The Flood Elasticity under Changing Conditions: An Application in a Tropical Monsoon Basin of Thailand

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Climate Elasticity: Definations

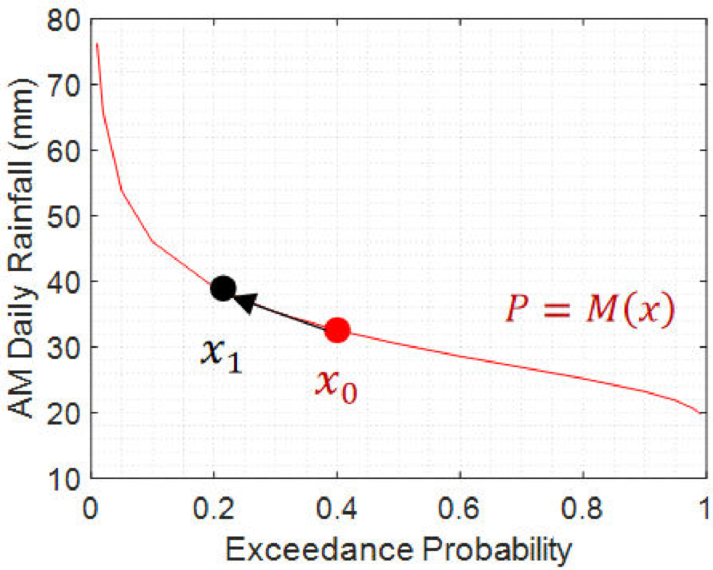
- Defination: the **relative response** of runoff to the **relative change** of precipitation;
- Schaake et al. (1990): runoff elasticity estimates the relationship between rainfall and runoff annually;
- Breinl et al. (2021): storm-flood elasticity derived from **frequency curves** estimates the relationship between daily storm and flood peaks;
- Current storm-flood elasticity analyses normally regard the relationship as constant **regardless of changing conditions**.

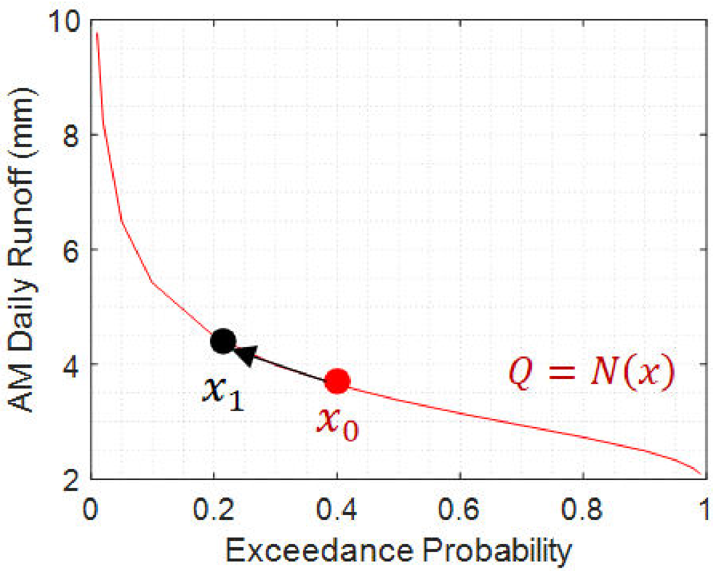
- C-C Relationship: a 1°C increase in temperature leads to a resultant 7% increase in precipitation extremes;
- Intense studies have predicted more and stronger precipitation extremes across the world due to global warming (Donat et al., 2016, NCC; Thackeray et al., 2022, NCC);
- The amplified flood magnitude in the future is predicted in most parts of the world, while the contribution of climate change to flood amplification is the strongest in Southeast Asia (Winsemius et al., 2015, NCC)

Rising Problems: What's for next?

- Current elasticity analyses ignore changing conditions:
  - ➢ The frequency curves should tell changing stories.
  - ✓ Time-varying frequency curves via GAMLSS!

- Analyses on the future flood changes:
  - ➢ The changes of flood peaks should be quantified.
  - ✓ Time-varying flood frequency curves show!
  - ➢ The roles of different factors should be clarified.
  - ✓ Elasticity analyses on different factors!





Storm-Flood-Frequency-Equivalence:

- Suppose storm and the resultant flood are at the same frequency.
- Suppose exceedance probability decrease from x_0 to x_1, design storm rise from P_0 to P_1, design flood rise from Q_0 to Q_1, correspondingly.

$$\varepsilon_0(x_0) = \frac{\frac{Q_1 - Q_0}{Q_0}}{\frac{P_1 - P_0}{P_0}} = \frac{P_0 f(P_0)}{Q_0 g(Q_0)}$$

$$\frac{\Delta Q}{Q} = \varepsilon_0 \frac{\Delta P}{P}$$

$$f(P) = \frac{\partial F}{\partial P} \quad g(Q) = \frac{\partial G}{\partial Q}$$

PDF Function

CDF Function

$$x = F(P) \Updownarrow P = M(x) \qquad x = G(Q) \Updownarrow Q = N(x)$$

Inverse Function

- Time-varying frequency curves:

➢ Covariates carrying information related to temporal variation should be employed in the frequency analyses.

✓ **Dew Point** (*DP*): strongly positively correlated to precipitation extremes and flood peaks as indicated by C-C relationship (Ali et al., 2018; Worawiwat el al., 2021).

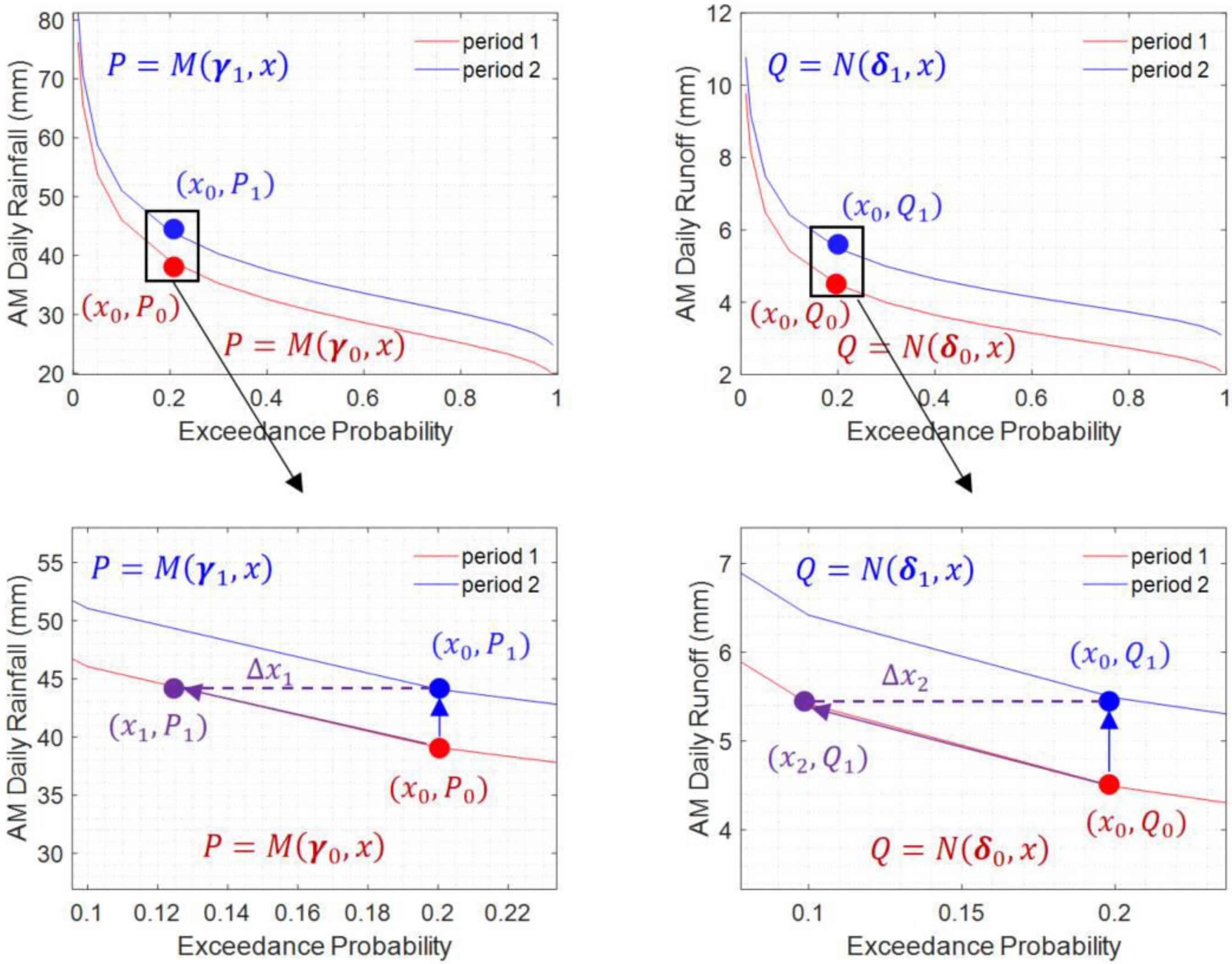
✓ **Forest Cover** (*FC*): strongly negatively correlated to flood peaks due to the hydrological restoration function of forest (Kim et al., 2019).

GAMLSS:

Regard distribution parameters as time-varying, herein the parameters change according to *DP* and *FC*.

$$P \sim GEV(\mu_{Pt}, \sigma_{Pt}, \xi_P) \quad \mu_{Pt} = \alpha_{P0} + \alpha_{P1} DP_t, \quad \sigma_{Pt} = \beta_{P0} + \beta_{P1} DP_t$$

$$Q \sim GEV(\mu_{Qt}, \sigma_{Qt}, \xi_Q) \quad \mu_{Qt} = \alpha_{Q0} + \alpha_{Q1} DP_t + \alpha_{Q2} FC_t, \quad \sigma_{Qt} = \beta_{Q0} + \beta_{Q1} DP_t + \beta_{Q2} FC_t$$



As the parameters changes from $\boldsymbol{\gamma}_0$ to $\boldsymbol{\gamma}_1$ ($\boldsymbol{\delta}_0$ to $\boldsymbol{\delta}_1$), the frequency curves shift from the red one to the blue one.

CDF Function

$$x = F(\boldsymbol{\gamma}, P) \Updownarrow P = M(\boldsymbol{\gamma}, x)$$

$$x = G(\boldsymbol{\delta}, Q) \Updownarrow Q = N(\boldsymbol{\delta}, x)$$

Inverse Function

$$\boldsymbol{\gamma} = (DP) \qquad \boldsymbol{\delta} = (DP, FC)$$

$$\varepsilon_C = \frac{\frac{\partial G}{\partial DP}}{\frac{\partial F}{\partial DP}} \varepsilon_0$$

$$\varepsilon_F = \frac{\frac{\partial G}{\partial DP} FC_0}{\frac{\partial F}{\partial DP} P_0} \frac{\partial M}{\partial DP} \varepsilon_0$$

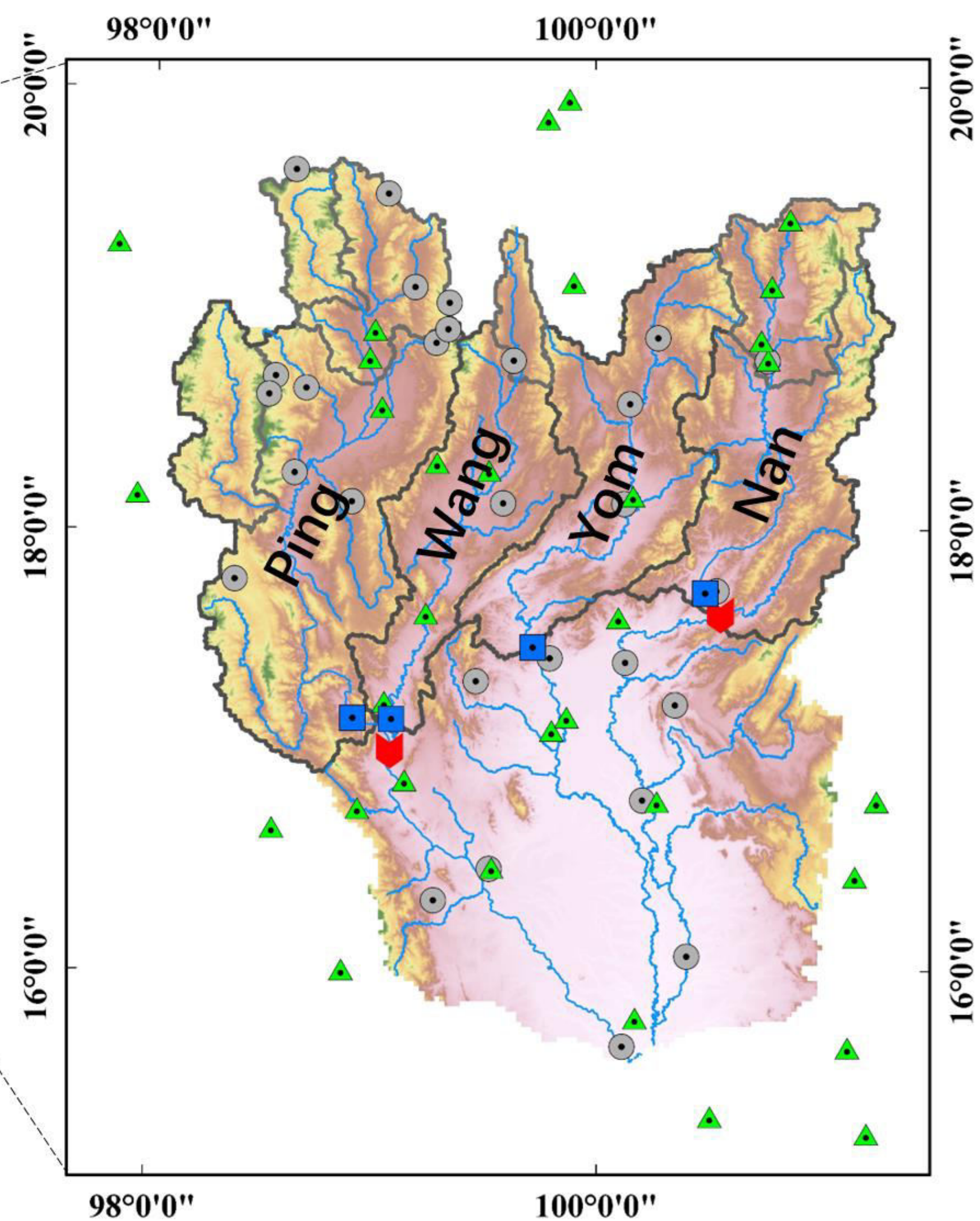
$$\frac{\Delta Q}{Q} = \varepsilon_C \frac{\Delta P}{P} + \varepsilon_F \frac{\Delta FC}{FC}$$

Study Region: UCPRB

The Upper Chao Phraya River Basin (UCPRB)

Area: 110,553 km^2

Annual Pre: 1100 mm



Legend

Elevation/m

Value

High : 2559 Low : 1

Meteorological Stations

Rain Gauges

Hydrological Stations

Reservoirs

River_Network

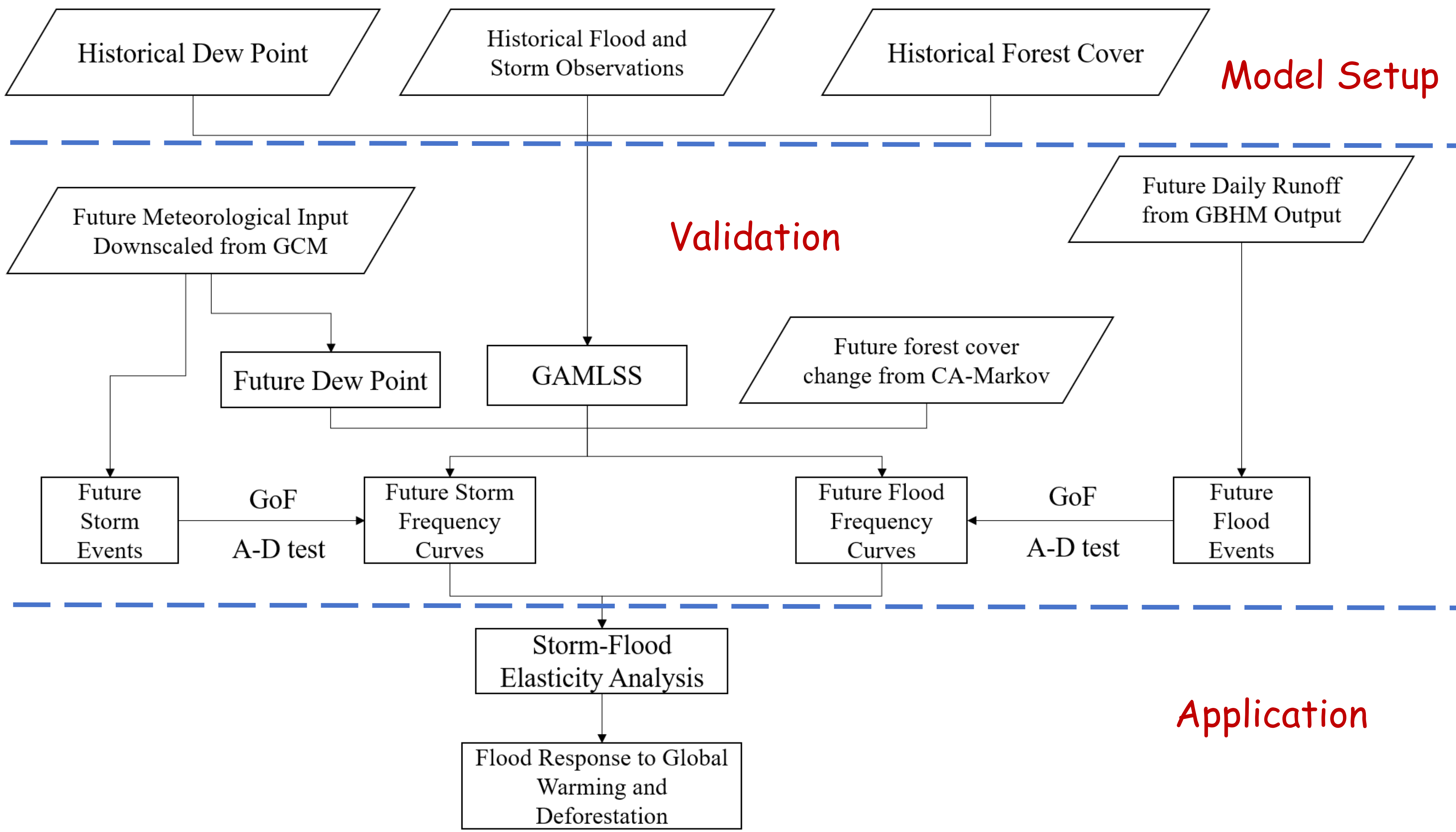
Data and Corresponding Resources

Variable	Temporal resolution	Spatial resolution	Time period available	Source
Runoff	Daily	/	1981-2014	Royal Irrigation Department
		/	2015-2099	Yang et al. (2023)
Precipitation	Daily	/	1981-2014	Thailand Meteorological Department
		2.5 km	2015-2099	Yang et al. (2023)
Relative Humidity	Daily	/	1981-2014	Thailand Meteorological Department
		2.5 km	2015-2099	Yang et al. (2023)
Mean Temperature	Daily	/	1981-2014	Thailand Meteorological Department
		2.5 km	2015-2099	Yang et al. (2023)
DEM	/	90 m	/	HydroSHEDS
Land use	Annual	100 m	1981-2014	Zhao et al. (2022)
			2015-2099	Yang et al. (2023)

historical values: mainly observations used for **model setup**

future values: from CMIP6 and hydrological models (Yang et al. 2023) used for **model validation and prediction**

Study Framework



Result: Time-Varying Frequency Curves

Storm and flood events are captured using the **Annual Maximum** method.

The parameters in the GAMLSS model are then estimated using **MCMC**.

- The GoF is quantified using **Anderson-Darling test**.
- The p-values are all larger than 0.05, so the models are accepted.

$$P \sim GEV(\mu_{Pt}, \sigma_{Pt}, \xi_P) \quad \begin{aligned} \mu_{Pt} &= \alpha_{P0} + \alpha_{P1} DP_t \\ \sigma_{Pt} &= \beta_{P0} + \beta_{P1} DP_t \end{aligned}$$

	α_{P0}	α_{P1}	β_{P0}	β_{P1}	p-value
Ping	28.99	3.24	7.60	2.91	0.967
Wang	27.95	5.50	6.24	1.72	0.686
Yom	28.73	7.98	10.51	2.71	0.738
Nan	26.06	9.49	10.74	3.71	0.742

parameters in storm distribution

$$Q \sim GEV(\mu_{Qt}, \sigma_{Qt}, \xi_Q) \quad \begin{aligned} \mu_{Qt} &= \alpha_{Q0} + \alpha_{Q1} DP_t + \alpha_{Q2} FC_t \\ \sigma_{Qt} &= \beta_{Q0} + \beta_{Q1} DP_t + \beta_{Q2} FC_t \end{aligned}$$

	α_{Q0}	α_{Q1}	α_{Q2}	β_{Q0}	β_{Q1}	β_{Q2}	p-value
Ping	2.99	2.19	-0.48	1.41	0.10	-0.11	0.702
Wang	2.31	2.14	-0.25	1.80	0.05	-0.43	0.996
Yom	3.02	1.99	-0.40	2.38	0.26	-0.58	0.970
Nan	6.97	3.40	-1.00	4.64	0.50	-0.69	0.810

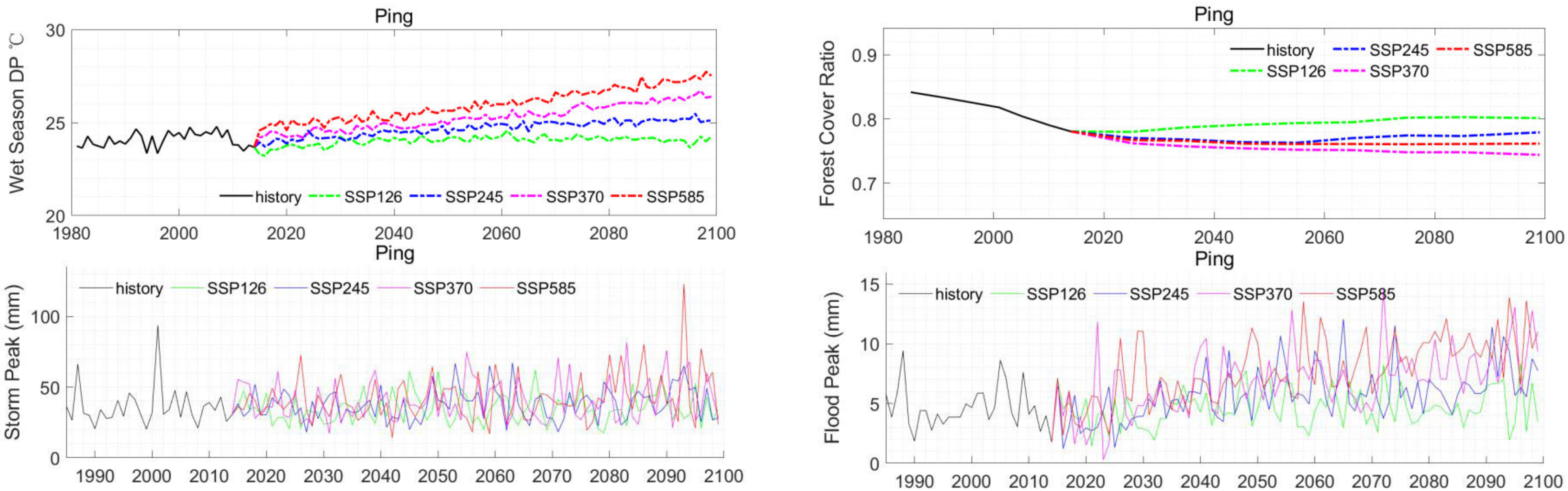
parameters in flood distribution

- Future distributions can then be estimated using the *DP* and *FC* predictions.
- The future is divided into 3 periods accordingly:

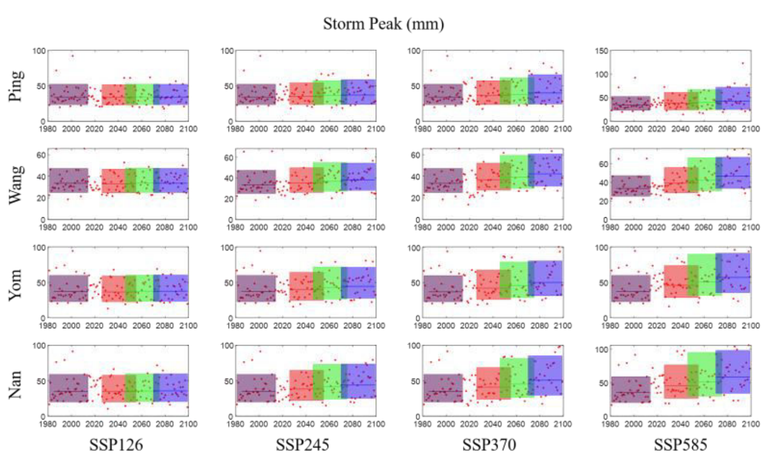
✓ Near-Future (2026-2055) ✓ Mid-Future (2046-2075) ✓ Far-Future (2070-2099)

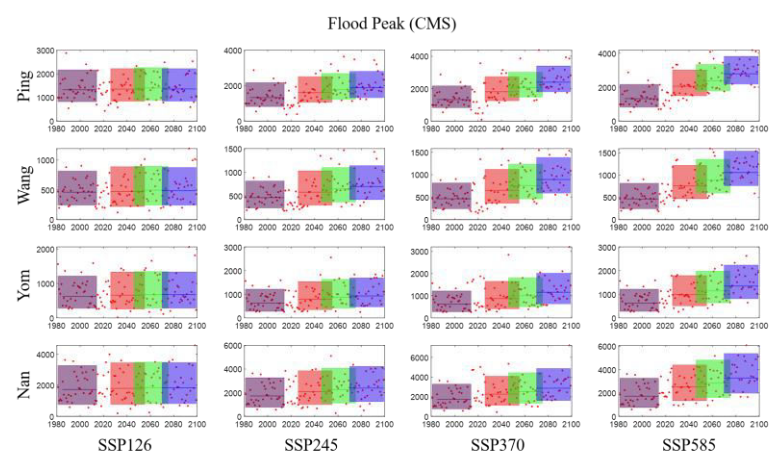
Result: Model Performance

The **covariates** (*DP, FC*) , **storm** and **flood** peaks from **process-based models** (PBMs) in the Ping subbasin.

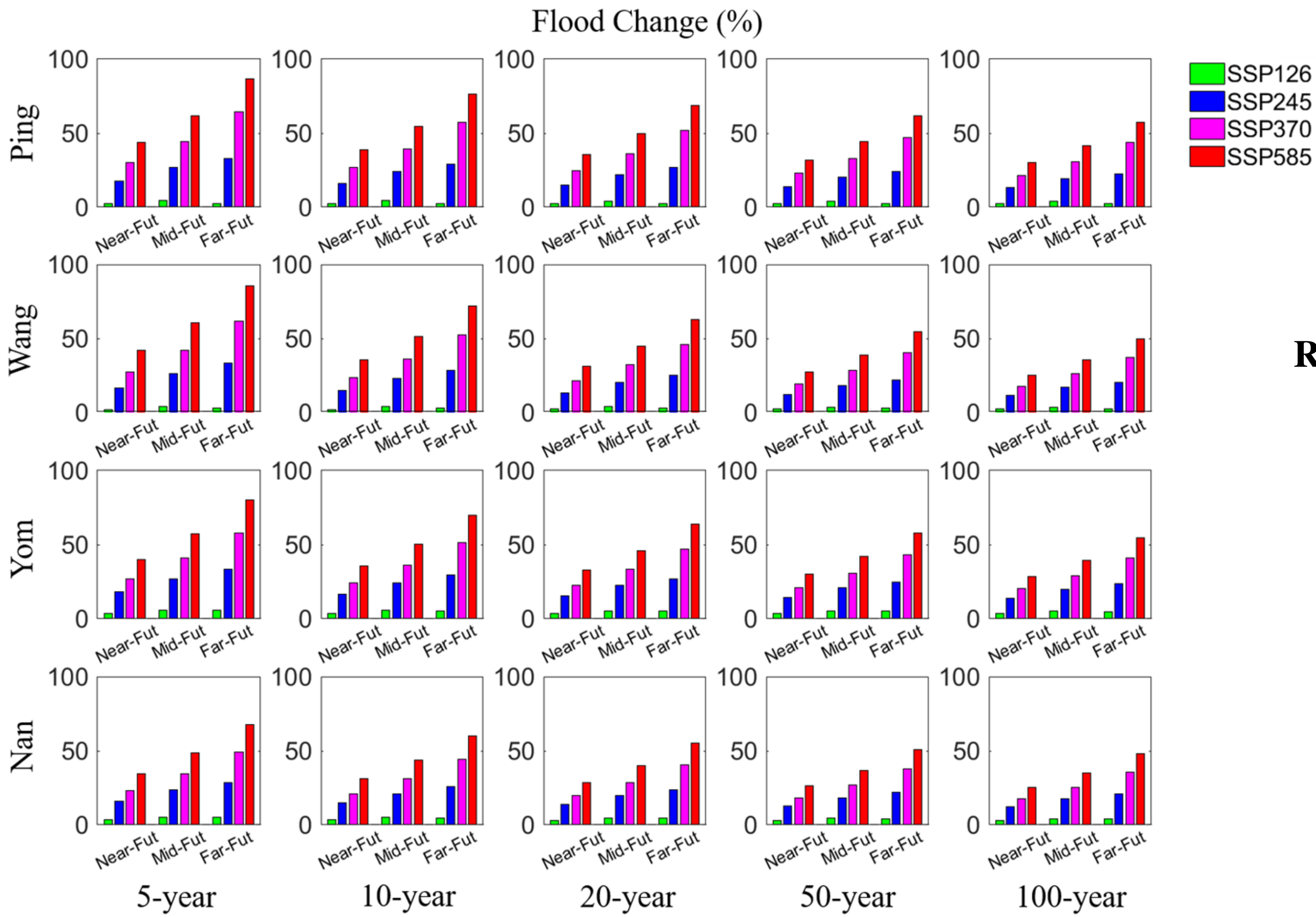


The future storm and flood distributions from PBMs and GAMLSS are compared using **A-D test**, and the result shows that GAMLSS captures the distributions well.





Result: Future Changes in Floods



Flood Response:

SSP585

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SSP370

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SSP245

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SSP126

- The flood peaks keep increasing till the late 21st century.
- Under the SSP585 scenario where the flood increase is the strongest, the flood increase at late 21st century can reach 47%~58%.

Result: Flood Elasticity

Flood Elasticity

- Positive correlation with storm and negative correlation with forest;
- Different storm-flood elasticity under stationary and nonstationary cases;
- Weaker elasticity for larger events.

Contribution Analyses

Climate-change-induced flood change

$$\frac{\Delta Q}{Q} = \varepsilon_C \frac{\Delta P}{P} + \varepsilon_F \frac{\Delta FC}{FC}$$

Deforestation-induced flood change

$$\varepsilon_0 = \frac{P_0 \frac{\partial F}{\partial P}}{Q_0 \frac{\partial G}{\partial Q}}$$

$$\varepsilon_C = \frac{\frac{\partial G}{\partial DP}}{\frac{\partial F}{\partial DP}} \varepsilon_0$$

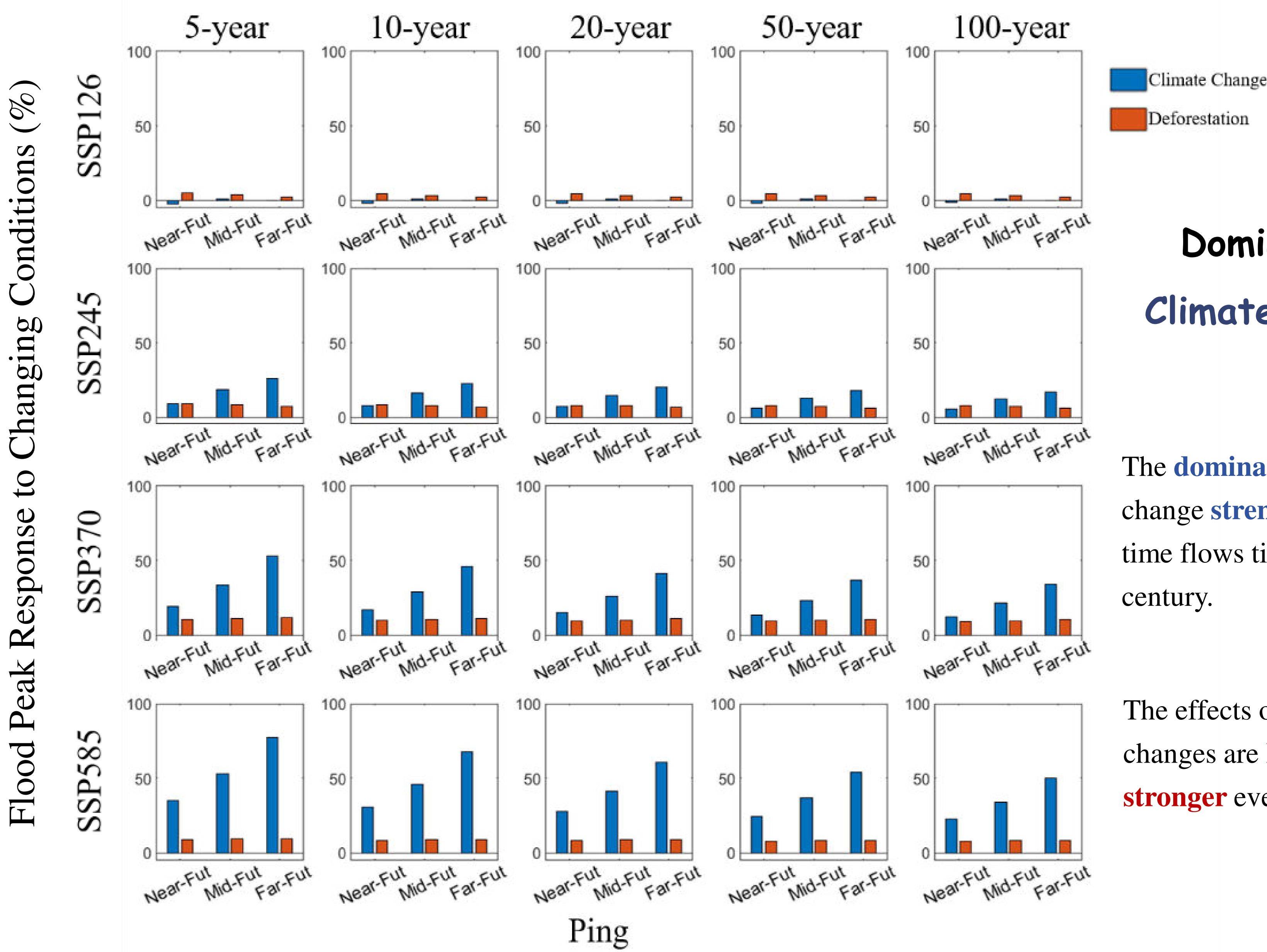
$$\varepsilon_F = \frac{\frac{\partial G}{\partial DP} FC_0}{\frac{\partial F}{\partial DP} P_0} \frac{\partial M}{\partial DP} \varepsilon_0$$

ε_0	return period				
	5	10	20	50	100
Ping	1.11	1.08	1.05	1.03	1.01
Wang	1.67	1.53	1.43	1.33	1.28
Yom	1.35	1.26	1.20	1.15	1.11
Nan	1.20	1.14	1.11	1.07	1.05

ε_C	return period				
	5	10	20	50	100
Ping	2.27	1.78	1.48	1.23	1.09
Wang	1.93	1.56	1.32	1.10	0.98
Yom	1.36	1.19	1.08	0.98	0.92
Nan	0.90	0.80	0.73	0.67	0.63

ε_F	return period				
	5	10	20	50	100
Ping	-1.43	-1.37	-1.32	-1.27	-1.25
Wang	-0.62	-0.61	-0.60	-0.59	-0.58
Yom	-0.71	-0.69	-0.68	-0.67	-0.66
Nan	-0.63	-0.60	-0.57	-0.55	-0.54

Result: Contribution Analyses



Dominance:

Climate Change

The **dominance** of climate change **strengthens** as time flows till late 21st century.

The effects of **land use** changes are **larger** for **stronger** events.

Summary

- Flood elasticity analyses under changing conditions:
  - ✓ **Employment of covariates**: Enabling the predictions of future floods;
  - ✓ **Statistical model** (GAMLSS): Validated by process-based models;
  - ✓ **Flood elasticity**: Weaker for stronger events;
  - ✓ **Storm-flood elasticity**: Different values under the nonstationary case.

- Future flood peak changes in the UCPRB:
  - ✓ **Future flood:** Increasing till late 21st century;
  - ✓ **Scenario**: SSP585>SSP370>SSP245>SSP126;
  - ✓ **Climate change:** Increasing dominance as time flows;
  - ✓ **Deforestation**: Larger effects for stronger events.

Zhao.B, T. Wang, D. Yang, S. Yang, W. Lu and J. Santisirisomboon (2023), The impacts of climatic and land surface characteristics on the storm-flood relationship in a tropical monsoon basin of Thailand, *Journal of Hydrology*, 616, doi.org/10.1016/j.jhydrol.2022.128809

Zhao.B, T. Wang, D. Yang, S. Yang and J. Santisirisomboon, The flood elasticity under changing conditions: an application in a tropical monsoon basin of Thailand, *Weather and Climate Extremes* (Under Review)

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Thanks for Your Attention!

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