XVIII
World Water Congress
International Water Resources Association (IWRA)

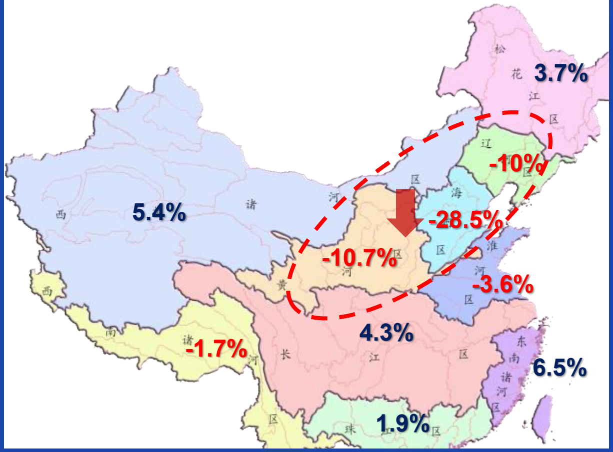
# Estimating the frequency of annual runoff under changing climate

Prof. Hanbo Yang

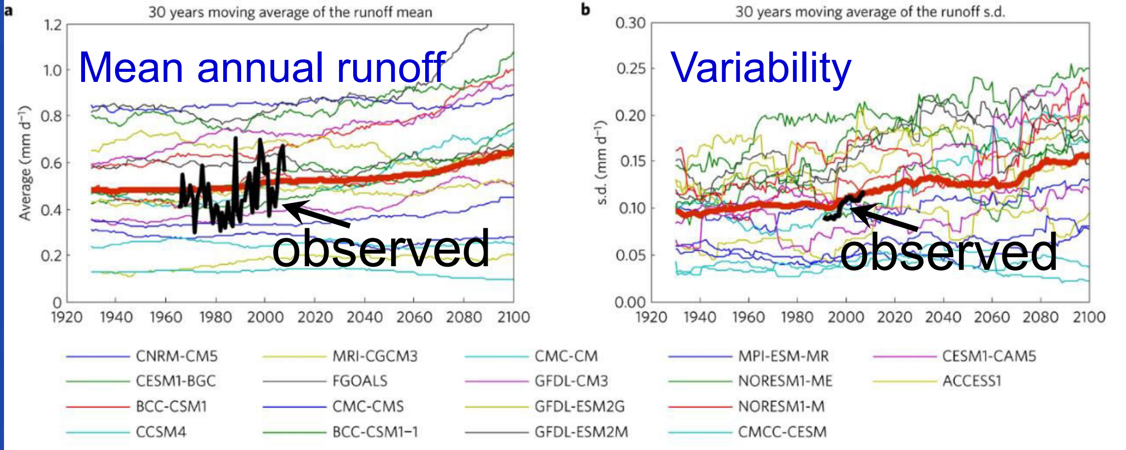
Presenter: Ziwei Liu
Tsinghua University
Beijing, China, 09. 2023

# Background

- Mean annual runoff significantly changed in some regions
- Concurrently, the inter-annual variability was also altered by climate change



mean annual runoff changes in 1980-2010 compared to 1956-1979



(Mohamed & Elfatih, 2017, NCC)

# Background

- **Stationarity, used for hydrologic designs, would be not held under the changing conditions**

## Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

**P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]**

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global investment in water infrastructure exceeds U.S.$500 billion (*1*).

The stationarity assumption has long been compromised by human disturbances in river basins. Flood risk, water supply, and water quality are affected by water infrastructure, channel modifications, drainage works, and land-cover and land-use change. Two other (sometimes indistinguishable) challenges to stationarity have been externally forced, natural climate changes and low-frequency, internal variability (e.g., the Atlantic multidecadal oscillation) enhanced

**An uncertain future challenges water planners.**

In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, however, we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning. Finding a suitable successor is crucial for human adaptation to changing climate.

*How did stationarity die?* Stationarity is dead because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers

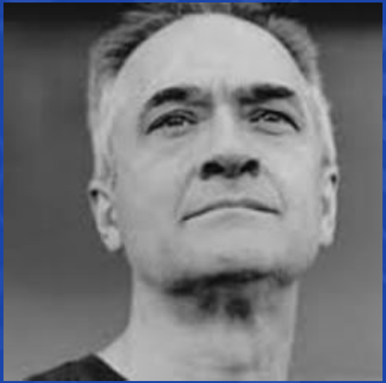
that has emerged from climate models (see figure, p. 574).

*Why now?* That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (*11*, *12*). Accounting for the substantial uncertainties of climatic parameters estimated from short records (*13*) effectively hedged against small climate changes. Additionally, climate projections were not considered credible (*12*, *14*).

Recent developments have led us to the opinion that the time has come to move beyond the wait-and-see approach. Projections of runoff changes are bolstered by the recently demonstrated retrodictive skill of climate models. The global pattern of observed annual streamflow trends is unlikely to have arisen from unforced variability and is consistent with modeled response to climate forcing (*15*). Paleohydrologic studies suggest that small changes in mean climate might produce large changes in extremes (*16*), although attempts to detect a recent change in global flood frequency have been equivocal (*17*, *18*). Projected changes in runoff during the multidecade lifetime of major water infrastructure projects begun now are large enough to push hydroclimate beyond the

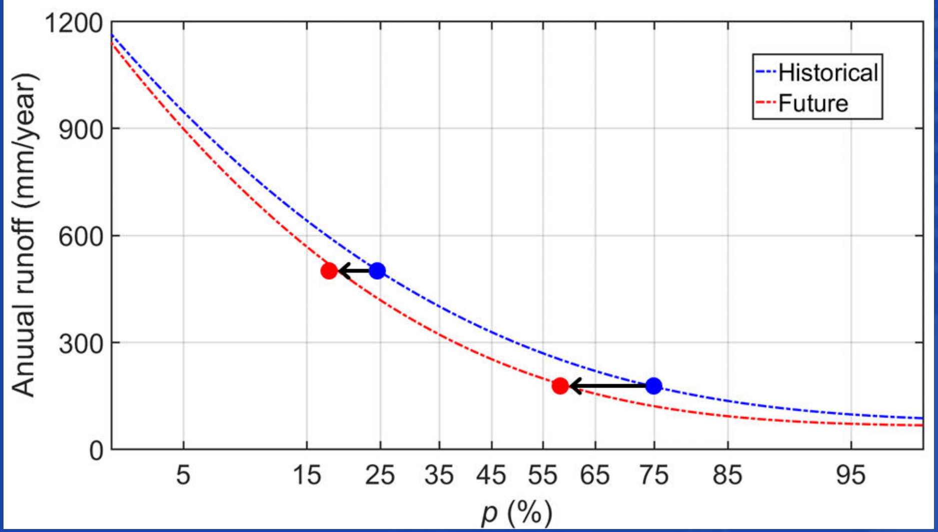
Science

AAAS



# Background

- **Questions:**
  - **why do the mean and inter-annual variability of annual runoff change?**
  - **how does the future annual runoff frequency change, and how can we quantify this?**



# Mean annual runoff

- **Budyko framework**

$$\boxed{E=\frac{E_0 P}{\left(P^n+E_0^n\right)^{1/n}}} \Rightarrow R=P-\frac{E_0 P}{\left(P^n+E_0^n\right)^{1/n}}$$

(Budyko, 1974; Yang, 2008, WRR)

$$\Downarrow$$

$$E_0=\frac{\Delta}{\Delta+\gamma}(R_{\mathrm{n}}-G)/\lambda+\frac{\gamma}{\Delta+\gamma}\cdot 6.43(1+0.536U_2)\left(1-RH\right)e_{\mathrm{s}}/\lambda$$

$$\Downarrow$$

$$\boxed{\frac{dR}{R}=\varepsilon_1\frac{dP}{P}+\varepsilon_2\varepsilon_3\frac{dR_{\mathrm{n}}}{R_{\mathrm{n}}}+\varepsilon_2\varepsilon_4 dT+\varepsilon_2\varepsilon_5\frac{dU_2}{U_2}+\varepsilon_2\varepsilon_6\frac{dRH}{RH}}$$

(Yang, 2011, WRR)

# Inter-annual variability

**mean value** →

$$dQ = \varepsilon_P dP + \varepsilon_0 dE_p$$

**first-order Budyko framework**

**variability** →

$$(dQ)^2 = \varepsilon_P^2 (dP)^2 + \varepsilon_{E_p}^2 (dE_p)^2 + 2\varepsilon_P \varepsilon_{E_p} dP dE_p$$

$$\sigma\left(Q\right) = \sqrt{\varepsilon_{E_0}{}^2 \cdot \sigma_{E_0}^2 + \varepsilon_P{}^2 \cdot \sigma_P^2 + 2 \cdot \varepsilon_{E_0} \cdot \varepsilon_P \cdot COV\left(E_0, P\right)}$$

**second-order Budyko framework**

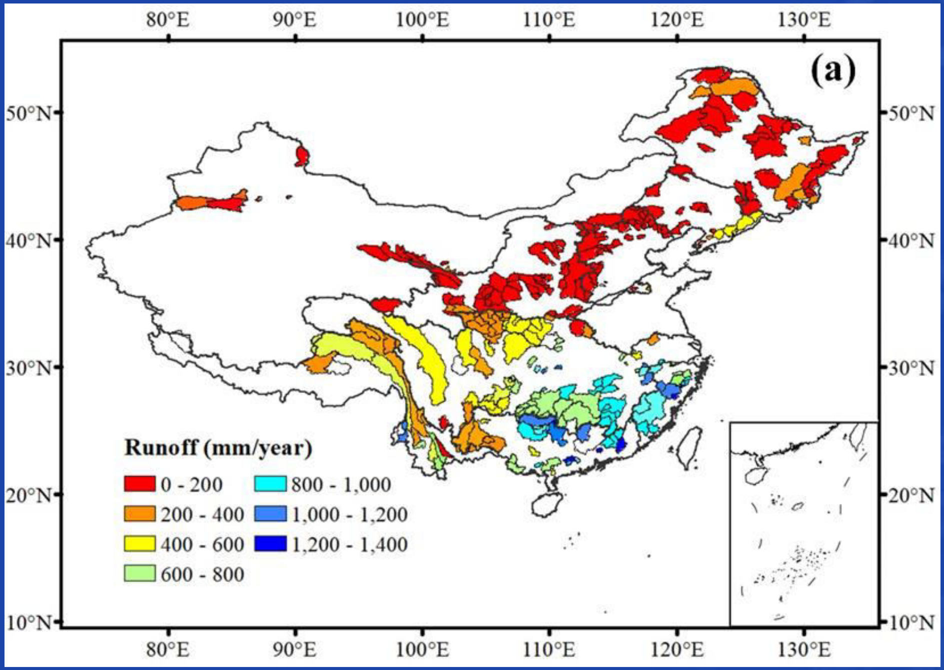
**variability of E$_0$ is much lower compared to precipitation**

$$\sigma(Q) = \varepsilon_P \sigma_P$$

$$C_v(Q) = \frac{\sigma(Q)}{\overline{Q}}$$

# Inter-annual variability

**291 basins across China**



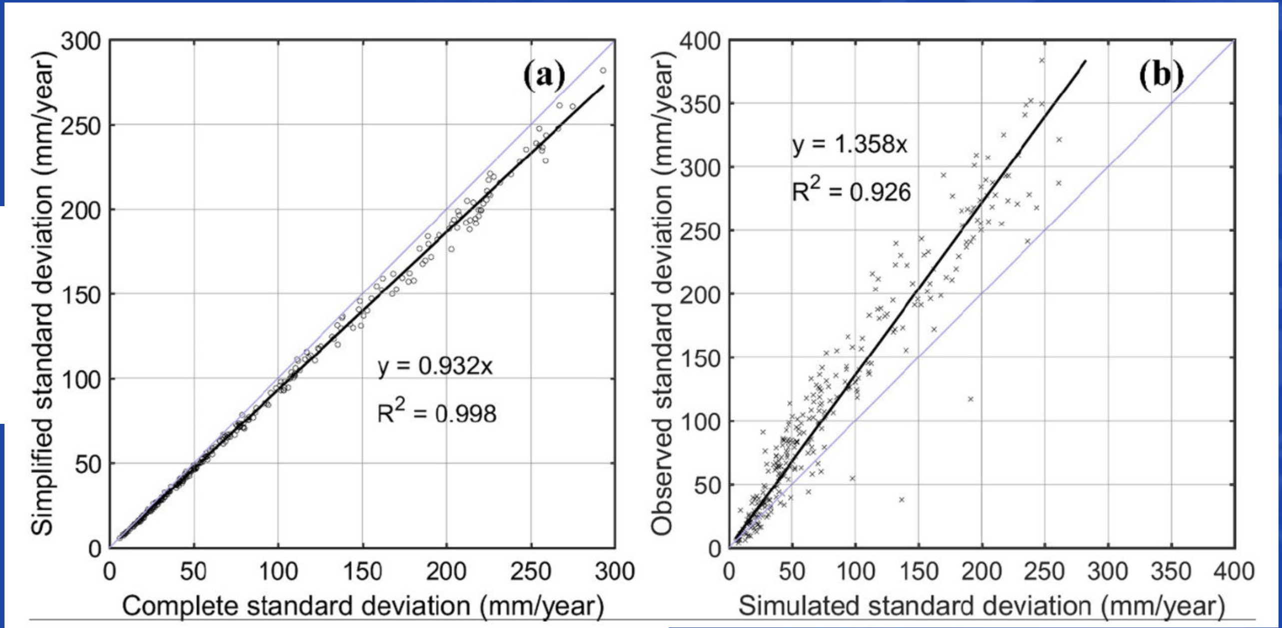
- size: 372~142,963km$^2$
- runoff data length: 1961-2000
- Meteorology data: ~1000 national stations

# Inter-annual variability

## ■ Estimation of inter-annual variability

- ➢ simplified equation is comparable to complete equation
- ➢ estimated variability can match observations well, but show a systematical underestimation

$$\sigma(Q) = \varepsilon_P \sigma_P$$

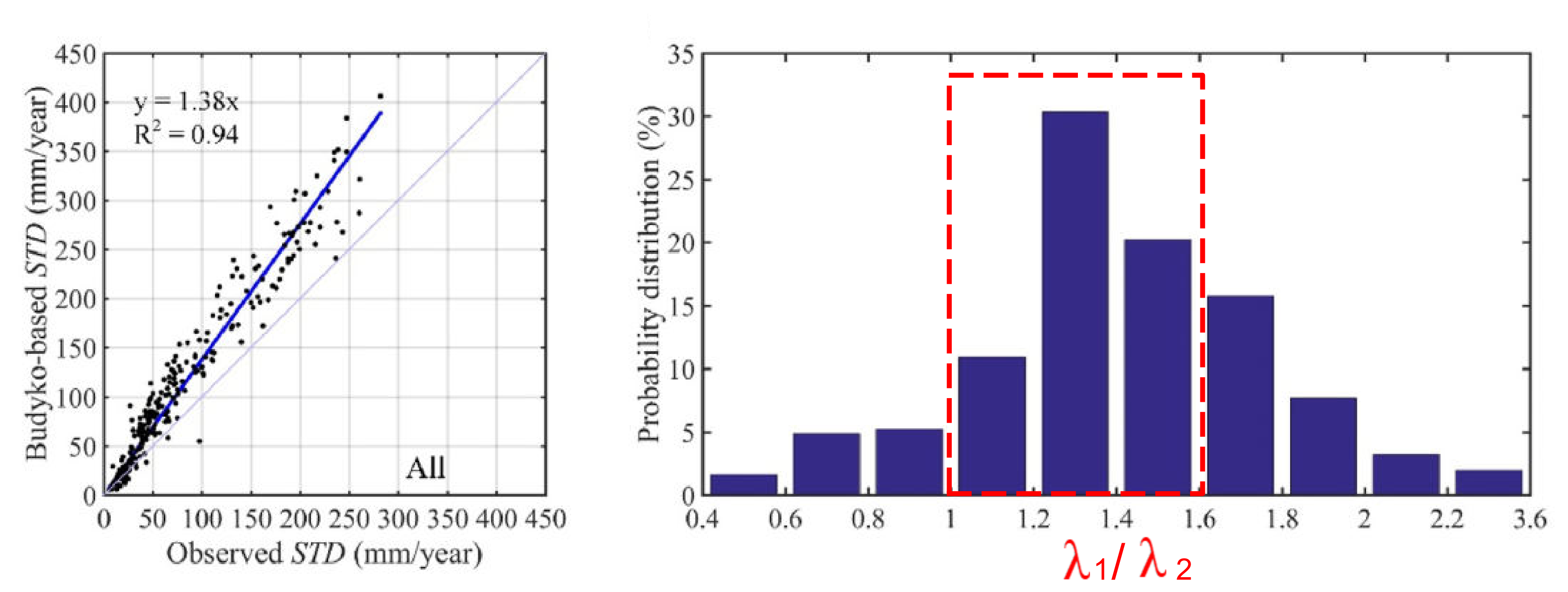


$$\sigma(Q) = \sqrt{\varepsilon_{E_0}{}^2 \cdot \sigma_{E_0}^2 + \varepsilon_P{}^2 \cdot \sigma_P^2 + 2 \cdot \varepsilon_{E_0} \cdot \varepsilon_P \cdot COV(E_0, P)}$$

# Inter-annual variability

- **The underestimation is stable in space and time**

$$\sigma_{obs} = \lambda\sigma_{est}$$



space

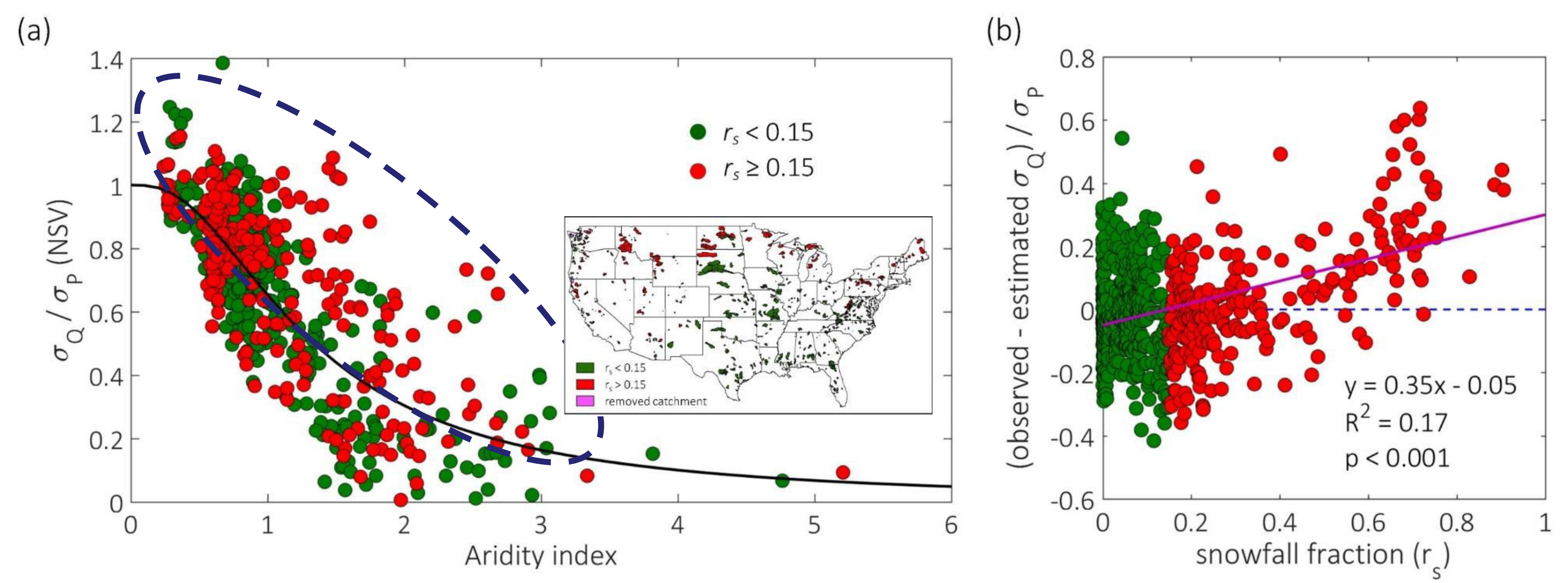
time

(Liu et al., 2021, JoH)

# Inter-annual variability

## ■ Effects of snowfall changes

$$\mathrm{NSV} = \frac{\sigma_Q}{\sigma_P} = \sqrt{\varepsilon_P^2 + \frac{\varepsilon_{\mathrm{PET}}^2\sigma_{\mathrm{PET}}^2}{\sigma_P^2} + \frac{2\varepsilon_P\varepsilon_{\mathrm{PET}}\mathrm{COV(P,PET)}}{\sigma_P^2}}$$

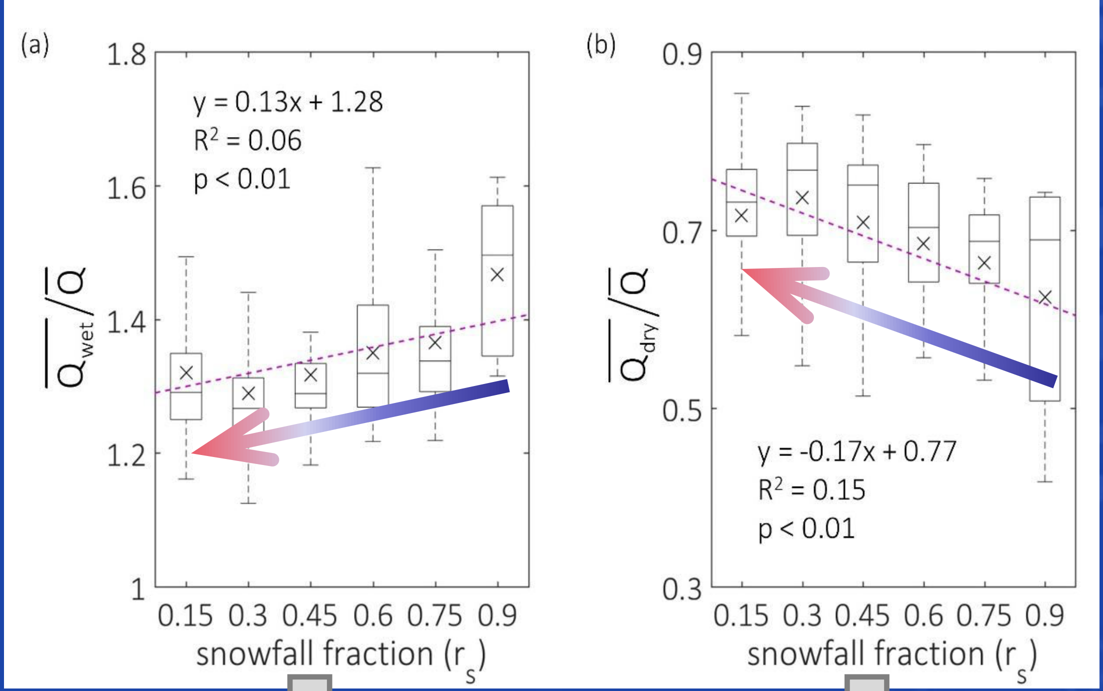


**Less snowfall, lower runoff variability**

*(Liu et al., 2022, GRL)*

# Inter-annual variability

## ■ Effects of snowfall changes



less snowfall, less reflected radiation, more evaporation, thus less runoff

less snowfall, lower soil moisture, less evaporation, thus more runoff

- **asymmetric effects of snowfall**
- **less snowfall:**

  **less runoff in the wet year, but more in the dry year**

*(Liu et al., 2022, GRL)*

# Frequency of annual runoff

- **Pearson-III curve**

$$f(x)=\frac{\beta^{\alpha}}{\Gamma(\alpha)}\cdot(x-a_0)^{\alpha-1}\cdot e^{-\beta(x-a_0)}$$

inputs: <u>mean annual runoff</u> and its <u>variability</u>

$$R=P-\frac{E_0P}{\left(P^n+E_0^n\right)^{1/n}}$$

$$\sigma(Q)=\varepsilon_P\sigma_P$$

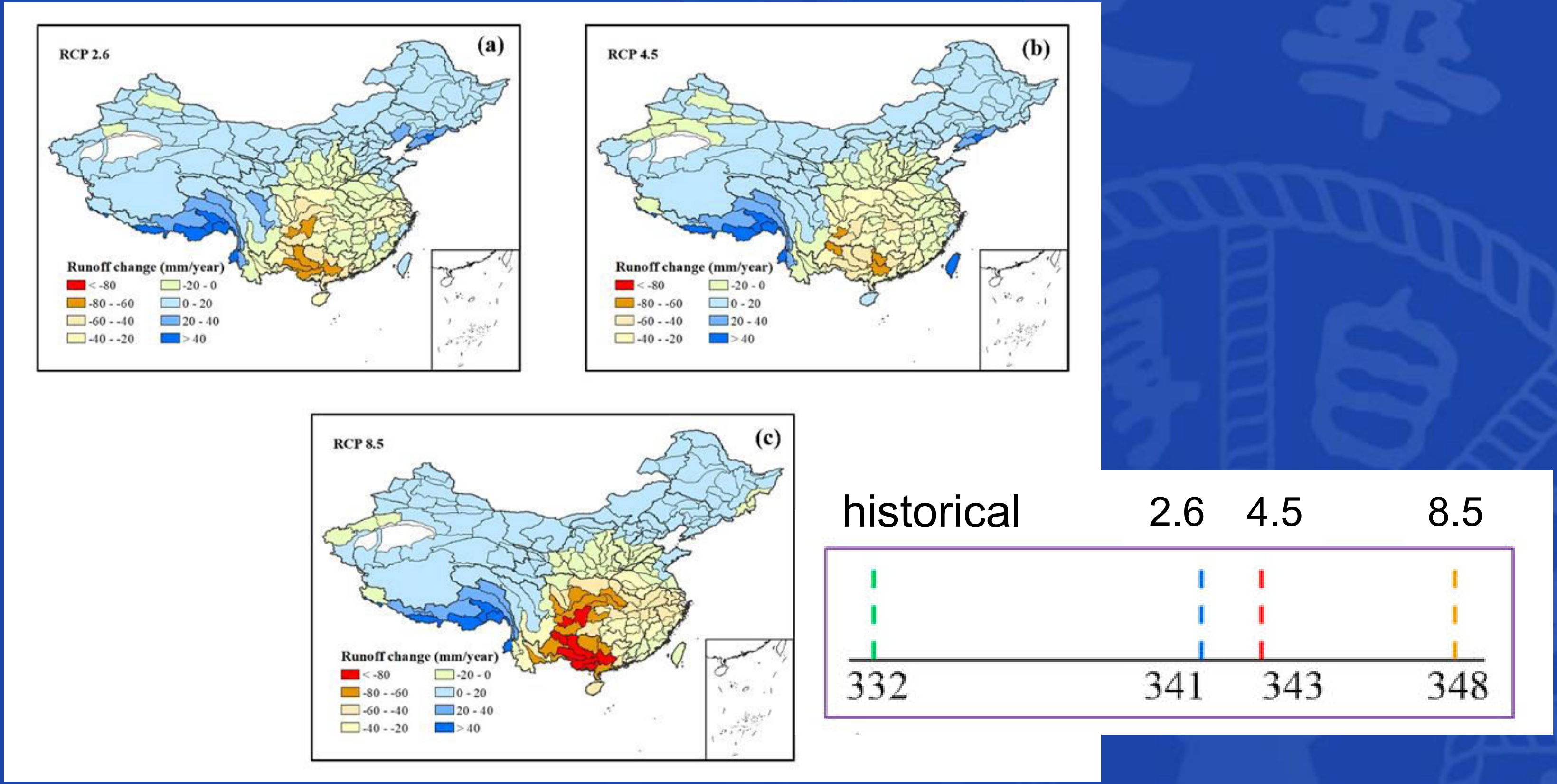
$$C_v(Q)=\frac{\sigma(Q)}{\overline{Q}}$$

**estimate these parameters in different periods**

# Applications

## Mean annual runoff predictions

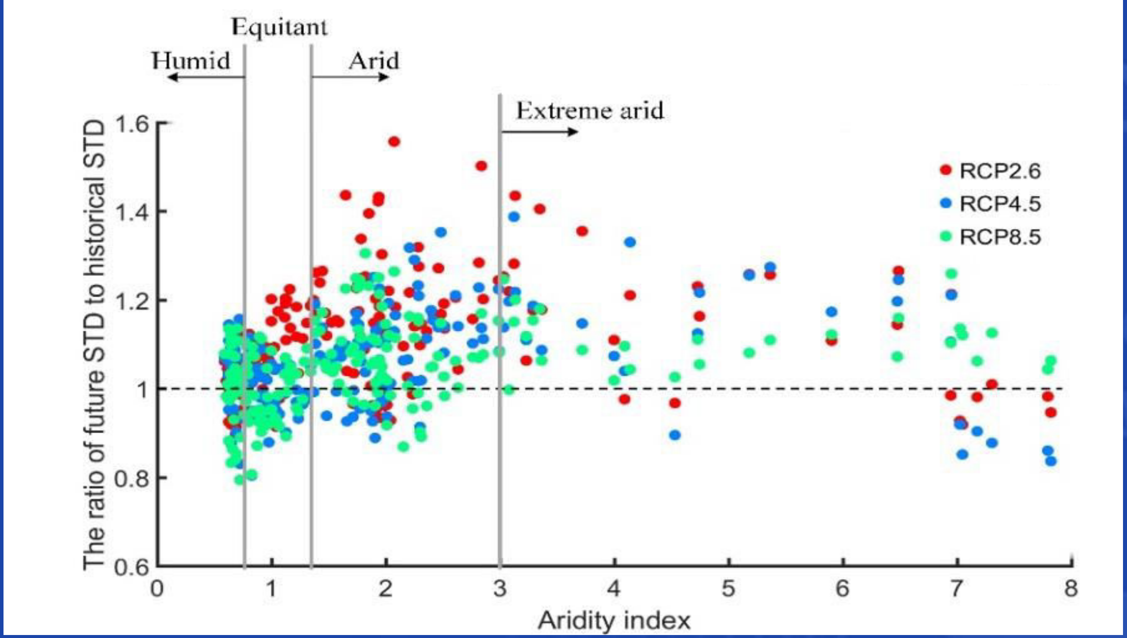
- Increase in northern China, but decrease in south
- little change in total amount under three RCPs



# Applications

## Inter-annual variability predictions

- more than 70% basins show increased variability, in which more than 90% dryland basins show increased trend

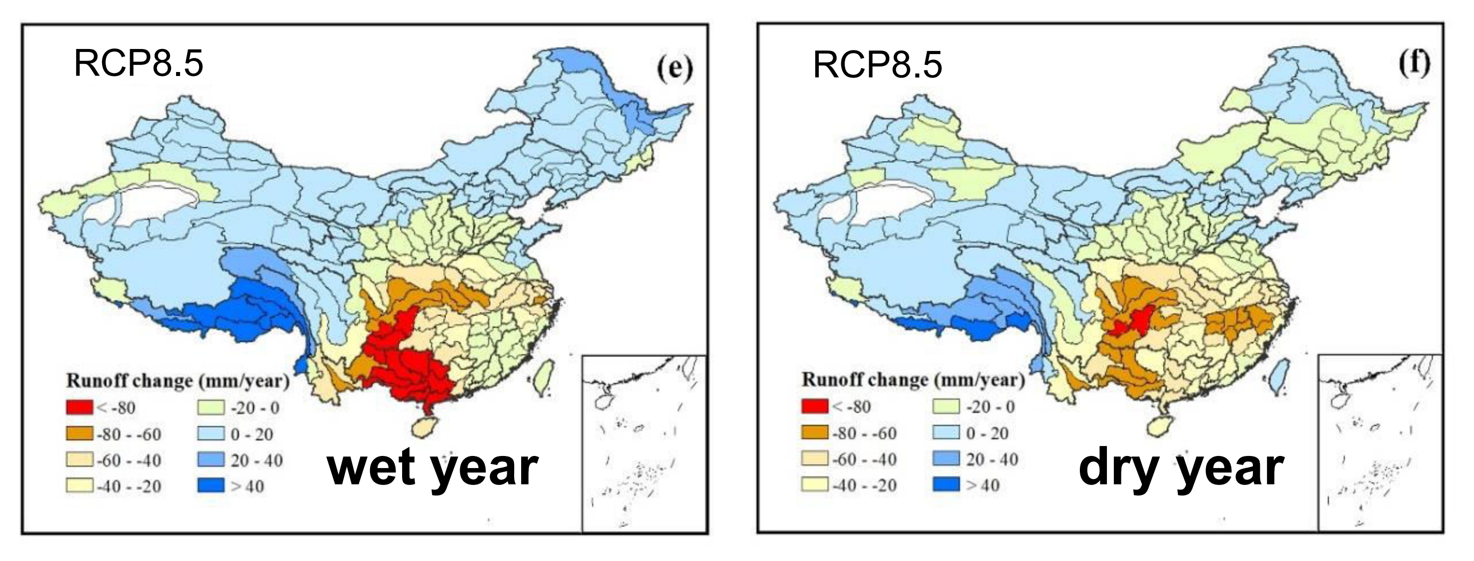


*(Liu et al., 2021, JoH)*

# Applications

## ■ Runoff changes in typical year

- ➢ decrease in southern China, largest in pearl river basin
- ➢ increase in dry regions, and decrease in wet regions

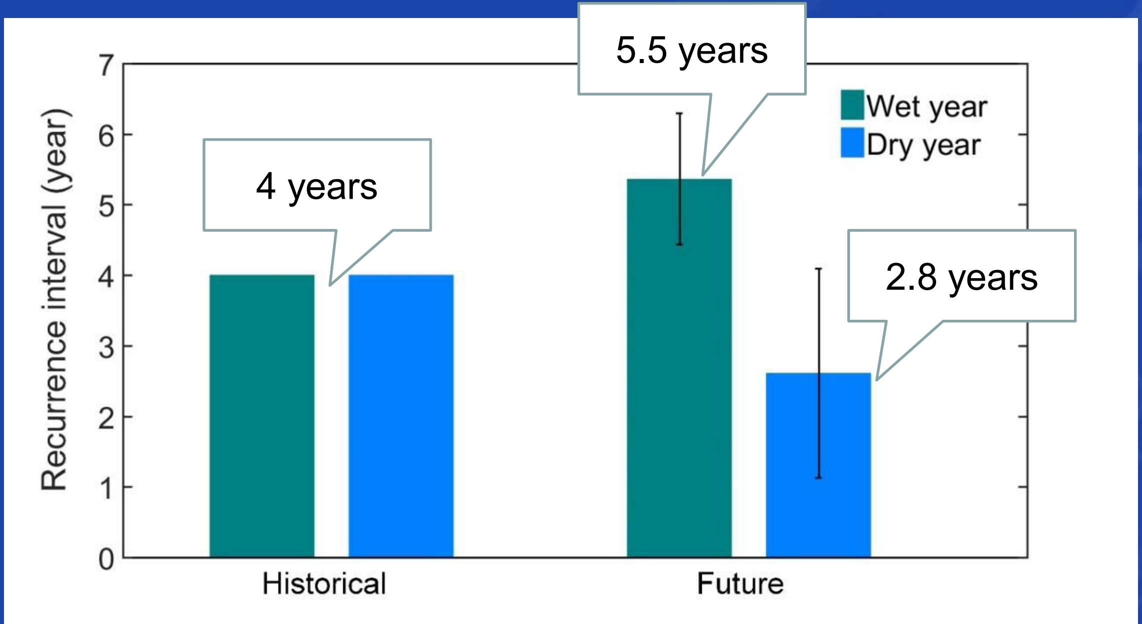


# Applications

## ■ Return period change in specific basin

- ➢ longer return period of wet year
- ➢ shorter return period of dry year

**More challenges for water resources management !**

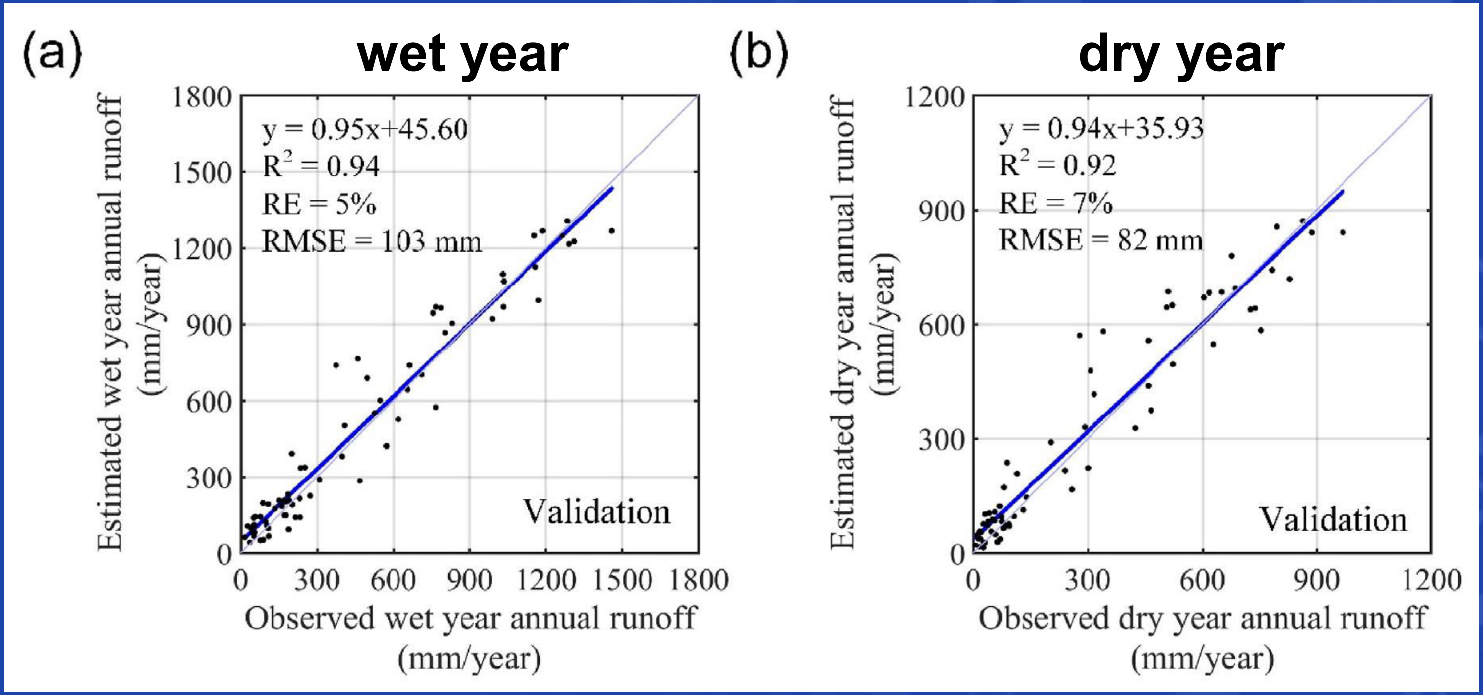


Beiluo river

# Applications

## The framework for ungauged basins

$$n=5.176-0.140\cdot ASL-0.027\cdot LON-0.281\cdot SI$$



*(Liu et al., 2022, ISWCR)*

# Take home message

**Theory**

An explicit framework was proposed to estimate the mean and variability of annual runoff, allowing us to estimate frequency of annual runoff that considers non-stationarity

⇩

**Application**

- Increasing inter-annual variability of runoff in China
- Shorter dry year return period, longer wet year return period
- More challenges in future water management

# References

- Yang, Hanbo*, and Yang Dawen, Derivation of climate elasticity of runoff to assess the effects of climate change on annual runoff, Water Resources Research, 2011, 47, W07526, doi:10.1029/2010WR009287
- Yang Hanbo*, Yang Dawen, and Hu Qingfang, An error analysis of the Budyko hypothesis for assessing the contribution of climate change to runoff, Water Resources Research, 2014, 50(12): 9620-9629
- Yang Hanbo*, Qi Jia, Xu Xiangyu, Yang Dawen, and Lv Huafang, The regional variation in climate elasticity and climate contribution to runoff across China, Journal of Hydrology, 2014, 517: 607-615
- Liu Ziwei, Yang Hanbo*, and Wang Taihua, A simple framework for estimating the annual runoff frequency distribution under a non-stationarity condition, Journal of Hydrology, 2021,592, 125550
- Liu Ziwei, Wang Taihua, Han Juntai, Yang Wencong, and Yang Hanbo*, Decreases in Mean Annual Streamflow and Interannual Streamflow Variability Across Snow-Affected Catchments Under a Warming Climate, Geophysical Research Letters, 2022, 49(3), doi:10.1029/2021GL097442
- Liu Ziwei, Yang Hanbo*, Wang Taihua, and Yang Dawen, Estimating the annual runoff frequency distribution based on climatic conditions and catchment characteristics: A case study across China, International Soil and Water Conservation Research, 2023， 11(3):470-481

XVIII
World Water Congress
International Water Resources Association (IWRA)

# Many Thanks!

**Ziwei Liu and Hanbo Yang**
**Tsinghua University**
**Beijing, China**

**contact:**
**yanghanbo@tsinghua.edu.cn; lzw_thu@163.com**