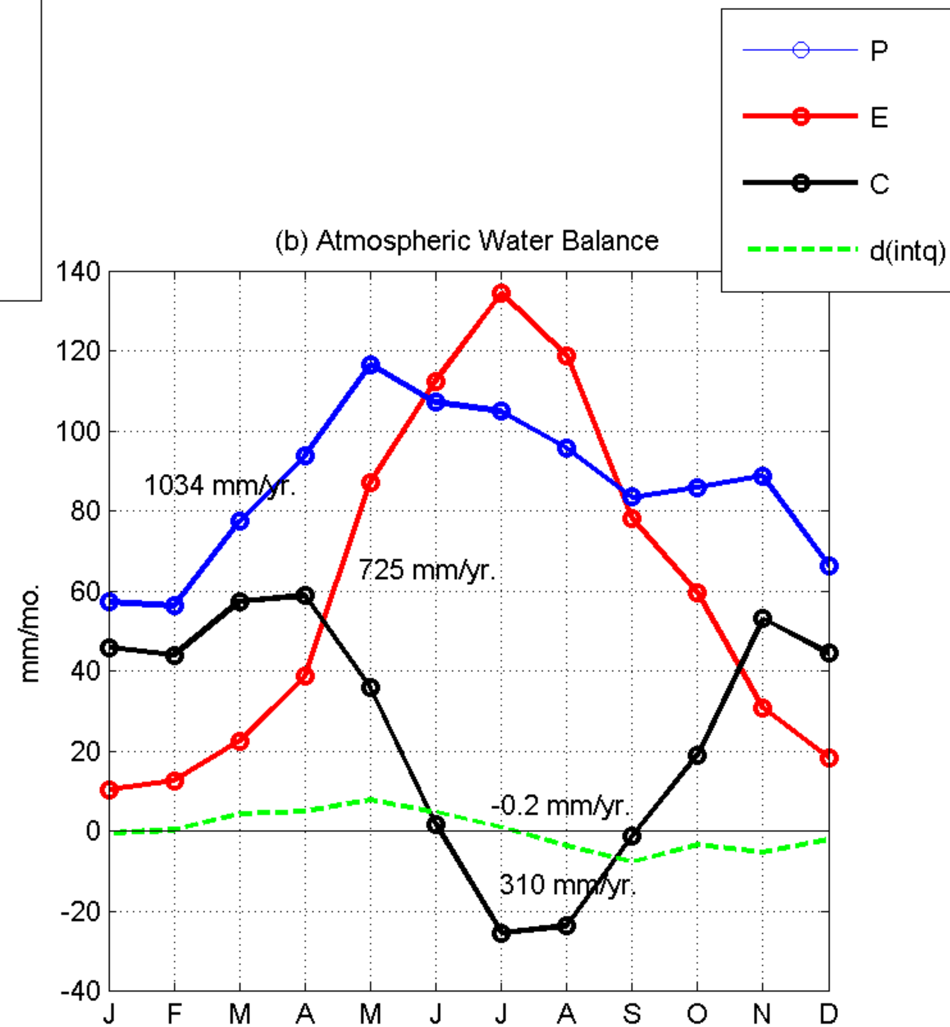
25-year (1985-2009) monthly time series in Illinois

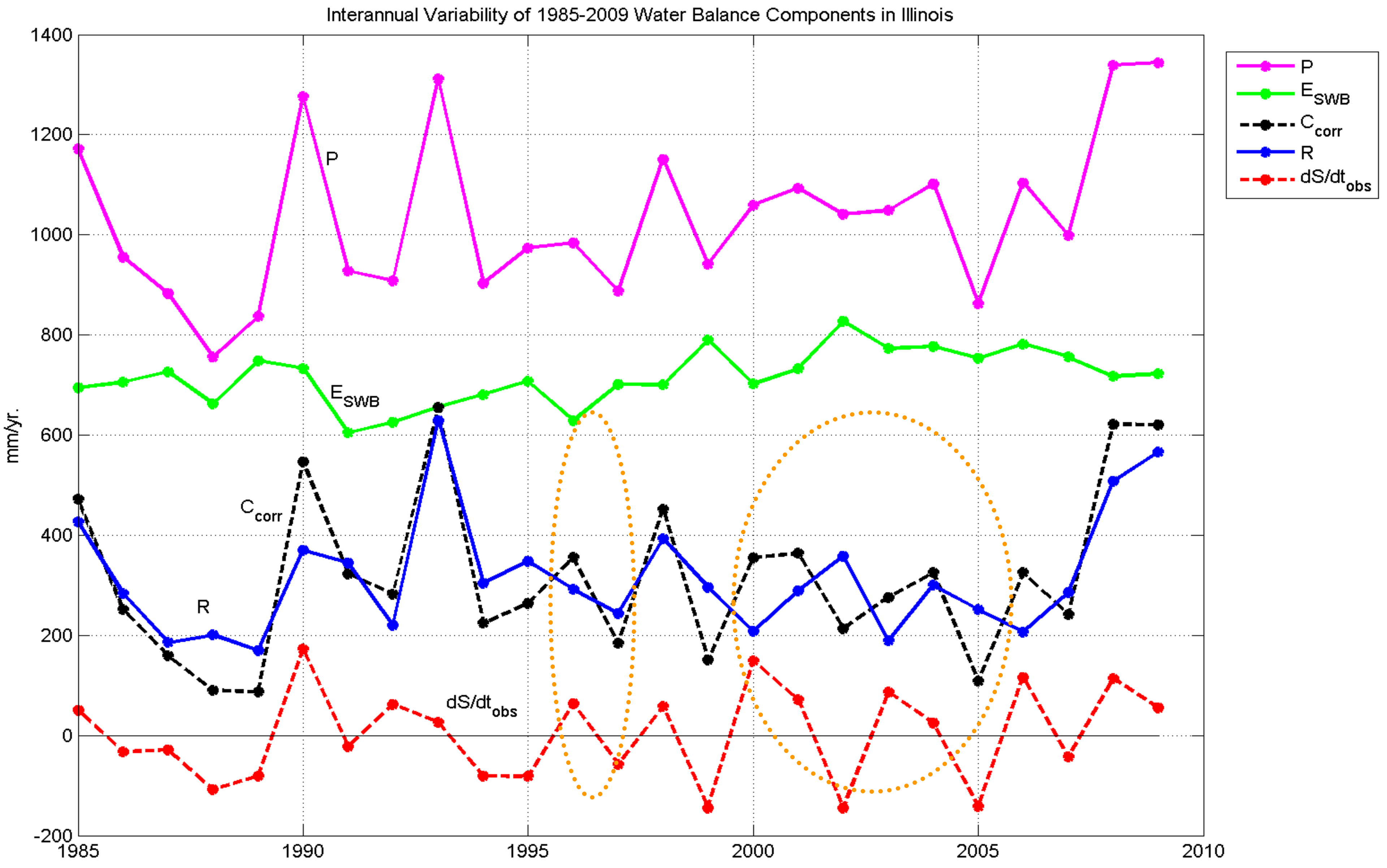


Note: Snow storage is relatively insignificant compared to SM & GW in Illinois

1985 – 2009 Mean Seasonal Cycles of Terrestrial and Atmospheric Water Balances

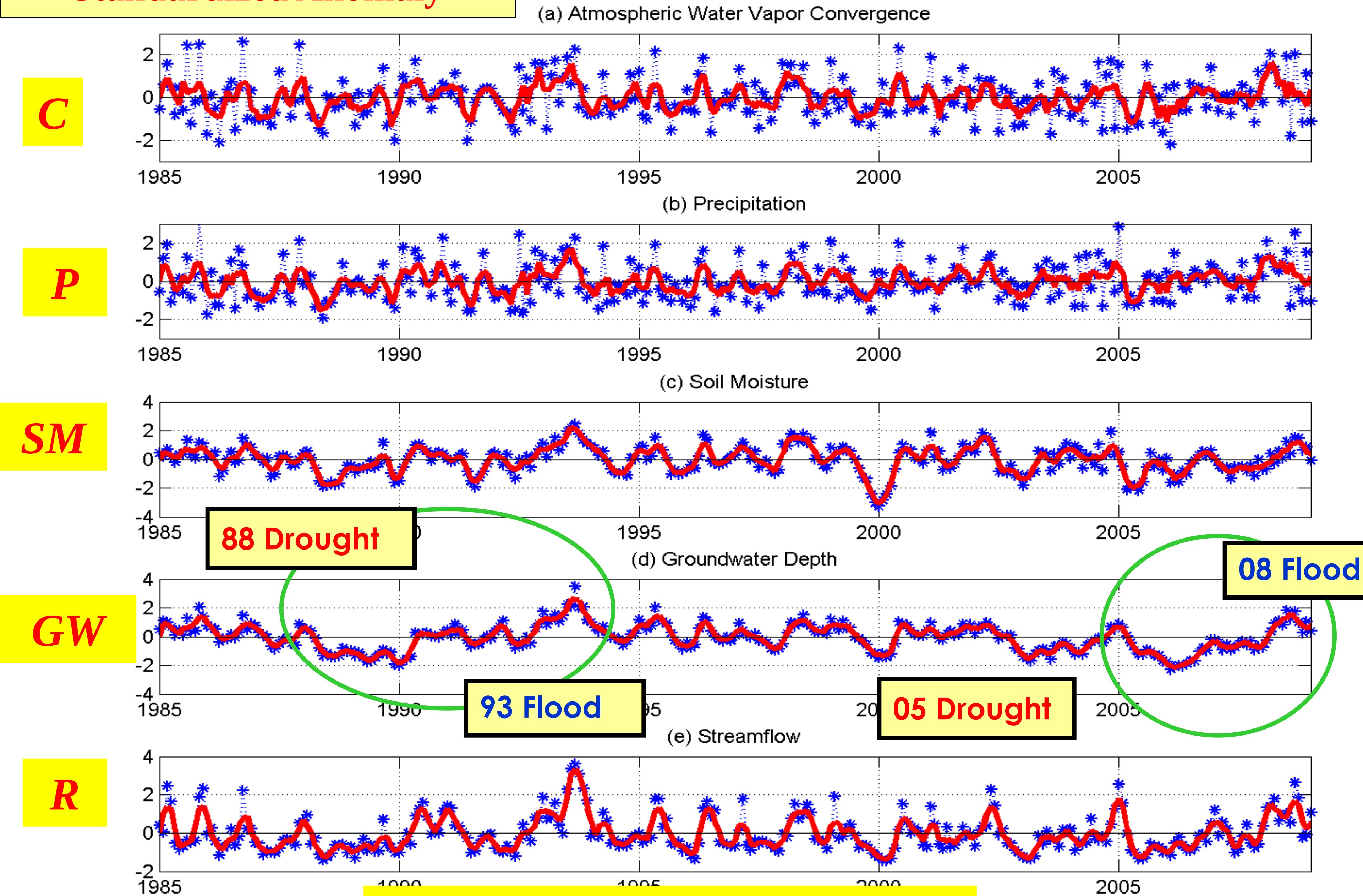




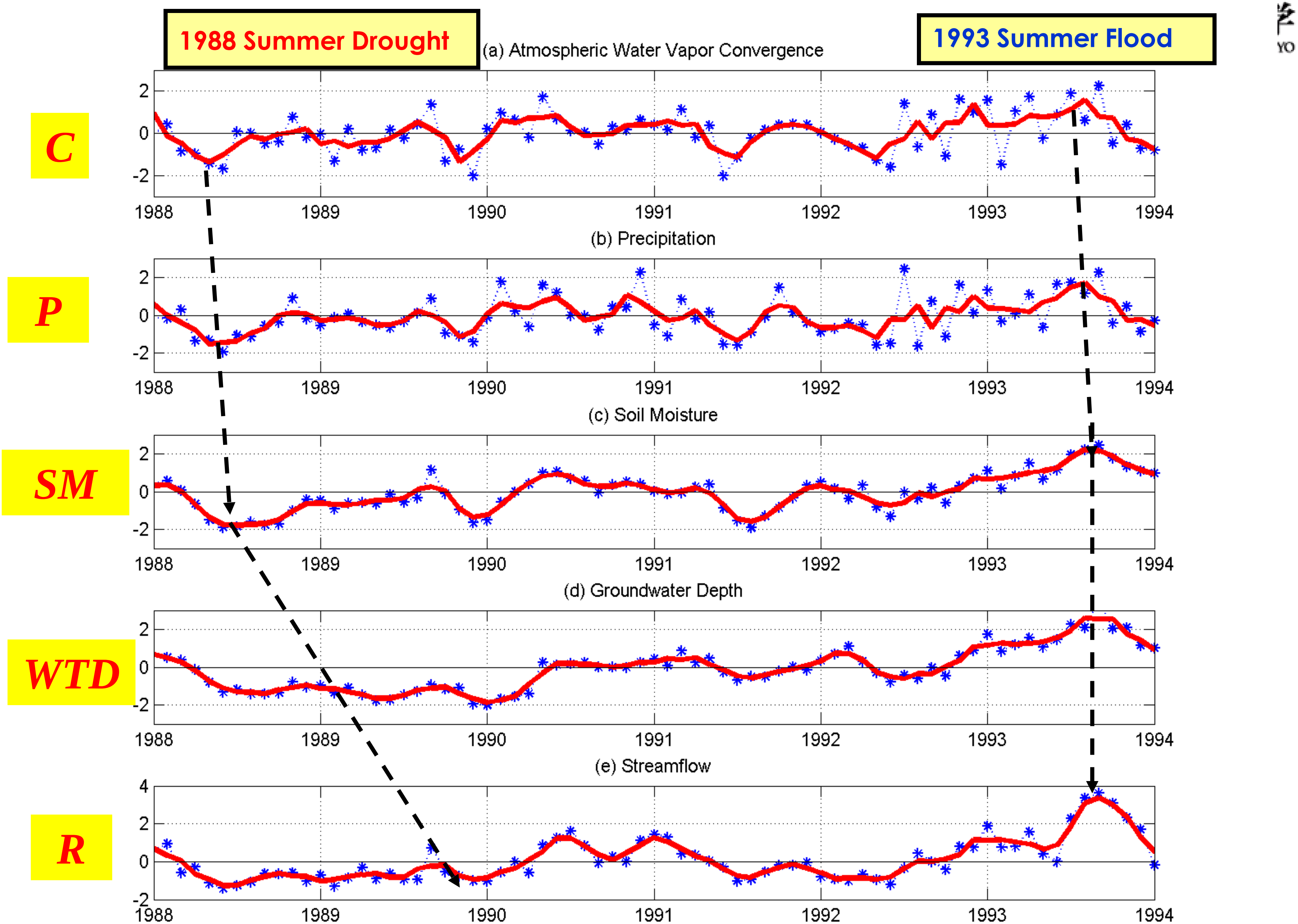


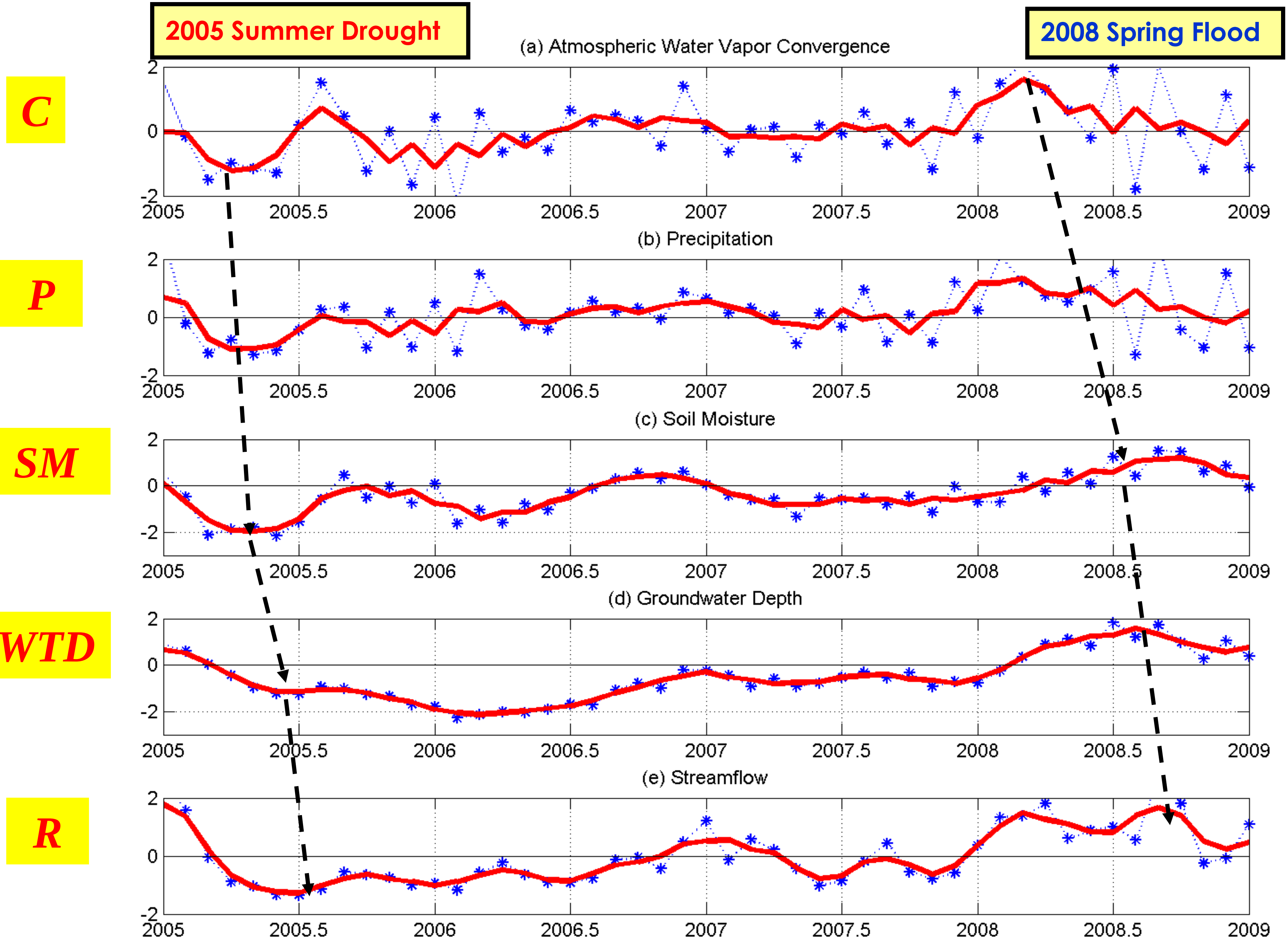
Carry-over effect with R lag behind C in 1996, 2000-2007

Standardized Anomaly



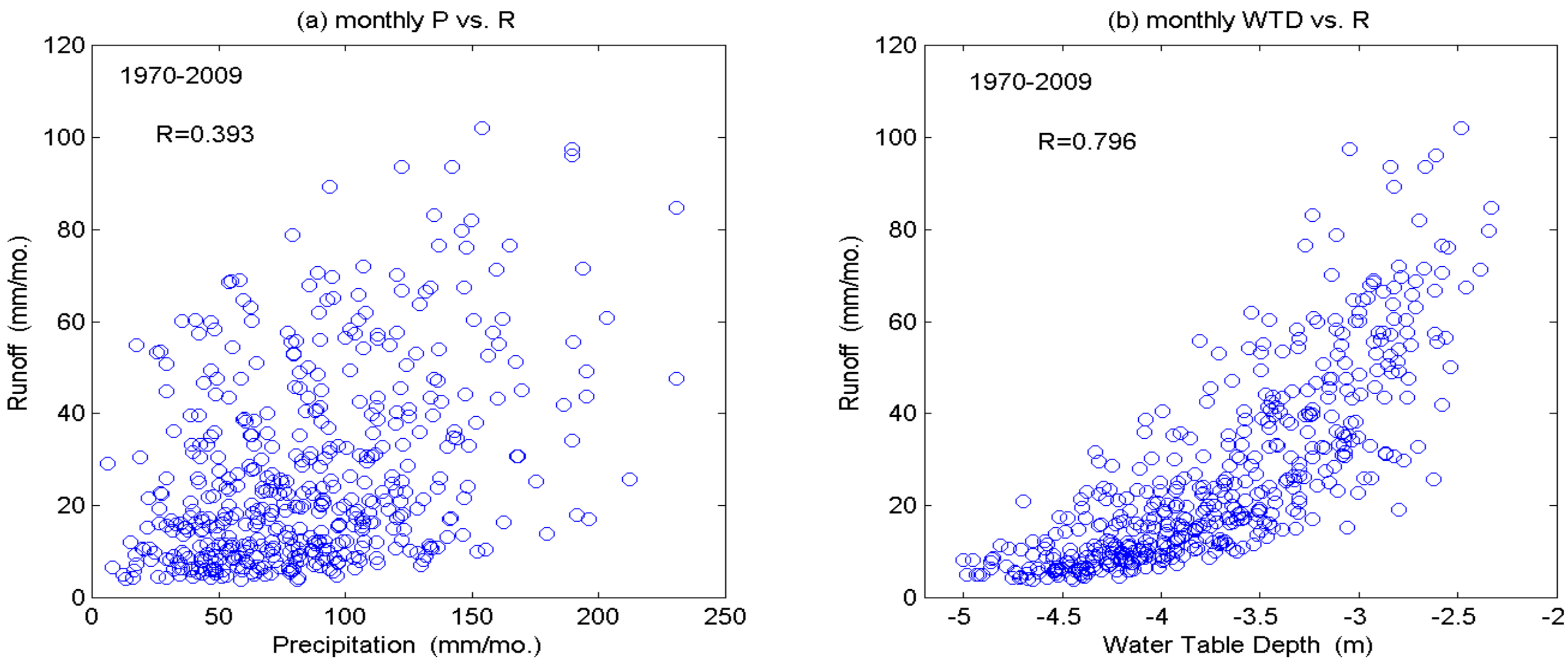
1985-2009 monthly time series in Illinois


1988 Summer Drought
1993 Summer Flood
(a) Atmospheric Water Vapor Convergence
(b) Precipitation
(c) Soil Moisture
(d) Groundwater Depth
(e) Streamflow
C
P
SM
WTD
R
1988
1989
1990
1991
1992
1993
1994



2005 Summer Drought
2008 Spring Flood
(a) Atmospheric Water Vapor Convergence
(b) Precipitation
(c) Soil Moisture
(d) Groundwater Depth
(e) Streamflow
C
P
SM
WTD
R
2
0
-2
2005
2005.5
2006
2006.5
2007
2007.5
2008
2008.5
2009

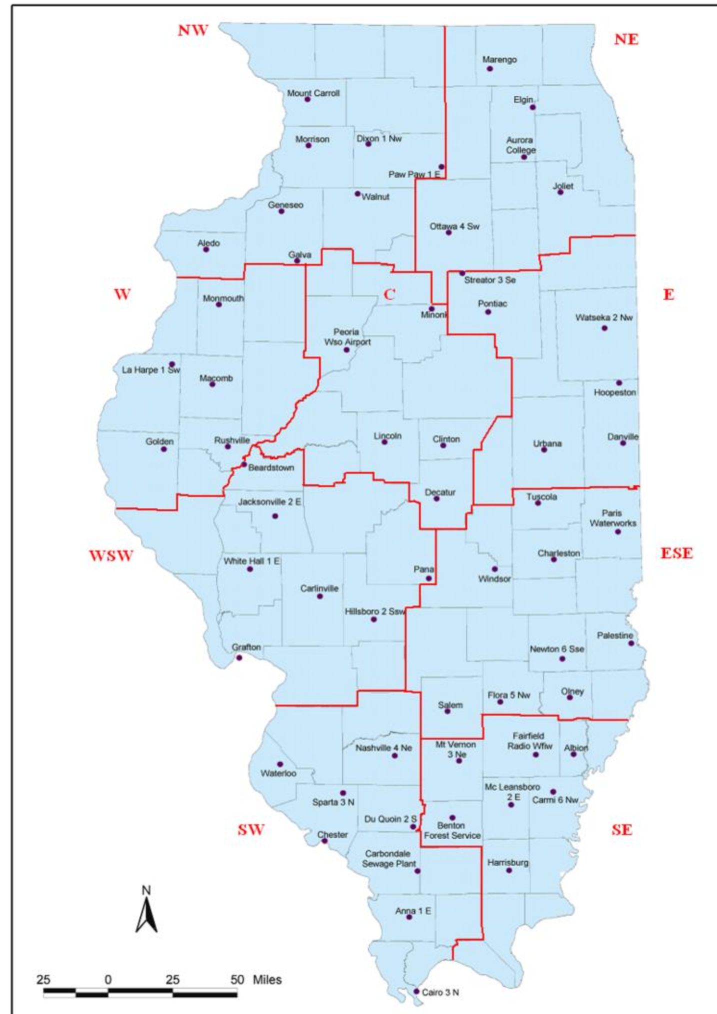
1979 – 2009 monthly P, R, GW Depth



Subsurface Runoff Dominates Runoff Generation in Illinois

Hydroclimatic Trend Detection in Illinois

- The monthly and annual temperature and precipitation were from Southern Climate Impacts Planning Program (SCIPP) over the last 40 years (1970-2009, data from 1895-).
- 60 NCDC climate stations across 9 climate divisions of Illinois to obtain monthly and annual maximum and minimum T, snowfall and snow/rain days in 1970-2009.
- Apply non-parametric Mann-Kendall test to the original time series and their 3-year, 5-year moving averages to detect the trends.
- Significant level for the statistically meaningful detection was set as 5% ($|Z| > 1.96$) to 1% ($|Z| > 2.58$).
- If statistically meaningful trend is identified, use both the (1) least-square method and (2) Kendall-Theil robust regression to find the magnitude of the trend

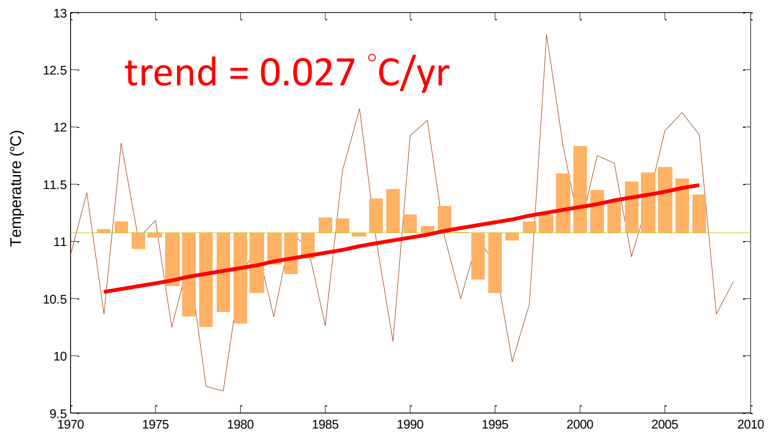


List of Data Used

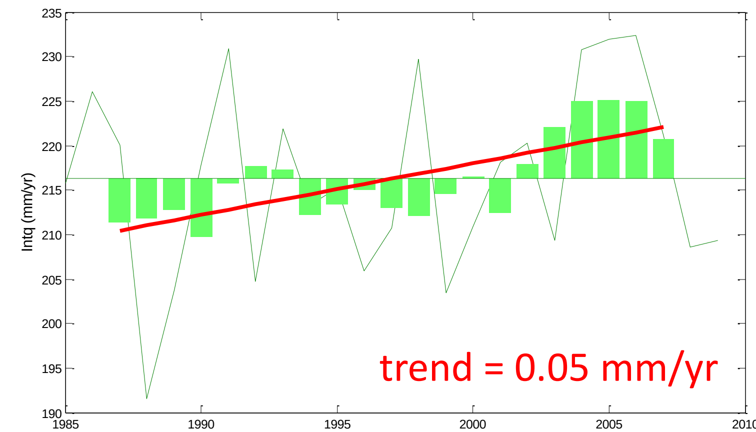
	Time series	Unit	Data sources and notes
T	**1970-2009**	**°C**	**State average, Southern Climate Impacts Planning Program (1895-)**
P	**1970-2009**	**mm/mo. or mm/yr.**	
T_{max}	**1970-2009**	**°C**	**Illinois State Water Survey (ISWS), mean value of 60 weather stations in 9 climate divisions.** **U.S. Cooperative Network snowfall (SF) were used to validate our result (R^2 = 0.99).**
T_{min}	**1970-2009**	**°C**	
Snow	**1970-2009**	**mm/mo. or mm/yr.**	
D_{snow}	**1970-2009**	**Days**	
D_{rain}	**1970-2009**	**Days**	
C	**1985-2009**	**mm/mo. or mm/yr.**	**NCEP/DOE R2 Reanalysis**
Intq	**1985-2009**	**mm**	**NCEP/DOE R2 Reanalysis**
E	**1985-2009**	**mm/mo. or mm/yr.**	**Estimated from Water Balance Computation**
R	**1970-2009**	**mm/mo. or mm/yr.**	**USGS streamflow stations**
GW	**1970-2009**	**m**	**ISWS in situ measurements**
SM	**1985-2009**	**mm**	**ISWS in situ measurements**
dS/dt	**1985-2009**	**mm/mo. or mm/yr.**	**Derived from ISWS SM and GW data**

Annual Trends: T, P, Intq and E

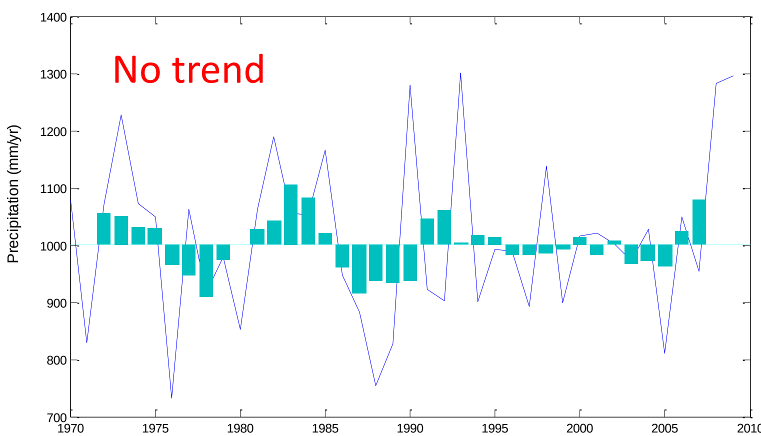
T (1970-2009, mean = 11.1 °C)



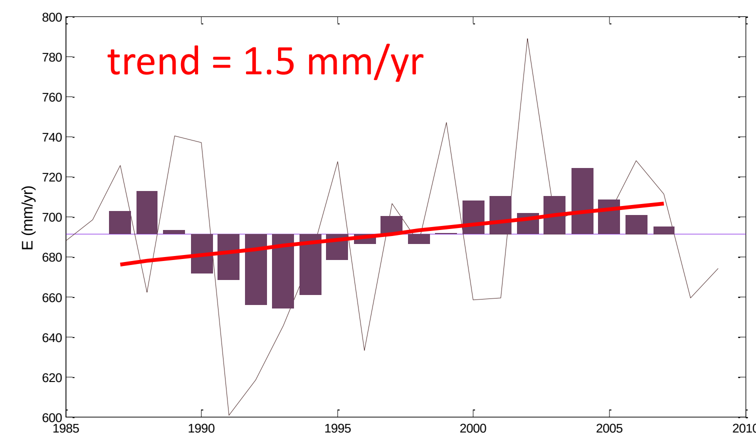
Intq (1985-2009, mean = 18 mm)



P (1970-2009, mean = 1007 mm/yr)

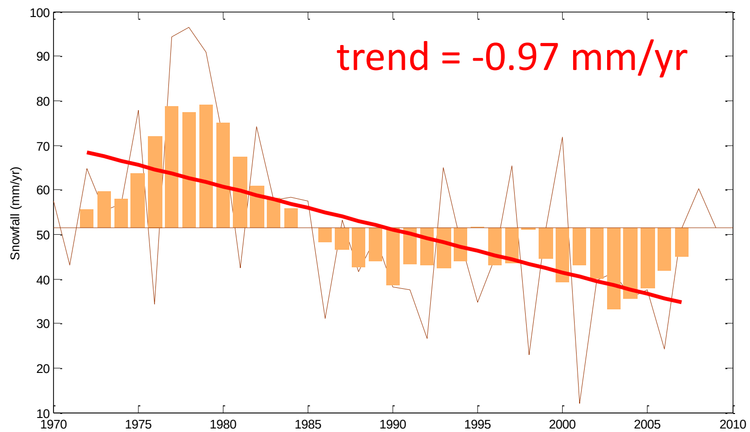


E (1985-2009, mean = 691 mm/yr)

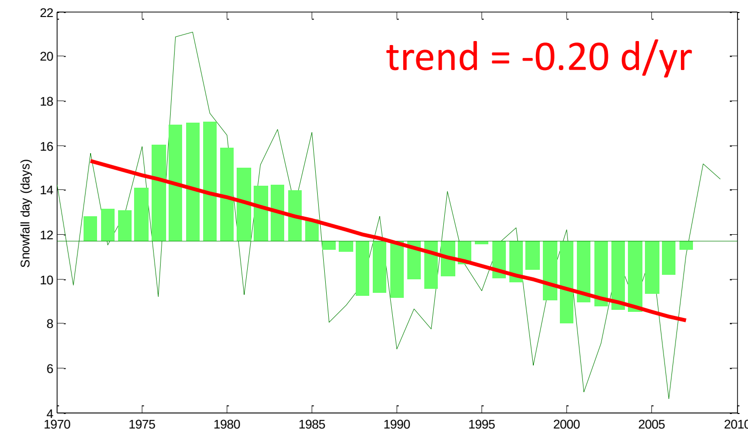


Annual Trends: Snowfall, Snow days, (monthly) T_{max} and T_{min}

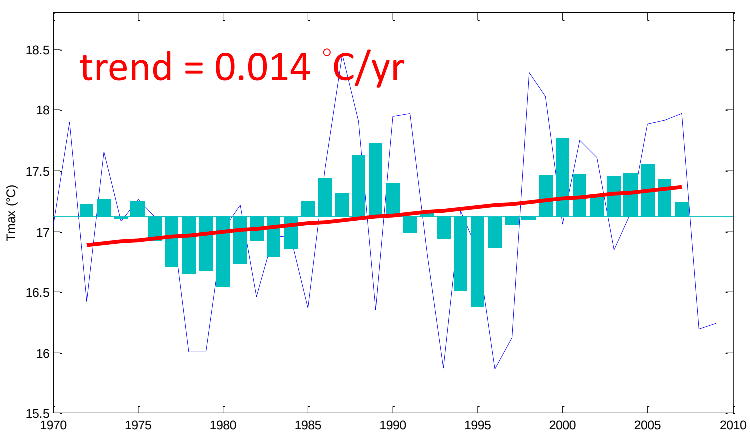
Snowfall (1970-2009, mean = 51.5 mm/yr)



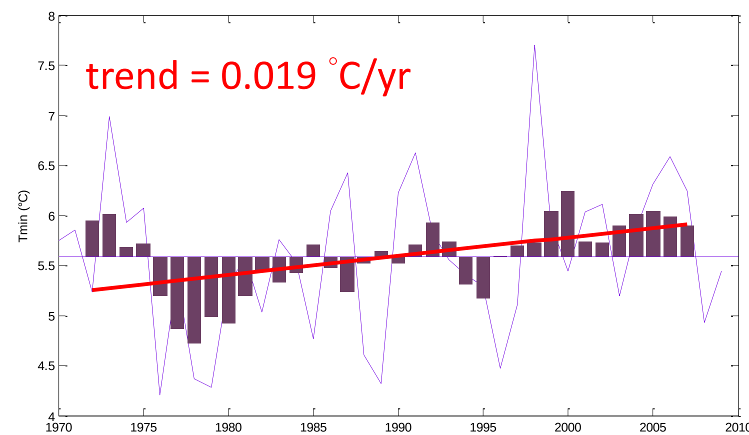
Snow days (1970-2009, mean = 11.7 day)



T_{max} (1970-2009, mean = 17.1 °C)

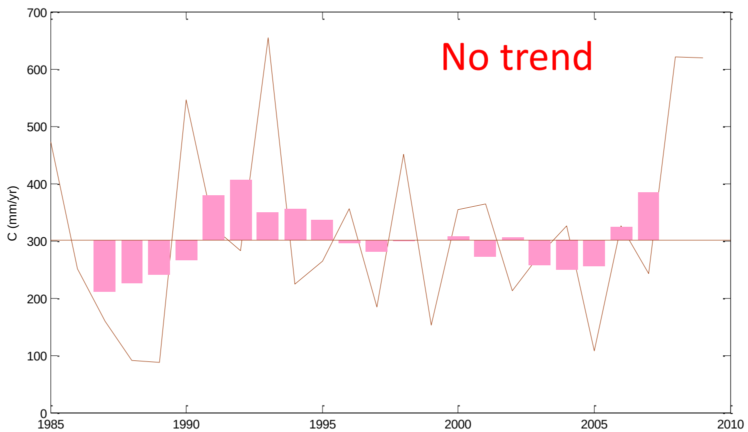


T_{min} (1970-2009, mean = 5.6 °C)

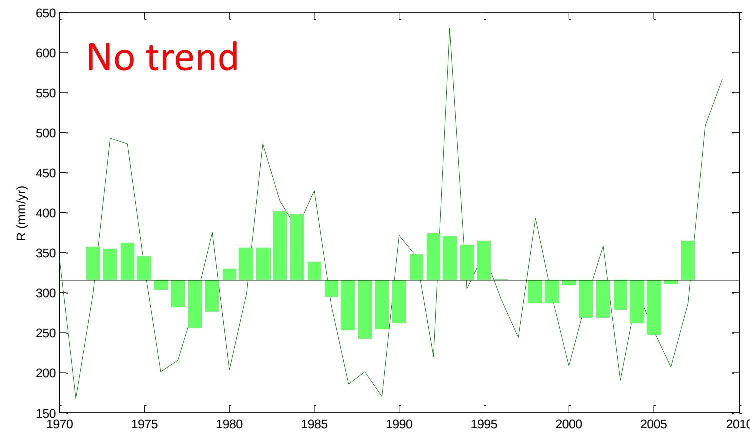


Annual Trends: C, R, SM and GW

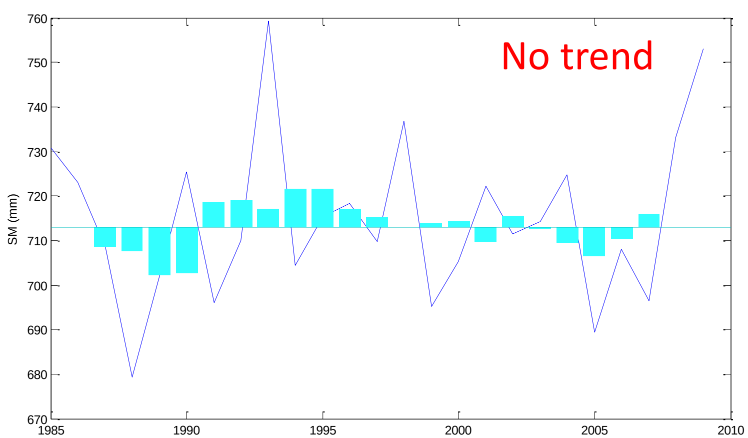
C (1985-2009, mean = 300.3 mm/yr)



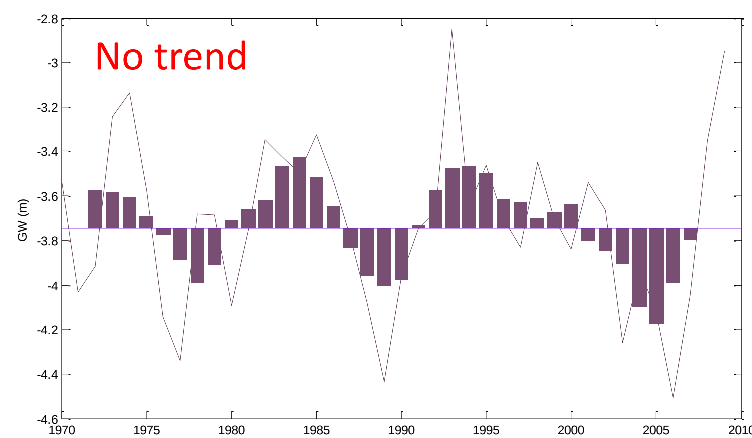
R (1970-2009, mean = 313.7 mm/yr)



2m - SM (1985-2009, mean = 713 mm)



GW Depth (1970-2009, mean = -3.74 m)



Monthly Trends (|Z| > 1.96 (95%) **and > 2.58 (99%))**

	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
T (° C)	**+ 0.03**	+ 0.12	+ 0.08						+ 0.013			**+ 0.04**
P (mm/mo.)		+ 0.84		**- 0. 90**							+ 0.41	
C (mm/mo.)											**+ 1.34**	
Intq (mm)		+ 0.09			+ 0.07	+ 0.06			+ 0.09		+ 0.15	
E (mm/mo.)		**+ 0.47**	**+ 1.48**								**- 0.47**	
R (mm/mo.)	**- 0.33**	+ 0.13		- 0.50	- 0.79		**+ 0.34**					
dS/dt (mm/mo.)											+ 1.35	
SM (mm)											**+ 1.06**	
GW (m)				**- 0.009**	**- 0.010**				**- 0.007**	**- 0.007**		

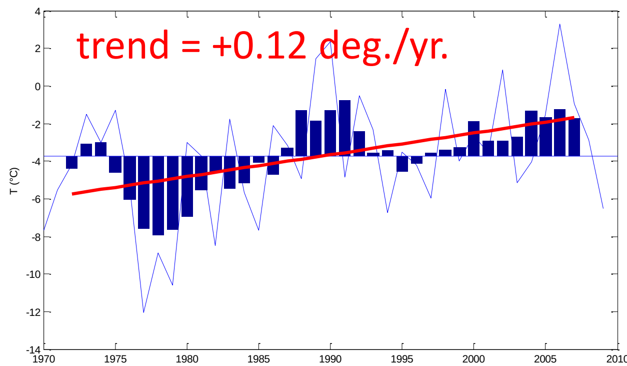
Monthly Trends (Winter)

Mean **(trend magnitude, %)**

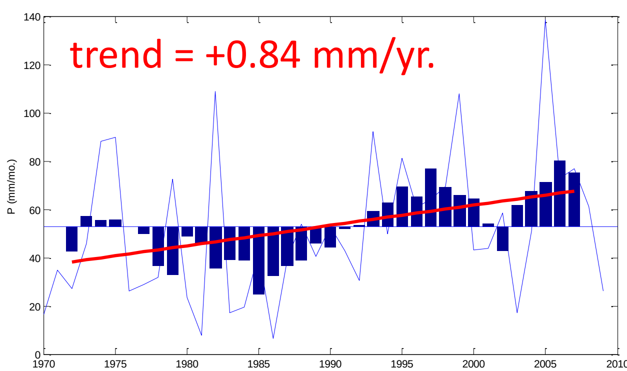
	Dec	Jan	Feb
T (° C)		**-3.72** **(+0.12)**	**-1.05** (+0.08)
T_{max} (° C)		**1.23** (+0.09)	**4.22** (+0.05)
T_{min} (° C)		**-8.18** (+0.11)	
P (mm/mo.)		**52.9** **(+0.84, +1.6%)**	
Snow (mm/mo.)	**16.6** (-0.11, -0.7%)	**11.8** (-0.23, -1.9%)	**6.3** (-0.22, -3.5%)
DAY_{snow} (d/mo.)	**3.89** (-0.02, -0.5%)	**2.70** (-0.06, 2.2%)	**1.35** (-0.05, -3.7%)
DAY_{rain} (d/mo.)			
C (mm/mo.)			
Intq (mm)		**8.25** **(+0.09, +1.1%)**	
E (mm/mo.)			
R (mm/mo.)	**27.1** (-0.33, 1.2%)	**29.6** **(+0.13, +0.4%)**	
dS/dt (mm/mo.)			
SM (mm)			
GW (m)			

January Trends: T, P, Snowfall, Intq, R

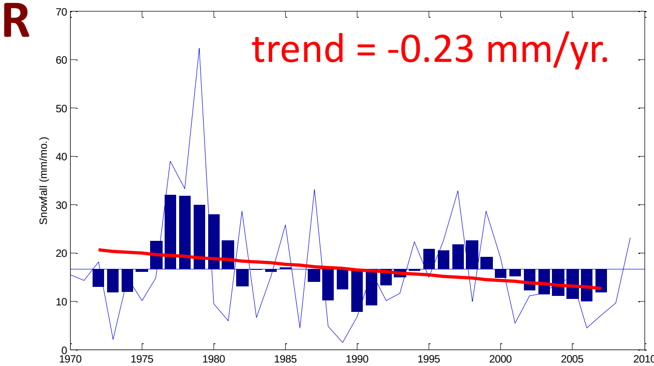
T (1970-2009, mean = -3.72 °C)



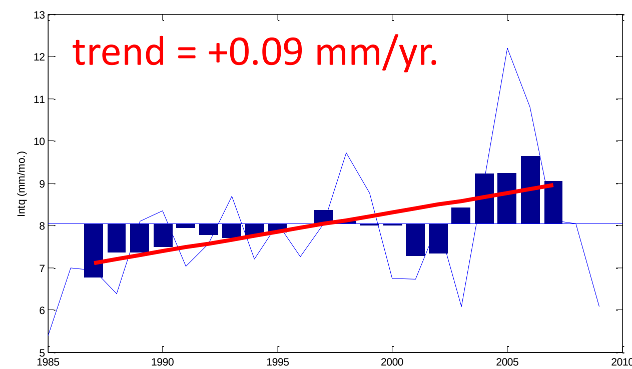
P (1970-2009, mean = 52.9 mm)



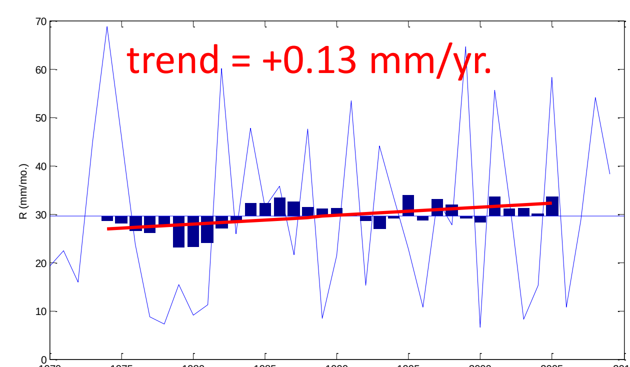
Snowfall (1970-2009, mean = 11.8 mm)



Intq (1985-2009, mean = 8.25 mm)



R (1970-2009, mean = 29.6 mm)



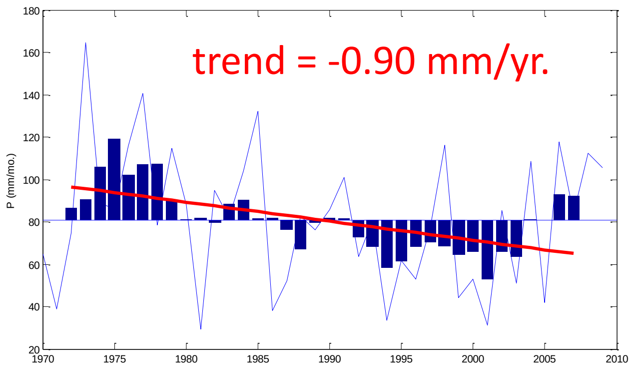
Monthly Trends (Spring)

Mean **(trend magnitude, %)**

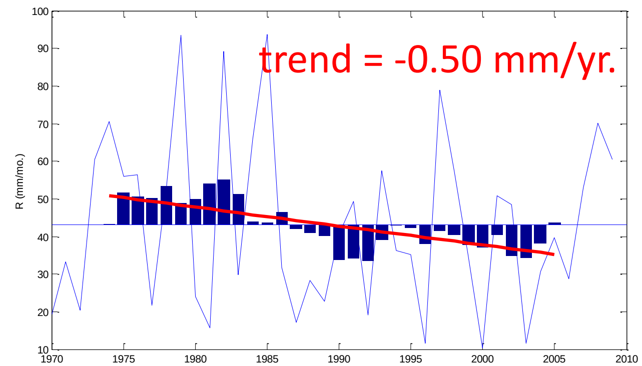
	Mar	Apr	May
T (° C)			
T_{max} (° C)			
T_{min} (° C)			
P (mm/mo.)	**80.8 (-0.90, -1.1%)**		
Snow (mm/mo.)	**6.28** (-0.16, -2.5%)	**1..28** (-0.07, -5.5%)	
DAY_{snow} (d/mo.)	**1.35** (-0.03, -2.2%)	**0.26** (-0.01, -3.8%)	
DAY_{rain} (d/mo.)	**9.72 (-0.08, -0.8%)**		
C (mm/mo.)			
Intq (mm)		**20.89** (+0.07, +0.3%)	**27.75** (+0.06, +0.2%)
E (mm/mo.)			
R (mm/mo.)	**43.0 (-0.50, -1.1%)**	**41.0 (-0.79, -1.9%)**	
dS/dt (mm/mo.)			
SM (mm)			
GW (m)	**-3.23 (-0.009)**	**-3.33 (-0.010)**	

March Trends: P, Snowfall, R, GW

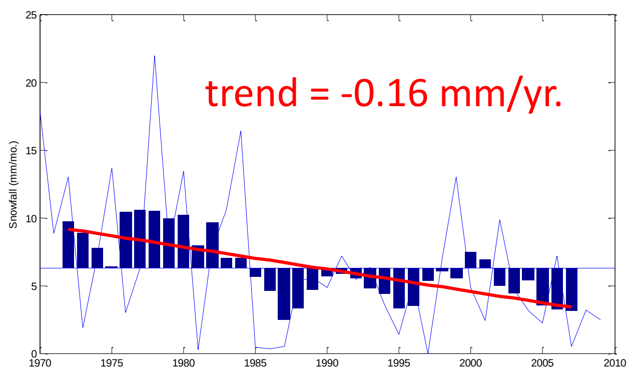
P (1970-2009, mean = 80.8 mm)



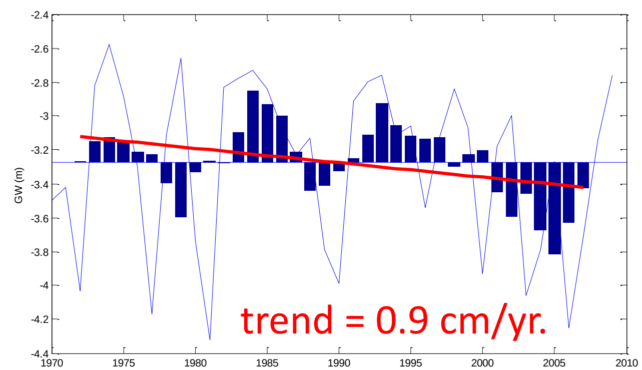
R (1970-2009, mean = 43.0 mm)



Snowfall (1970-2009, mean = 6.28 mm)



GW (1970-2009, mean = -3.23 m)



Monthly Trends (Summer)

Mean **(trend magnitude, %)**

	Jun	Jul	Aug
T (° C)			**23.0** (+0.013)
T_{max} (° C)	**25.9** (-0.033)		
T_{min} (° C)	**16.0** (+0.019)		**17.1** (+0.017)
P (mm/mo.)			
Snow (mm/mo.)			
DAY_{snow} (d/mo.)			
DAY_{rain} (day/mo.)			
C (mm/mo.)			
Intq (mm)			**24.19** (+0.094, +0.4%)
E (mm/mo.)			
R (mm/mo.)	**30.9** (+0.34, +1.1%)		
dS/dt (mm/mo.)			
SM (mm)			
GW (m)			**-4.11** (-0.007)

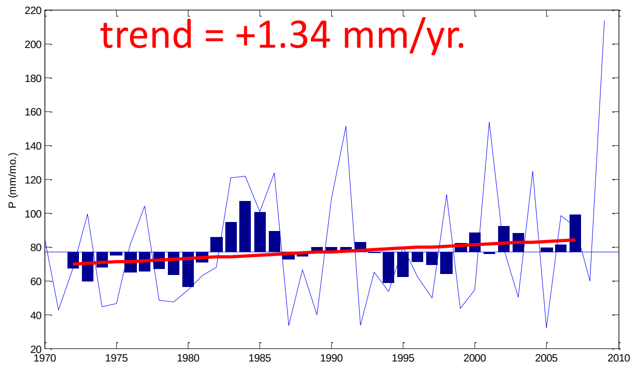
Monthly Trends (Autumn)

Mean **(trend magnitude, %)**

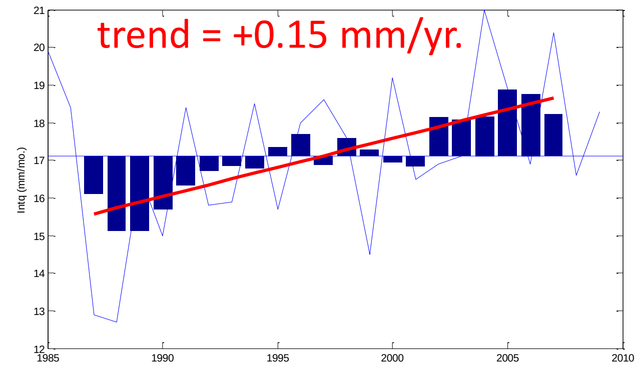
	Sep	Oct	Nov
T (° C)			**5.59** (+0.04)
T_{max} (° C)	**25.86** (+0.02)		
T_{min} (° C)			
P (mm/mo.)		**76.88 (+1.34, +1.7%)**	
Snow (mm/mo.)			**2.97** (-0.18, -6.0%)
DAY_{snow} (d/mo.)			**0.68** (-0.03, -4.4%)
DAY_{rain} (d/mo.)			**9.04** (-0.05, +5.5%)
C (mm/mo.)		**21.51 (+0.41, +1.9%)**	
Intq (mm)		**17.12 (+0.15, .+0.9%)**	
E (mm/mo.)		**49.17** (-0.46, -0.9%)	
R (mm/mo.)			
dS/dt (mm/mo.)		**17.12 (+1.35)**	
SM (mm)		**673.1 (+1.06)**	
GW (m)	**-4.24** (-0.007)		

October Trends: P, C, Intq, E, SM

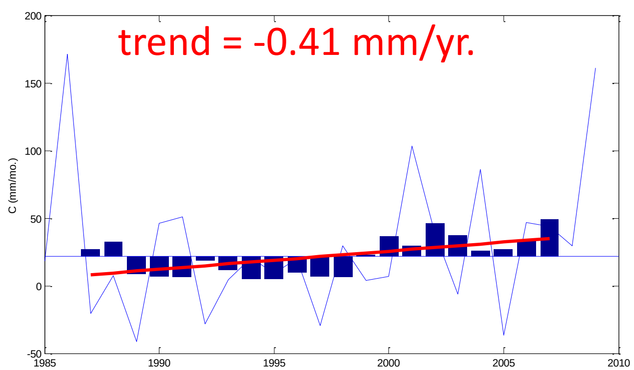
P (1970-2009, mean = 76.88 mm)



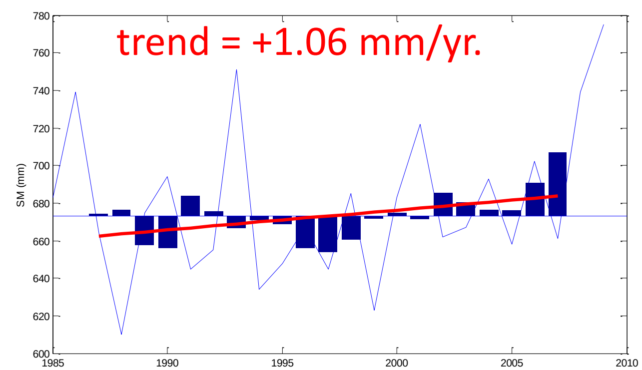
Intq (1985-2009, mean = 17.12 mm



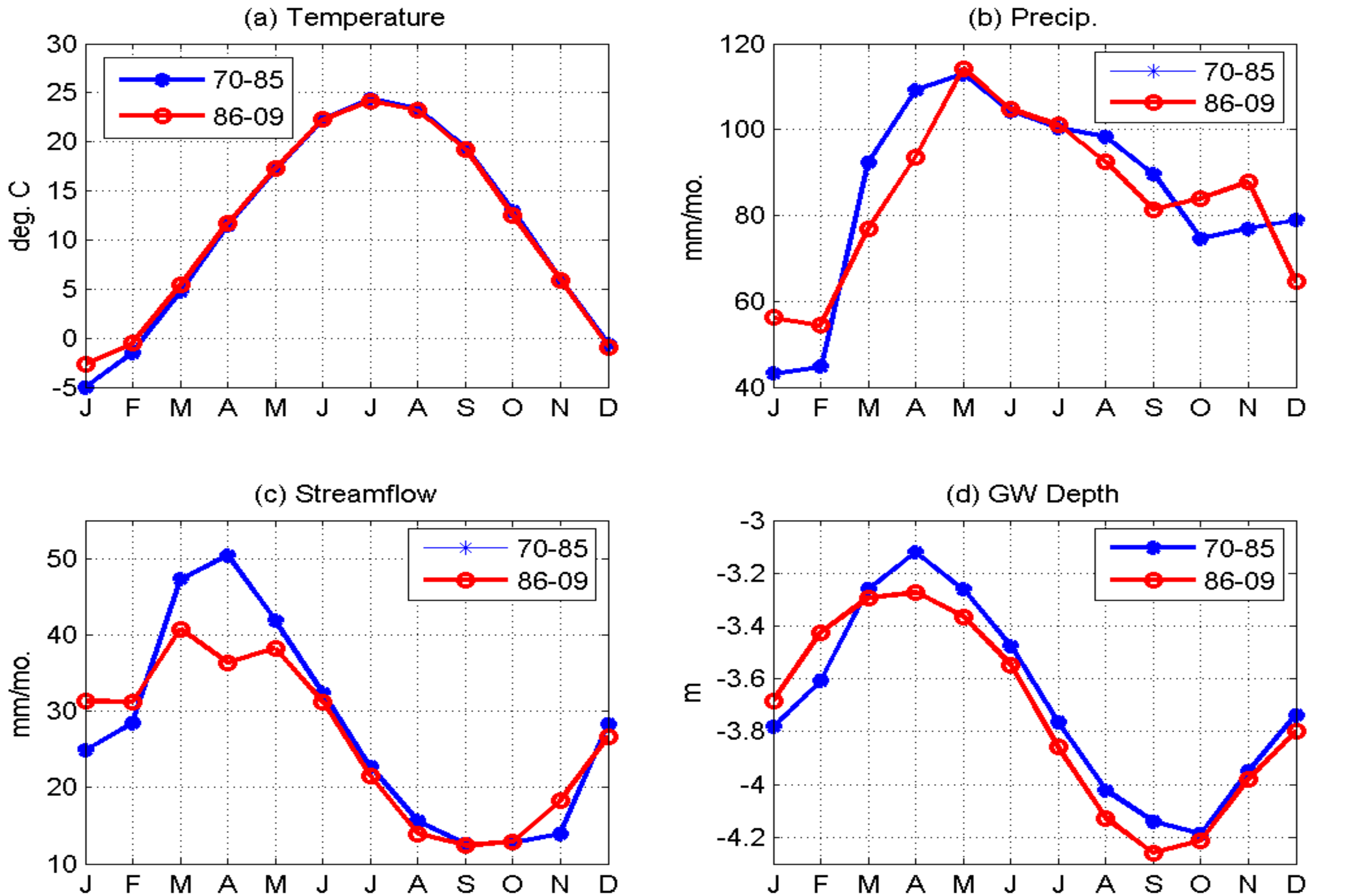
C (1985-2009, mean = 21.5 mm)



SM (1985-2009, mean = 673.1 mm)



Shift in Seasonal Cycle: 1970-1985 vs. 1986-2009



Conclusions

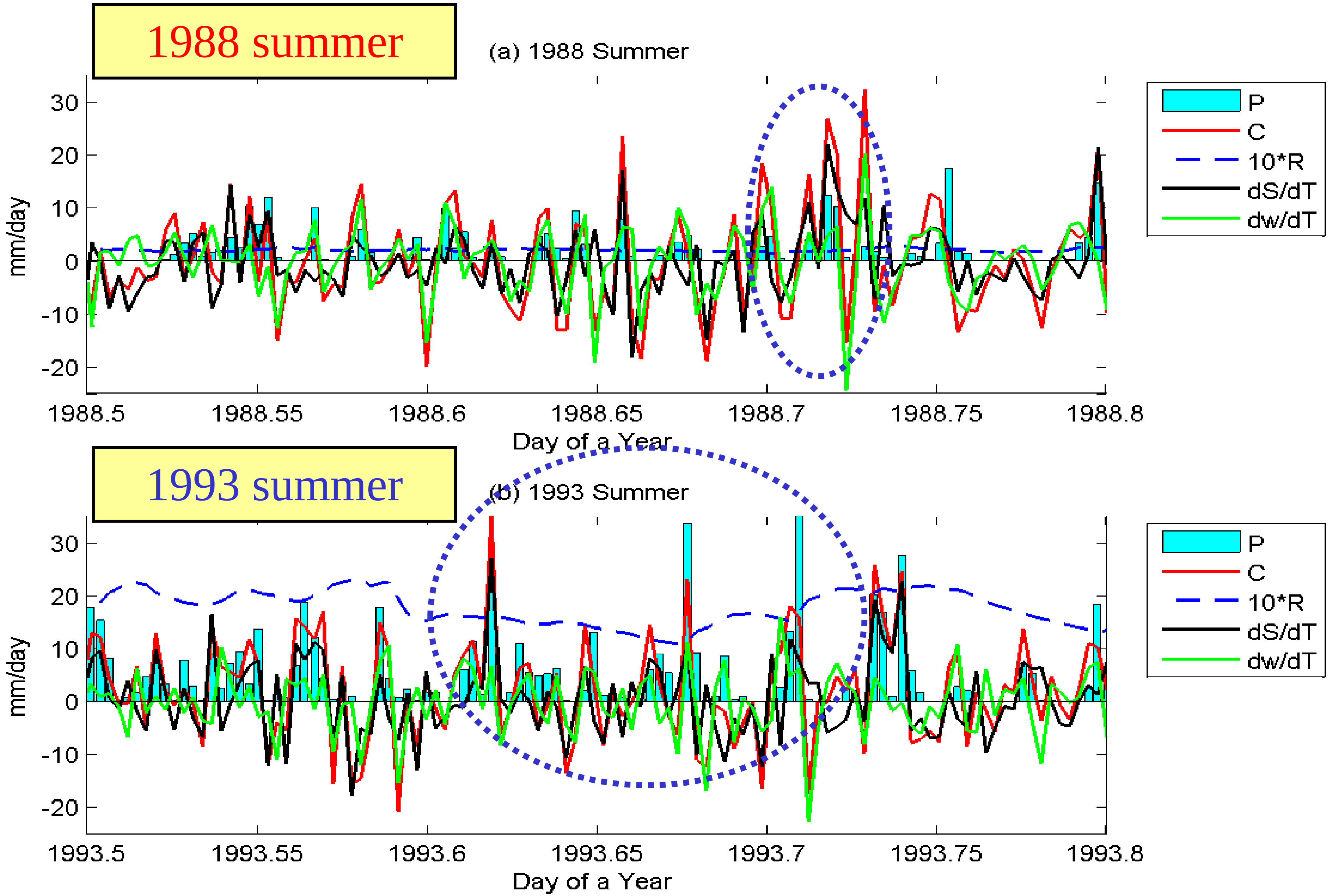
- **Statistically significant trends (confidence level > 95%) identified from 1970-2009 annual time series of major hydroclimatic variables in Illinois: T increased by 0.027° C/yr., leading to intq and E both increased. P has no significant trend detected. Snowfall amount and snow days decreased, and Tmax and Tmin both increased.**
- **Winter months accounted for most of annual T increase. The following "direction-wise" consistent trends among major water balance components are identified:**
  - ✓ **For January, T increased winter (+ 0.11° C/yr.). Intq increases 1.6.%/yr., P increases 1.1 %/yr.. which led to +0.4%/yr. increase in runoff.**
  - ✓ **For March, no trend was detected for T, Intq, C and E, but a -1.1 %/yr. decreasing trend was identified for Precip. As a result, Runoff showed decreased trends in March (-1.1 %/yr.) and propagated into April (-1.9 %/yr.), also GW showed declining trend for the two months(~1 cm per month).**
  - ✓ **For October, no trend was found in T, but Precip. increased 1.3 mm/yr., C and Intq also increase +1.9 %/yr. and +0.9 %/yr., respectively. Soil moisture shows positive trend, and Total water storage change dS/dt show a consistent response of 1.3 mm/yr.**

Thank you

Pat Yeh
Institute of Industrial Science, The University of Tokyo
Email: patyeh@iis.u-tokyo.ac.jp

ILLINOIS 1985-2009 **Annual (25)** **Monthly (300)** **Anamoly(300)** **Daily (9131 days)**	Precip.	Evapo.	Corr. Vapor Converg.	Runoff	dS/dT	S
Precip.	1 1 1 1	0.113 0.343 0.028 0.338	**0.945** 0.443 **0.831** **0.600**	**0.791** 0.365 0.456 0.049	**0.662** 0.316 **0.731** **0.539**	**0.707** 0.273 0.471 -
Evapo.		1 1 1 1	-0.218 **-0.686** **-0.511** **-0.281**	-0.163 -0.174 -0.169 -0.038	-0.180 **-0.725** **-0.506** **-0.603**	-0.279 -0.338 -0.202 -
Corrected Vapor Converg.			1 1 1 1	**0.828** 0.473 0.462 0.047	**0.712** **0.921** **0.912** **0.754**	**0.784** **0.568** **0.506** -
Runoff				1 1 1 1	0.197 0.104 0.104 -0.040	**0.877** **0.775** **0.752** -
dS/dT					1 1 1 1	0.274 0.291 0.266 1

Daily Dynamics of Water Balance Components



1988 Drought vs. 1993 Flood