Assessment of Runoff sensitivities to changes in precipitation at the Indochina Region

Patinya Hanittinan, Ph.D.
Postdoctoral Fellow
Hydrology and Water Resources Engineering
Graduate School of Engineering, Kyoto University

Content

- **Background and Introduction**
  - Database for Policy Decision Making for Future Climate Change (d4PDF)
  - Forcing data
- **Study area**
- **Research Objectives and methodology**
- **Results and Discussions**
  - *d4PDF precipitation reproducibility*
  - *Relationship between the precipitation and total runoff indices*
  - *Runoff elasticities to change in precipitation at the Indochina Region*

Current State of Climate Change in the 21st Century

Figure SPM.1b
Observed change in surface temperature 1901-2012

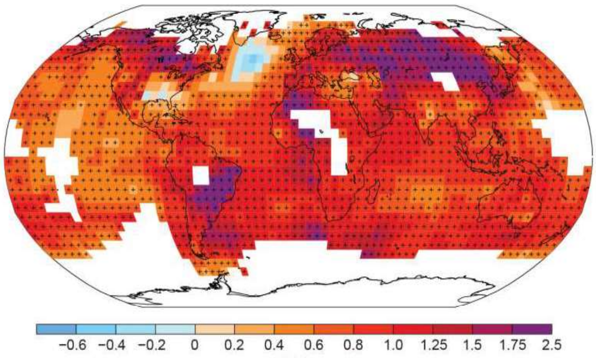


Figure SPM.2
Observed change in annual precipitation over land

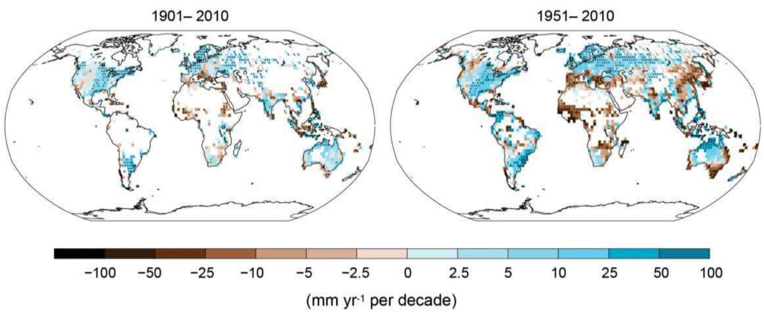


Figure SPM.7a
Global average surface temperature change

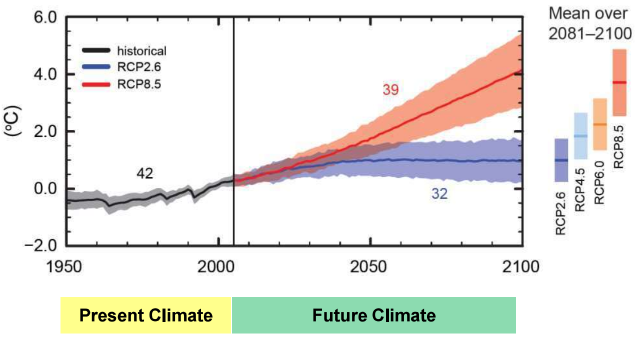
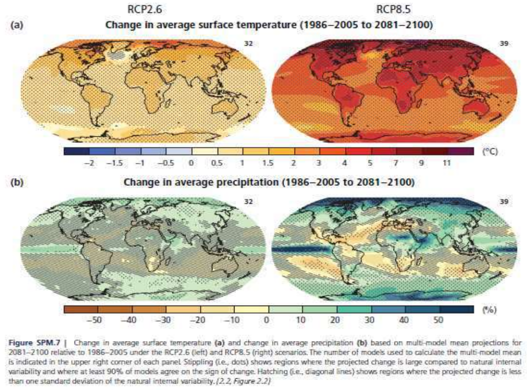
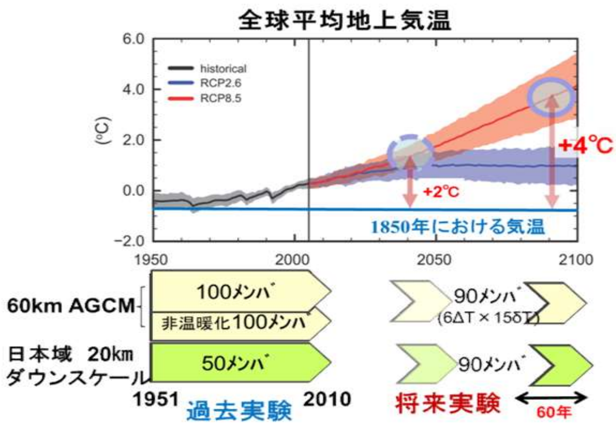


Figure SPM.7b and 7c
Change in average surface temperature & average precipitation



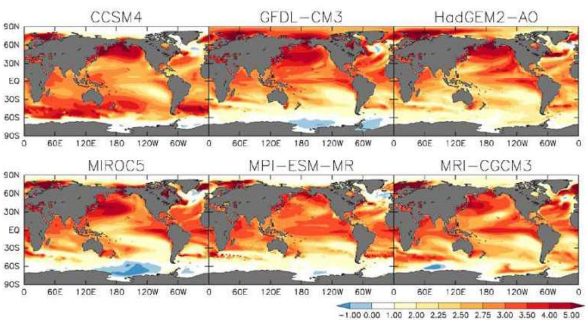
Source: IPCC WGI 5th Assessment Report (AR5)

Database for Policy Decision Making for Future Climate Change (d4PDF)

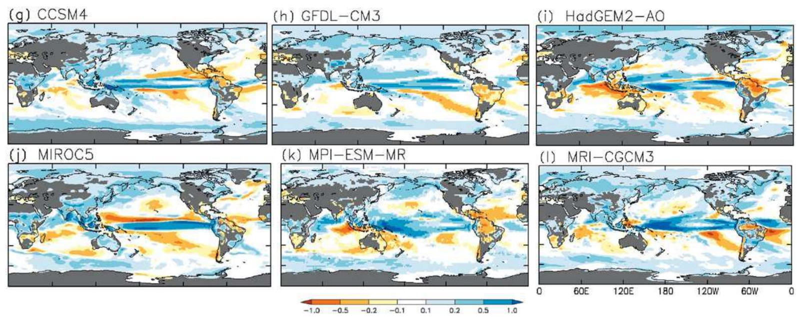


database **for P**olicy **D**ecision making for **F**uture climate change
/ 地球温暖化対策に資するアンサンブル気象予測データベース

- **Multiple-realization, single-model climate ensemble**
- **Present climate (HPB: 1951-2011)**
  - 100-member ensemble → (m001-m100) through the perturbation of the initial and boundary conditions (SST, SiC)
- **Future climate (HFK: 2051-2111)**
  - +4K scenarios where the global mean surface temperature will rise by 4 degree from the pre-industrial era
  - 15-member ensemble (m101-m115) for each future SST



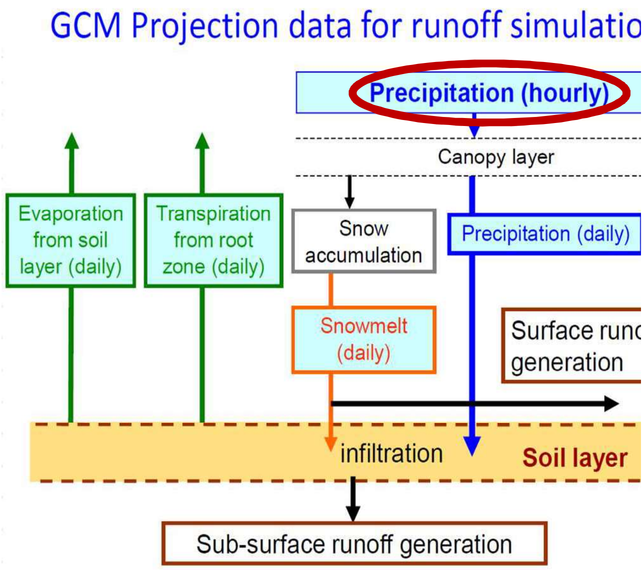
1) Annual-mean horizontal distributions of SST change (K) for the six ΔSST ensemble experiments

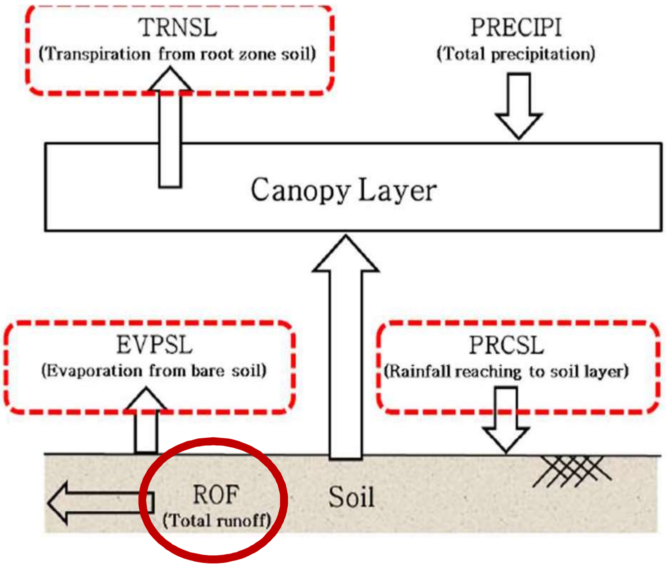


2) Annual-mean horizontal distributions of precipitation changes normalized by the global-mean SST change (mm/day-K)

文部科学省 MEXT
JAMSTEC 国立研究開発法人 海洋研究開発機構 JAPAN AGENCY FOR MARINE-EARTH SCIENCE AND TECHNOLOGY
京都大学防災研究所 Disaster Prevention Research Institute, Kyoto University
国立研究開発法人 国立環境研究所 National Institute for Environmental Studies
東京大学 大気海洋研究所 Atmosphere and Ocean Research Institute, The University of Tokyo
筑波大学 University of Tsukuba

d4PDF Forcing data: Schematic Parameter Diagram



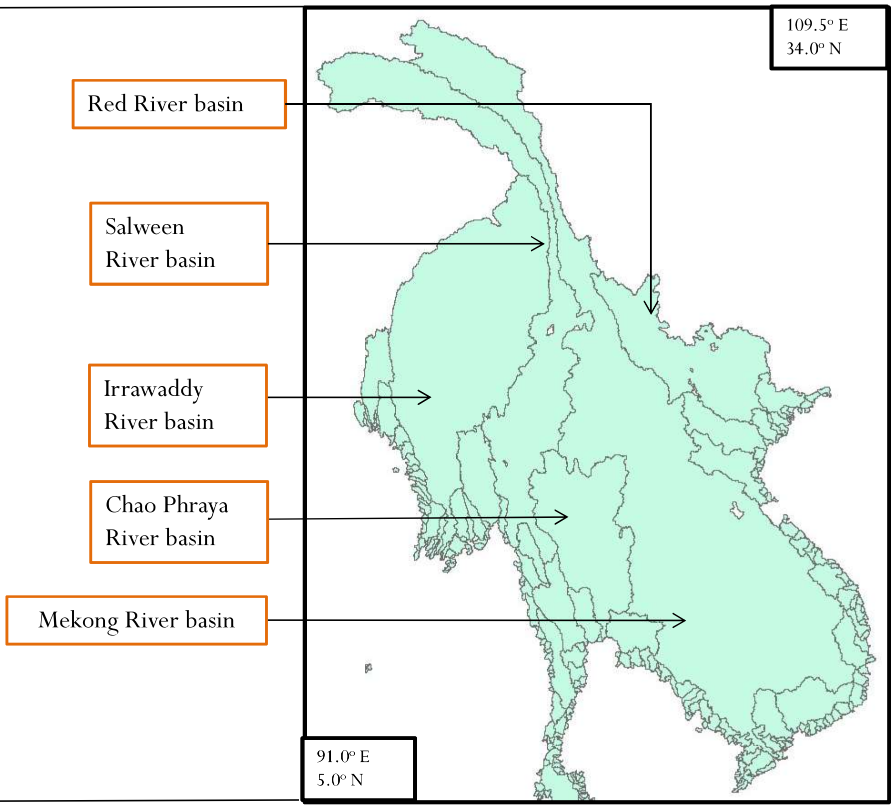


Present Climate (1951 – 2011)

Future Climate) (2051 – 2111)

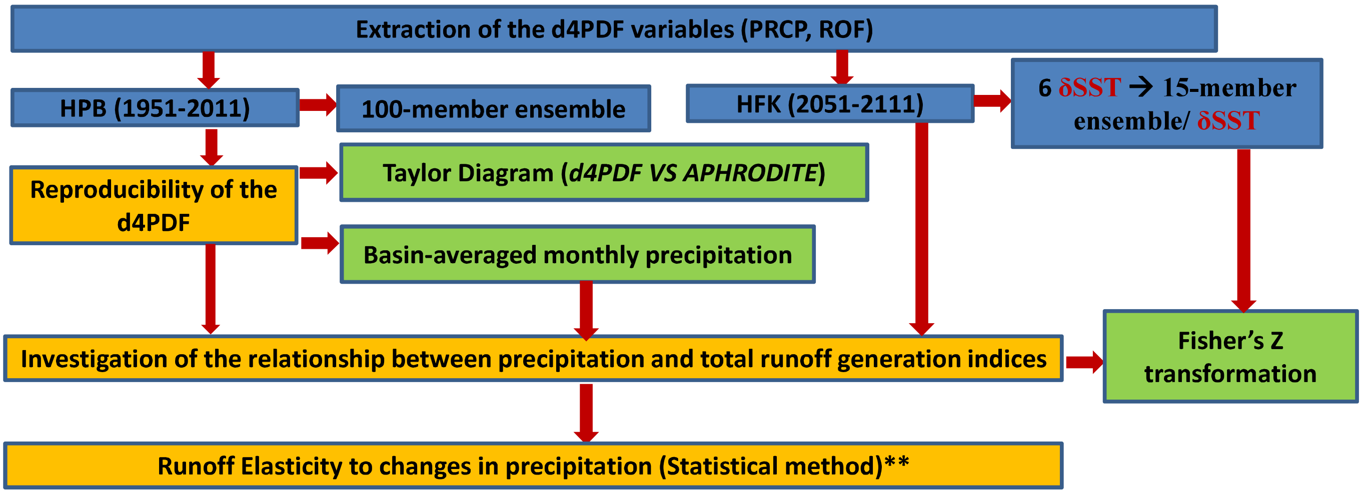
20th Century → **21st Century**

STUDY AREA: Indochina Peninsula



TITLE RESEARCH **Objectives and methodologies**

1. To evaluate the performance of the **d4PDF** in reproducing precipitation indices (Annual, seasonal, intensity, frequency) at the Indochina Region
2. Investigation of the relationship between precipitation and total runoff indices in terms of ***runoff elasticity*** under changing climate



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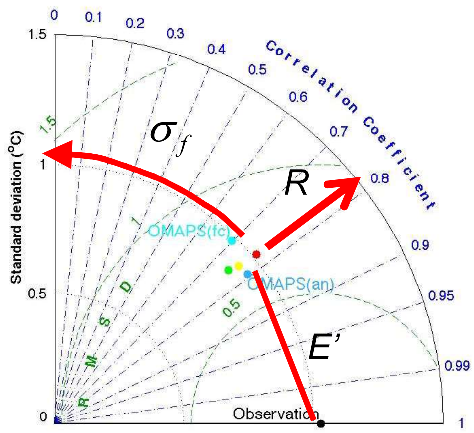
TOUGOU Integrated Research Program for Advancing Climate Models

Reproducibility of the d4PDF precipitation indices



Taylor, K., 2001: JGR, 106, D7, 7183-7192

Taylor Diagram

The correlation coefficient R between f and r is defined as:

$$R = \frac{\frac{1}{N}\sum_{n=1}^{N}(f_n - \bar{f})(r_n - \bar{r})}{\sigma_f \sigma_r} \quad \text{-(1)}$$

Where $\bar{f}$ and $\bar{r}$ are the mean value and σ_f and σ_r are the standard deviations of model *(f)* and reference *(r) fields*, respectively.

The statistic most often used to quantify differences in two fields is the RMS difference ***E***, which for fields *f* and *r* is defined by

$$E = \left[\frac{1}{N}\sum_{n=1}^{N}(f_n - r_n)^2\right]^{1/2} \quad \text{-(2)}$$

And the centered pattern RMS difference is defined by

$$E' = \left[\frac{1}{N}\sum_{n=1}^{N}\left[(f_n - \bar{f}) - (r_n - \bar{r})\right]^2\right]^{1/2} \quad \text{-(3)}$$

In order to isolate the differences in the pattern s from the differences in the means of two fields , E can be resolved into two components. The overall "bias" is defined as

$$\bar{E} = \bar{f} - \bar{r} \quad \text{-(4)}$$

The three components from (2), (3), and (4) add quadratically to yield the full mean square difference

$$E^2 = \bar{E}^2 + E'^2 \quad \text{-(5)}$$

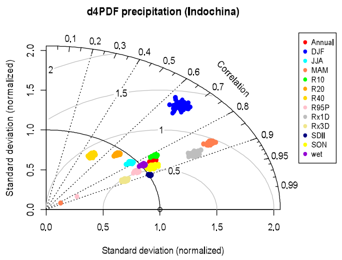
$$E'^2 = \sigma_f^{\,2} + \sigma_r^{\,2} - 2\sigma_f\sigma_r R \quad \text{-(6)}$$

Indices Glossary

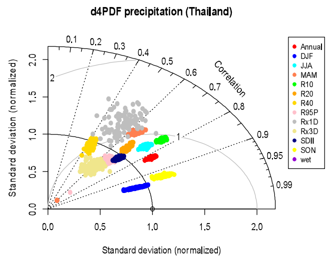
ID	Units	Indicator name	Definitions
Annual and seasonal precipitation indices			
PRCPTOT	mm	Annual total wet-day precipitation	Annual total PRCP in wet days (RR ≥ 1 mm)
JJA	mm	Early monsoon precipitation (June to August)	Cumulative PRCP during June to August
SON	mm	late monsoon precipitation (September to November)	Cumulative PRCP during September to November
Wet	mm	Total wet-season precipitation (June to November)	Cumulative PRCP during June to November
DJF	mm	Early dry-season precipitation (December to February)	Cumulative PRCP during December to February
MAM	mm	Late dry-season precipitation (March to May)	
Intensity-based indices			
Rx1D	mm	Max 1-day precipitation amount	Annual maximum 1-day precipitation
Rx3D	mm	Max 3-day precipitation amount	Annual maximum 3-day precipitation
SDII	mm day^{-1}	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP ≥ 1.0 mm) in the year
R95p	mm	Very wet days	Annual total PRCP when RR > 95th percentile
frequency-based indices			
R10	Day	Number of heavy precipitation days	Annual count of days when PRCP ≥ 10 mm
R20	Day	Number of very heavy precipitation days	Annual count of days when PRCP ≥ 20 mm
R40	Day	Number of days above 40 mm	Annual count of days when PRCP ≥ 40 mm

Reproducibility of the d4PDF's precipitation

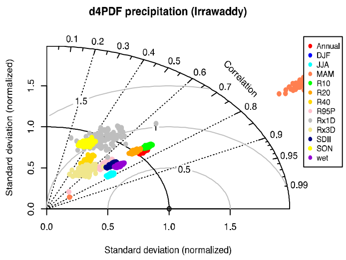
Taylor's Diagram (pattern correlation and spatial variabilities)



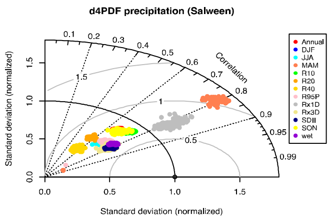
Indochina



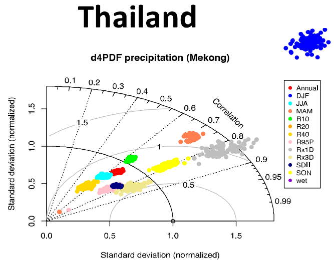
Thailand



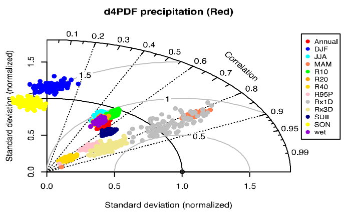
Irrawaddy



Salween

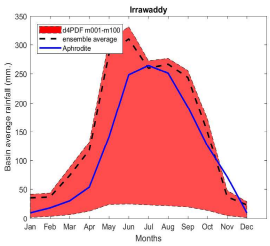


Mekong

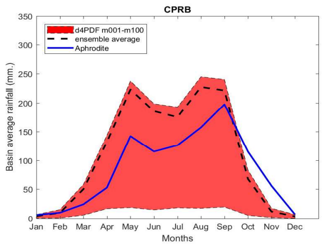


Red

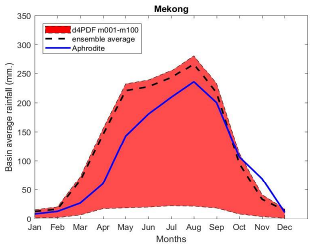
Monthly Precipitation climatology



Irrawaddy



CPRB

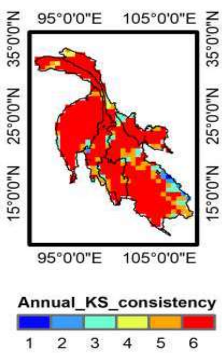


Mekong

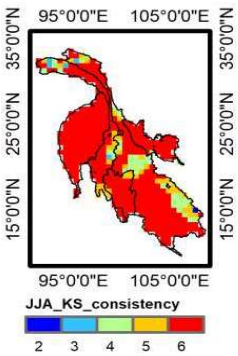
Assessment of the Future changes in Precipitation

Significance of the distribution of changes in the precipitation indices

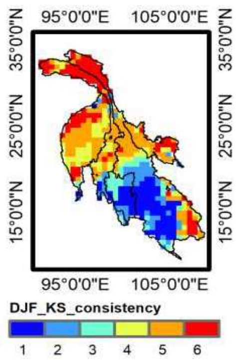
Annual PRCPTOT



JJA



DJF



Non-parametric two-sample KS-test

$$D_n(x) = \sup_x \left| F_{1,n}(x) - F_{2,n'}(x) \right|$$

Criterion for the rejection of the null hypothesis

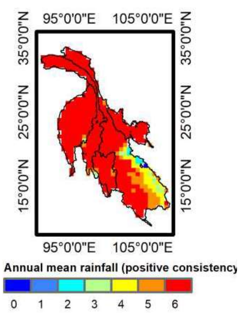
Rejection

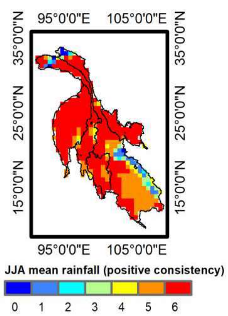
$$D_s > \left[-\frac{1}{2}\left(\frac{1}{n} + \frac{1}{n'}\right) ln\left(\frac{\alpha}{2}\right) \right]^{1/2}$$

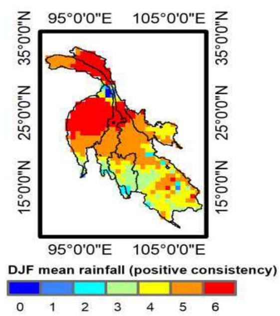
No Rejection

$$D_s < \left[-\frac{1}{2}\left(\frac{1}{n} + \frac{1}{n'}\right) ln\left(\frac{\alpha}{2}\right) \right]^{1/2}$$

Significance of the changes in the mean of the precipitation indices







Welch's correction t-test (U-test)

$$U = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2}}}$$

$$\nu \approx \frac{\left(\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2}\right)^2}{\frac{S_1^4}{N_1^2 \nu_1} + \frac{S_2^4}{N_2^2 \nu_2}}$$

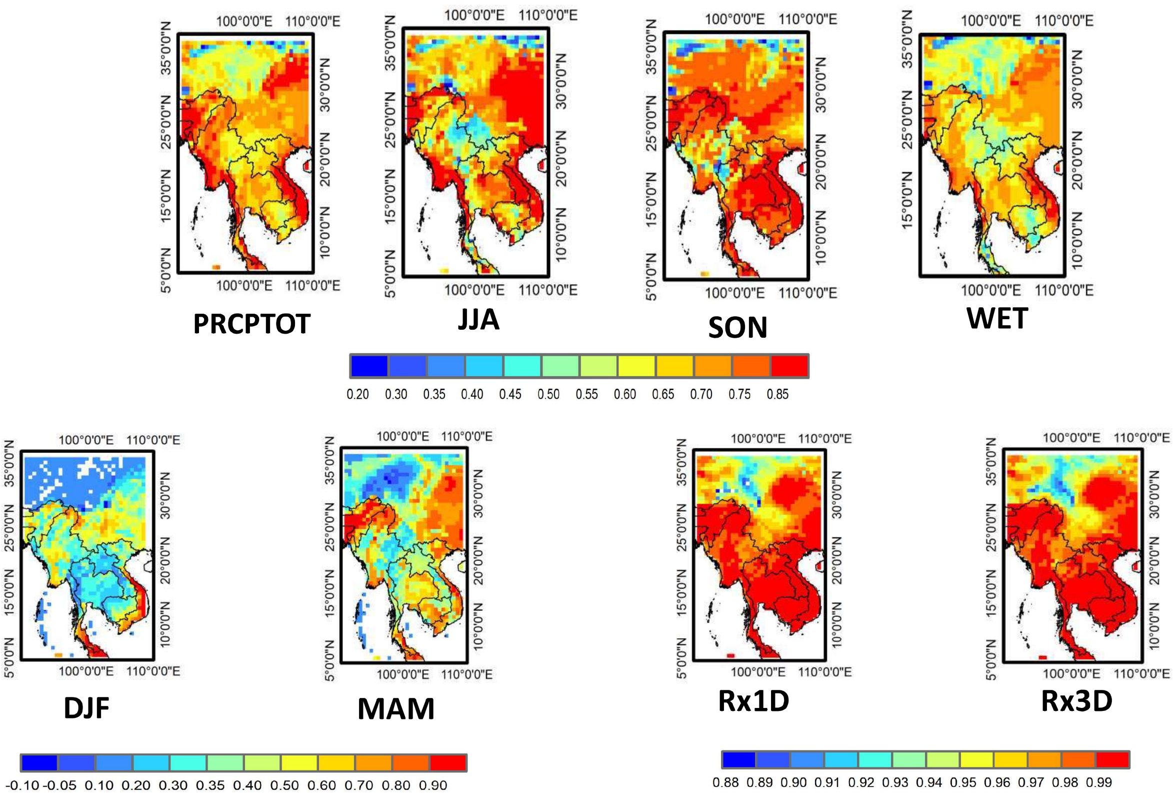
Rejection

$U > U_{critical;\ \alpha,\ \nu}$

No Rejection

$U < U_{critical;\ \alpha,\ \nu}$

Relationship between precipitation and total runoff indices



Runoff Elasticity to changes in Precipitation (Statistical methods**)

It is one of the important indicators quantifying the sensitivity of runoff to climate change!

- ***Climate elasticities of runoff:***
  - The proportional change in runoff (R) to the change in climatic variables (Fu et al., 2007)
  - Reliable estimation of climate elasticity is a key to ***understand the projection of the hydrologic response to climate change***
  - Typically, Precipitation (P) has an important impact on runoff.
  - Therefore, the relationship of elasticity of runoff (R) to P was first defined by Schaake (1990) as

$$\epsilon_P(P,R) = \frac{dR/R}{dP/P} \qquad \text{------(1)}$$

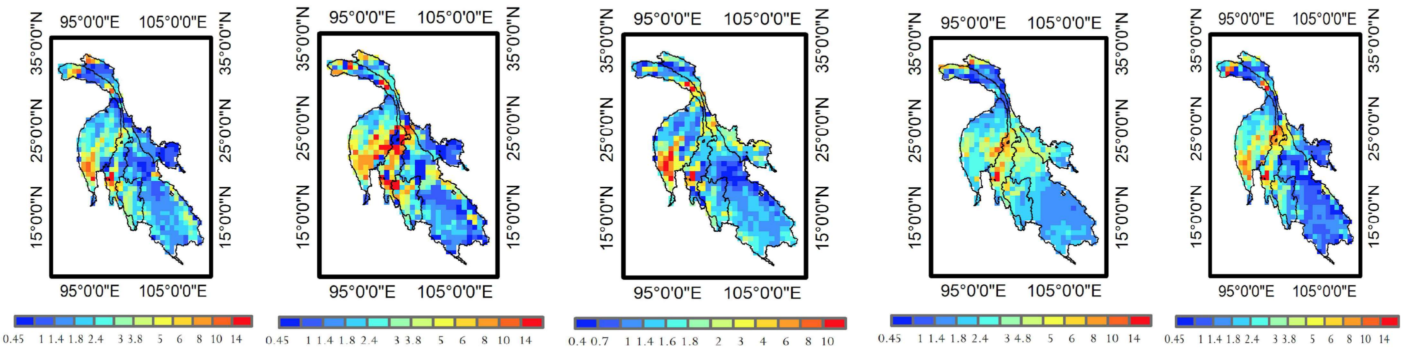
Adopting the framework provided by Eq. (1), we modified the runoff elasticity estimation formula using median descriptive statistics **(Sankarasubramanian *et al.*, 2001):**

$$\varepsilon_P(P,R) = median\left[\frac{(R_i - \bar{R})/\bar{R}}{(P_i - \bar{P})/\bar{P}}\right] \qquad \text{------(2)}$$

where $\bar{R}$ and $\bar{P}$ denote the 100-member means of runoff and precipitation extreme indices under the present climate (1951–2010). The value of the right-hand term in Eq. (2) is calculated for each pair of R_i and P_i

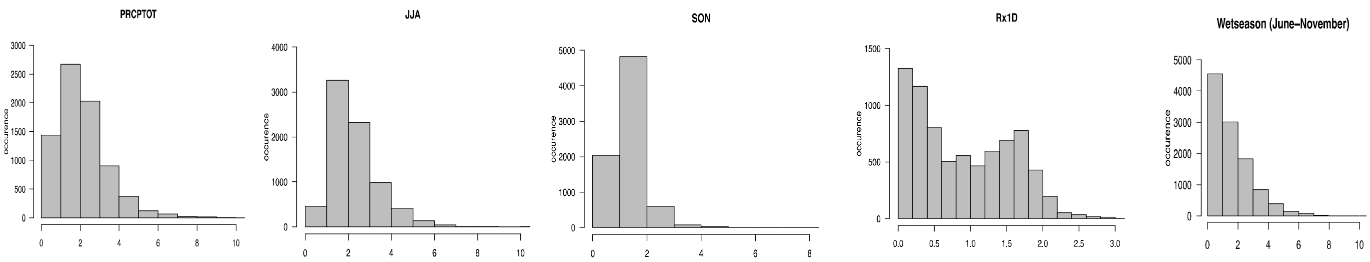
Runoff Elasticity to changes in Precipitation (Statistical methods**)

Runoff Elasticity to changes in the precipitation indices



PRCPTOT **JJA** **SON** **Rx1D** **WET**

Histogram of the runoff elasticity distribution



Discussions

1. Reproducibility of the d4PDF precipitation indices

- **Close grouping of dots** representing the other indices indicated that the simulated uncertainty attributable to sampling variability was not very large
- **Broad disagreements** in the ***Rx1D*** biases among the d4PDF ensembles and the **underperformance of dry-season indices** (***DJF***, ***MAM***) in basin-scale simulation
- **The major limitation** of Taylor's method
  - it can only express the terms of variance and correlation
  - Can not accurately determine the performance of hydroclimate variable with a high-degree of nonlinear dependences

2. Statistical significance of the Future projections of d4PDF precipitation

- Results of the ***KS-test*** and ***parametric U-test*** showed that the changes in precipitation climatology and its associated extreme are consistently **significant** at the Indochina Region.

3. Runoff elasticity to changes in precipitation at the Indochina Region

- The results at the study area were largely comparable with **Tang and Lettenmeier** (2012), and **Berghuijs *et al.*** (2017)
  - 1) The runoff elasticity is **always** larger than unity, which mean runoff response is **faster** than the precipitation
  - 2) The $\varepsilon_P(P, R)$ = 1.28 is however lower than these studies at annual scale, where the median elasticity is reported at **1.90**
- ***Major limitation of current approach***
  - No consideration about the effect of runoff elasticity to changes in evapotranspiration at all.
  - Can not determine the relative contribution between **P and E** to the sensitivity of the total runoff generation (***R***)
  - Other factors that needs to be incorporated is ***catchment characteristics (n)***

Thank you very much for your kind attention!

Email: Patinyah@hotmail.com
hanittinan.patinya.5n@kyoto-u.ac.jp

APPENDIX

Assessment of Runoff sensitivities under climate change (2)

- Aside from precipitation change, there are much more factors
  - **Air Temperature** (*T*)
  - **Net Radiation** (R_n)
  - **Wind speed at a height of 2 m** (U_2)
  - **Relative Humidity** (*RH*)
  - **…. And so on….**

$$dR/R = \varepsilon_a \, dP/P + \varepsilon_b \, dT/T + \varepsilon_c \, dR_n/dR_n + \varepsilon_d \, dU_2/U_2 \qquad \text{------(3)}$$

Yang and Yang (2011)

Where ε_a, ε_b, ε_c, and ε_d are the climate elasticities.

We do not know for sure how many climatic variable need to be considered when assessing climate change effects on runoff and which the dominant variable in theory are.

- **Sankarasubamanian *et al.* (2001)** classified ways to estimate the runoff elasticity, e.g., ***Analytical derivation*, empirical estimation the changes in runoff and change in climate from historical data**

Assessment of Runoff sensitivities under climate change (4): Analytical Derivation (1)

- **Benefit of using analytical derivation for the estimation of runoff elasticities**
  - 1) clear in theory
  - 2) It does not depend on a large amount of historical climate and runoff data

Derivation of the climate elasticity of temporal runoff (1)

$$E = \frac{E_0 P}{(P^n + E_0^n)^{1/n}} \qquad \text{------(4)}$$

Where parameter ***n*** represents the effect of catchment characteristics. Denoting equation (4) as E = f(E_0, *P*, *n*) according to the "***Budyko hypothesis***" (Budyko, 1974), we can express the total differential as

$$dE = \frac{\partial f}{\partial P} dP + \frac{\partial f}{\partial E_0} dE_0 + \frac{\partial f}{\partial n} dn \qquad \text{------(5)}$$

$$dR = \left(1 - \frac{\partial f}{\partial P}\right) dP - \frac{\partial f}{\partial E_0} dE_0 - \frac{\partial f}{\partial n} dn \qquad \text{------(6)}$$

When no consideration is given to the interannual changes in catchment characteristics, dn = 0. We then divide the equation (6) using ***R* = *P* – *E***, and obtain the following:

$$\frac{dR}{R} = \left(1 - \frac{\partial f}{\partial P}\right) \frac{P}{P - E} \frac{dP}{P} - \frac{\partial f}{\partial E_0} \frac{E_0}{P - E} \frac{dE_0}{E_0} \qquad \text{------(7)}$$

$$\frac{dR}{R} = \varepsilon_1 \frac{dP}{P} + \varepsilon_2 \frac{dE_0}{E_0} \qquad \text{------(8)}$$

Assessment of Runoff sensitivities under climate change (5): Analytical Derivation(2)

Derivation of the climate elasticity of temporal runoff (2)

Potential evapotranspiration (E_0), which is a part of the equation (4) can be calculated using the Penman equation **(Penman, 1948)**

$$E_0 = \frac{\Delta}{\Delta+\gamma}(R_n - G)/\lambda + \frac{\gamma}{\Delta+\gamma}6.43(1+0.536U_2)(1-RH)\,e_s/\lambda \qquad \text{------(9)}$$

Roderick et al. (2007) developed a differential model to separate the contributions of climatic variable change from change in pan evaporation:

$$dE_p \approx \frac{\partial E_p}{\partial R_n}dR_n + \frac{\partial E_p}{\partial U_2}dU_2 + \frac{\partial E_p}{\partial D}dD + \frac{\partial E_p}{\partial T}dT \qquad \text{------(10)}$$

Similarly, the contributions of climatic variables to the change in potential evaporation can be estimated

$$dE_0 \approx \frac{\partial E_0}{\partial R_n}dR_n + \frac{\partial E_0}{\partial T}dT + \frac{\partial E_0}{\partial U_2}dU_2 + \frac{\partial E_0}{\partial RH}dRH \qquad \text{------(11)}$$

Furthermore,

$$\frac{dE_0}{E_0} = \left(\frac{R_n}{E_0}\frac{\partial E_0}{\partial R_n}\right)\frac{dR_n}{R_n} + \left(\frac{1}{E_0}\frac{\partial E_0}{\partial T}\right)dT + \left(\frac{U_2}{E_0}\frac{\partial E_0}{\partial U_2}\right)\frac{dU_2}{U_2} + \left(\frac{RH}{E_0}\frac{\partial E_0}{\partial RH}\right)\frac{dRH}{RH} \qquad \text{------(12)}$$

$$\frac{dE_0}{E_0} = \varepsilon_3\frac{dR_n}{R_n} + \varepsilon_4 dT + \varepsilon_5\frac{dU_2}{U_2} + \varepsilon_6\frac{dRH}{RH} \qquad \text{------(13)}$$

Where ε_3, ε_4, ε_5, and ε_6 are the elasticity of potential evaporation with respect to changes in R_n, T, U_2, and RH, respectively.

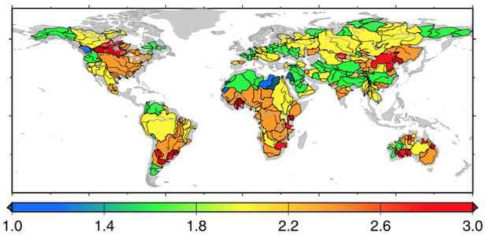
Combining equations (8) and (13), we obtain the following:

$$\frac{dR}{R} = \varepsilon_1\frac{dP}{P} + \varepsilon_2\varepsilon_3\frac{dR_n}{R_n} + \varepsilon_2\varepsilon_4 dT + \varepsilon_2\varepsilon_5\frac{dU_2}{U_2} + \varepsilon_2\varepsilon_6\frac{dRH}{RH} \qquad \text{------(14)}$$

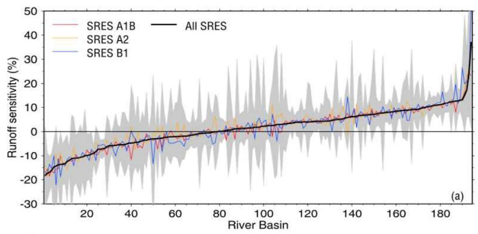
$$\frac{dR}{R} = P^* + R_n^* + T^* + U_2^* + RH^* \qquad \text{------(15)}$$

Results from previous studies - $\varepsilon_{R,T}$

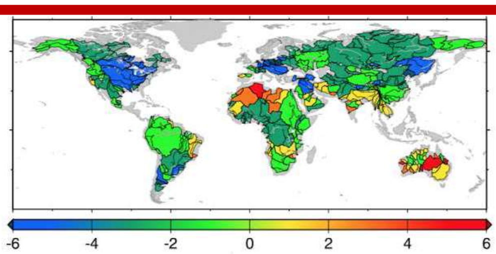
Tang and Lettenmeier (2012) - GRL



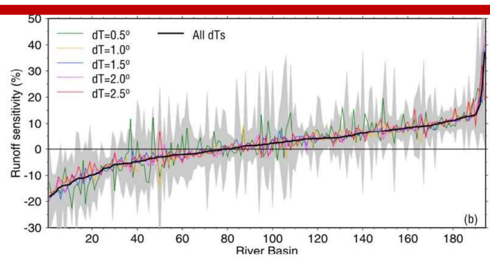
$\varepsilon_{R,P}$ with respect to a basin mean annual precipitation



$\varepsilon_{R,P}$ (percent per degree C GMT change) from different set of GCMs



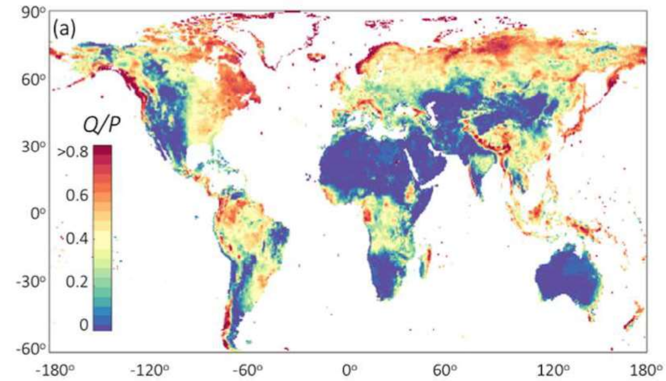
$\varepsilon_{R,P}$ with respect to a temperature for a global 194 river basins



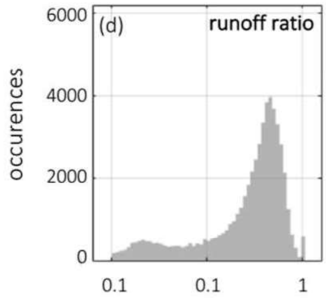
$\varepsilon_{R,P}$ (percent per degree C GMT change) varied with different dT

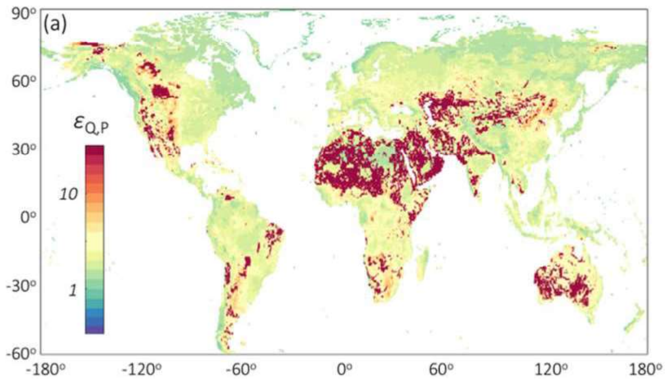
Results from previous studies - $\varepsilon_{R,P}$

Berghujis et al. (2018) - WRR

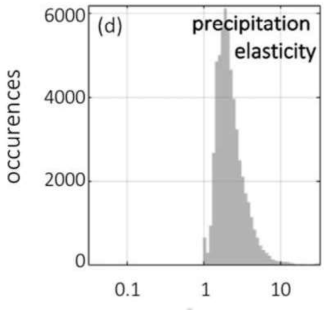


R/P





$\varepsilon_{R,P}$



Assessment of the contribution to runoff elasticity from changes in Precipitation, evapotranspiration, and other factors

Budyko Framework (1974) hypothesized a functional relationship between Evapotranspiration (E) and the two climate variables, Precipitation(P) and potential evapotranspiration (E_0) as an average over a long-enough time scale

$$\boldsymbol{E = f(P, E_0)}$$

- Energy & precipitation (P) constraints on evaporation (E)
  - Based on the ***MCY model***

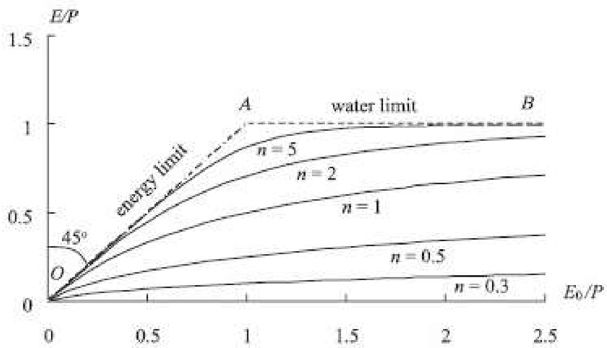
$$E = \frac{P\,E_0}{\left(P^n + E_0^n\right)^{1/n}}.$$

Budyko Framework

- **E_o** is maximum theoretical evaporation (E is energy limited)
- **E** is also limited by water availability (determined by P)
- **n** is a catchment-specific parameter

If $P \gg E_o$, $E \rightarrow E_o$

If $E_o \gg P$, $E \rightarrow P$



Yang et al. (2008) WRR

Different Formulas for the Budyko hypothesis

Parametric and non-parametric estimation of water availability under the Budyko assumptions

Formula	Parameter	Reference
$E=P[1-\exp(-E_0/P)]$	None	***Schreiber (1904)***
$E= E_0\tanh(P/E_0)$	None	***Ol'Dekop (1911)***
$E=P/[1+(P/E_0)^2]^{0.5}$	None	***Pike (1964), Turc (1954)***
$E = \{P[1-\exp(-E_0/P)]\ E_0\tanh(P/E_0)\}^{0.5}$	None	***Budyko (1958)***
$E = P + E_0 - (P^\omega+E0^\omega)^{1/\omega}$	ω	***Fu (1981)***
$E=E_0/P/(1+(E_0/P)^n)^{1/n}$	n	***MCY model (Mezentsev, 1955; Choudhury, 1995; Yang et al., 2008)***
$E=P/[1+w(E_0/P)]/[1+w(E_0/P) + P/E_0$	w	***Zhang et al. (2001)***

Assessment of Runoff sensitivities under climate change (1): Analytical Derivation (1)

$$E = \frac{E_0 P}{(P^n + E_0^n)^{1/n}} \qquad \text{------(1)}$$

$$dQ = \left(1 - \frac{\partial E}{\partial P}\right) dP - \frac{\partial E}{\partial E_0} dE_0 - \frac{\partial E}{\partial n} dn \qquad \text{------(3)}$$

When a consideration is given to the interannual changes in catchment characteristics, dn > 0. We then divide the equation (6) using ***Q= P – E***, and obtain the following:

$$\frac{dQ}{Q} = \left(\mathbf{1} - \frac{\boldsymbol{\partial E}}{\boldsymbol{\partial P}}\right) \frac{\boldsymbol{P}}{\boldsymbol{P-E}} \frac{dP}{P} - \frac{\boldsymbol{\partial E}}{\boldsymbol{\partial E_0}} \frac{\boldsymbol{E_0}}{\boldsymbol{P-E}} \frac{dE_0}{E_0} - \left[\left(\frac{\boldsymbol{\partial E}}{\boldsymbol{\partial n}}\right)\left(\frac{\boldsymbol{n}}{\boldsymbol{P-E}}\right)\right] \frac{dn}{n} \qquad \text{------(4)}$$

$$\frac{dQ}{Q} = \boldsymbol{\varepsilon_{Q,P}} \frac{dP}{P} + \boldsymbol{\varepsilon_{Q,E_0}} \frac{dE_0}{E_0} + \boldsymbol{\varepsilon_{Q,n}} \frac{dn}{n} \qquad \text{------(5)}$$

$$\varepsilon_{Q,P} = \frac{\partial Q/Q}{\partial P/P} = \frac{\left\{1 - \frac{1}{\left(1+\left(\frac{P}{E_0}\right)^n\right)^{1+1/n}}\right\}}{\left\{1 - \frac{1}{\left(1+\left(\frac{P}{E_0}\right)^n\right)^{1/n}}\right\}} \qquad \varepsilon_{Q,E_0} = \frac{\partial Q/Q}{\partial E_0/E_0} = \frac{1}{[1+(E_0/P)^n]^{1+1/n}} \cdot \frac{1}{\left\{\frac{1}{E_0/P} - \frac{1}{[1+(E_0/P)^n]^{1/n}}\right\}}$$

$$\varepsilon_{Q,n} = \frac{\partial Q/Q}{\partial n/n} = \frac{(P^n \ln P + E_0^n \ln E_0)(P^n + E_0^n)^{-(1+1/n)}}{\left\{\frac{1}{E_0} - \frac{1}{(P^n + E_0^n)^{1/n}}\right\}}$$

Assessment of Runoff sensitivities under climate change (2): Analytical Derivation (2)

Derivation of the climate elasticity of temporal runoff (2)

Concept of "water availability"

$$F(\phi,\omega) = \frac{E}{P} \approx 1 - \frac{Q}{P}$$

Where parameter ϕ is aridity (E_0/P), and ω is a parameter that account for all other factors that influence the mean-annual partitioning of precipitation (e.g., climate seasonality, soils, vegetation, topography, and etc.).

Fu (1981) presented the parametric equation that quantify the "water availability"

$$F(\phi,\omega) = 1 + \phi - (1+\phi^{\omega})^{\frac{1}{\omega}} \qquad \text{------(6)}$$

Where $\phi > 0$, $\quad 1 \le \omega \le \infty, and\ \phi = E_0/P$

By rewriting Fu's equation whereby aridity is expanding to E_0/P allows expressing Q as

$$Q(P, E_0, \omega) = P\left(-\frac{E_0}{P} + \left(1 + \left(\frac{E_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}}\right) \qquad \text{------(7)}$$

$$\frac{dQ}{Q} = \left(1 - \frac{\partial E}{\partial P}\right)\frac{P}{P-E}\frac{dP}{P} - \frac{\partial E}{\partial E_0}\frac{E_0}{P-E}\frac{dE_0}{E_0} - \left[\left(\frac{\partial E}{\partial n}\right)\left(\frac{\omega}{P-E}\right)\right]\frac{d\omega}{\omega} \qquad \text{------(8)}$$

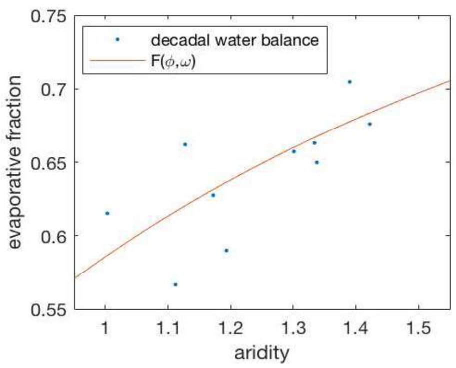
$$\varepsilon_{Q,P} = \frac{\partial Q/Q}{\partial P/P} = \frac{(\phi^{\omega}+1)^{\frac{1}{\omega}-1}}{-\phi + (1+\phi^{\omega})^{\frac{1}{\omega}}}$$

$$\varepsilon_{Q,E_0} = \frac{\partial Q/Q}{\partial E_0/E_0} = \frac{\phi^{\omega}(\phi^{\omega}+1)^{\frac{1}{\omega}-1} - \phi}{-\phi + (1+\phi^{\omega})^{\frac{1}{\omega}}} \qquad \varepsilon_{Q,\omega} = \frac{\partial Q/Q}{\partial \omega/\omega} = \frac{(\phi^{\omega}+1)^{\frac{1}{\omega}} \cdot \left(\frac{\phi^{\omega}\ln(\phi)}{\phi^{\omega}+1} - \frac{ln(\phi^{\omega}+1)}{\omega}\right)}{-\phi + (1+\phi^{\omega})^{\frac{1}{\omega}}} \qquad \text{------(9)}$$

Assessment of Runoff sensitivities under climate change (3)

Estimation of a catchment-specific parameter (n, ω)

E/P



E_0/P

When $\quad F(\phi,\omega) = 1 + \phi - (1+\phi^{\omega})^{\frac{1}{\omega}}$

Or $\quad F(\phi,n) = \dfrac{\phi}{(1+\phi^{n})^{1/n}}$

Where, $F(\phi,\omega)$ and $F(\phi,n)$

are known as the water availability or evaporative faction

ω = catchment-specific parameter (Fu's model)

n = catchment-specific parameter (MCY's model)

Typically, a long-term annual average (indicated by subscript i) of precipitation (P), potential evapotranspiration (E0), and actual evapotranspiration (E) to find the optimal n or ω for each catchment, using parametric equation of the Budyko's assumption. The optimal fit for catchment parameter is determined via a minimized root mean square error of the fit:

$$\sum\left(\left(F\left(\frac{E_{P_i}}{P_i},\omega\right) - \frac{E_i}{P_i}\right)^2\right) \qquad \text{Fu's model (Fu, 1981)}$$

$$\sum\left(\left(F\left(\frac{E_{P_i}}{P_i},n\right) - \frac{E_i}{P_i}\right)^2\right) \qquad \text{MCY model (Mezentsev, 1955; Choudhury, 1995; Yang et al., 2008)}$$

Tentative Research Objectives

1. Assessment of relative importance of changes in P, E_0, and n/ω to runoff

$$\theta_x = \frac{\left|\varepsilon_{Q,x}\right|}{\left|\varepsilon_{Q,P}\right| + \left|\varepsilon_{Q,E_0}\right| + \left|\varepsilon_{Q,(n,\omega)}\right|}$$

Where θ_x is the relative sensitivity of Q to each factor x ((n,ω), E_p, and P) . θ_x can vary from close to zero, to close to one, whereby $\theta_P + \theta_{E_P} + \theta_{(n,\omega)} = 1.0$

1.1 Comparison at the Indochina Basins between the Present and Future climate by applying the d4PDF dataset.

1.2 Comparison of the results from two parametric Budyko-type formula. The relationship between n and ω at the Indochina River Basins.

2. Runoff sensitivity analysis of the Budyko space of P, E_0, and n/ω with respect to the aridity index (ϕ)at each of the Indochina River Basin (CPRB, Mekong, Irrawaddy, Salween, Red)

2.1 P vs ϕ

$$\left|\frac{\partial Q}{\partial P}\zeta P\right| vs\ \phi(E_0, P)$$

2.2 E_0 vs ϕ

$$\left|\frac{\partial Q}{\partial E_0}\zeta E_0\right| vs\ \phi(E_0, P)$$

2.3 (n,ω) vs ϕ

$$\left|\frac{\partial Q}{\partial (n,\omega)}\zeta(n,\omega)\right| vs\ \phi(E_0, P)$$

Where $\zeta = \frac{\Delta P}{P} = \frac{\Delta E_0}{E_0} = \frac{\Delta(n,\omega)}{(n,\omega)}$