ASSESSING THE IMPACT OF CLIMATE CHANGE ON HYDROLOGICAL RISK

Presented by Ke-Sheng Cheng

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Introduction

- Aiming to assess the impact of climate change on water resources and to formulate adaptation strategies, the Water Resources Agency (WRA) initiated a four-year (2010 – 2013) ***Climate Change Impact Assessment and Adaptation program* (CCIAP)**.
- Due to the nature of water resources planning and design for which WRA bears the administrative responsibility, it is imperative for CCIAP to consider the impact of climate change at local and event scales.
- Thus, among a group of CCIAP projects, this project aims to assess the impact of climate change on event rainfall and streamflow properties in Taiwan.

Importance of climate change impacts on stormwater hydrology

- Key factors in water resources management and engineering design
  - Design rainfall depth
  - Flood of 100-year return period
  - Drought of specific return periods

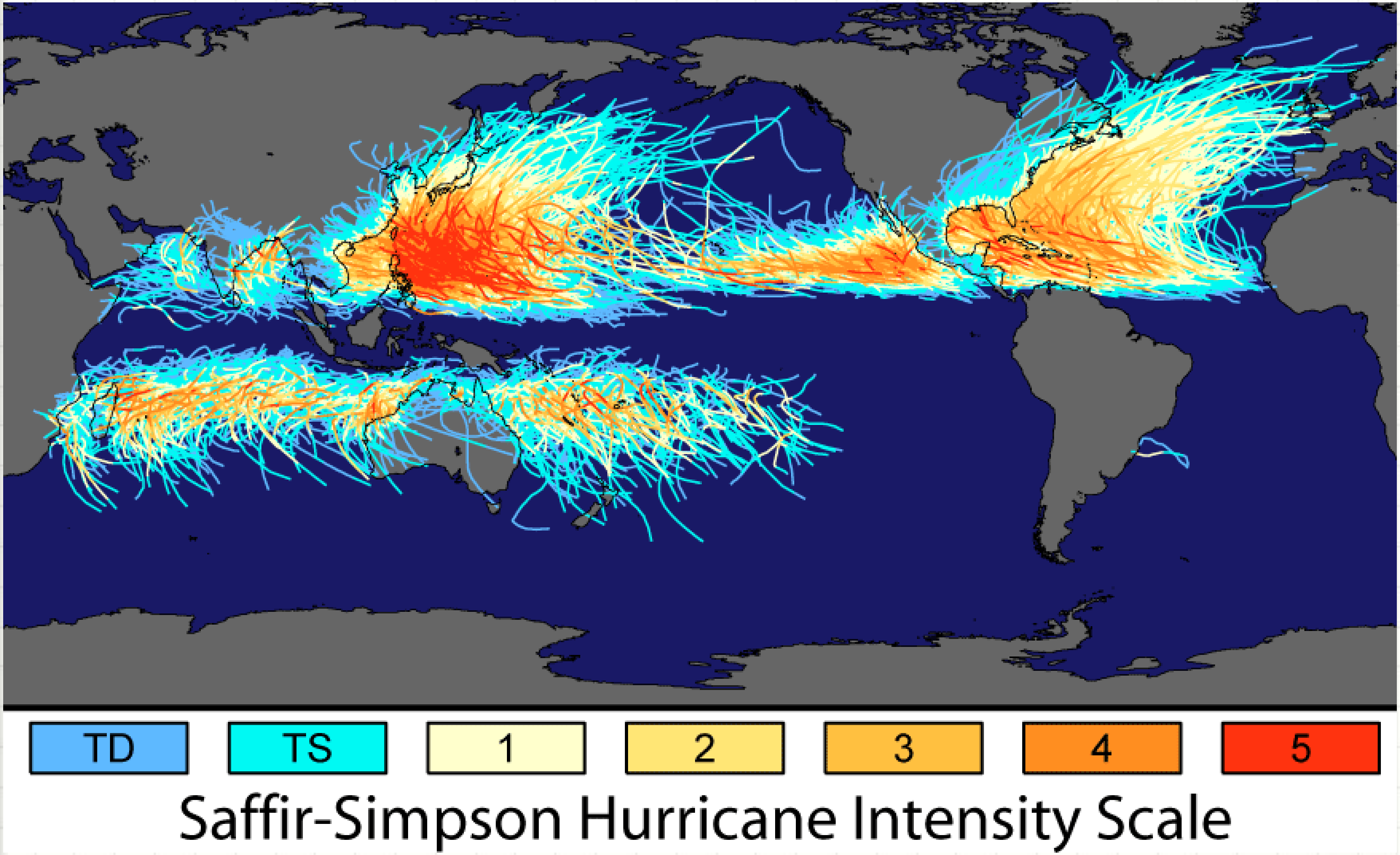
Hydrological extremes at site- or regional scale in space and event scale in time

GCMs are more skillful at predicting means (averages) of precipitation or temperature than any higher order statistics.

- Climate models generally do not yield reliable projections for ***extreme*** parameters.

- Other consequences of storm events
  - Storm-induced landslides
  - Soil erosion and reservoir sediment yield by extraordinary storm events
  - etc.

Historic tropical cyclone tracks



The tracks of nearly 150 years of tropical cyclones. The map is based on all storm tracks available from the National Hurricane Center and the Joint Typhoon Warning Center through September 2006.

Impact assessment by statistical downscaling

- Statistical downscaling utilizes relationships between GCM outputs and historical data to yield finer spatial and temporal resolution climate data at regional- or site-level.
  - GCM outputs
  - Local observations
- Temporal downscaling is conducted mostly from monthly to daily scale.

Outputs from GCMs/RCMs
(Monthly scale)

Weather generator, ANN

Storm parameters
(Event occurrences, duration, total rainfall depth, time variation of rain rates)

Strom-type specific
- Monsoon rainfall
- Convective storms
- Typhoons

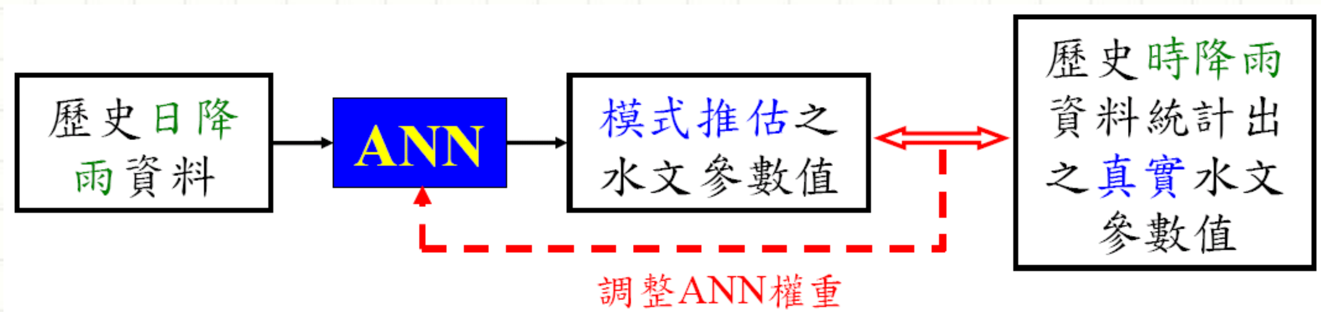
Stochastic Storm Rainfall Simulation Model
(A large set of sample annual rainfall series.)

Inputs for Hydrological Models
(Hourly scale)

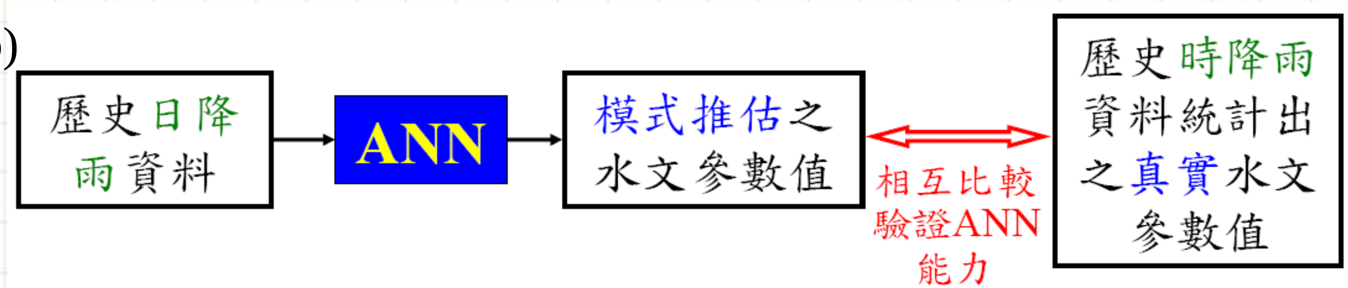
Storm Parameters Estimation Using ANN (Support Vector Machine)

- 類神經網路日資料判讀模式簡介：
  - 模式輸入項為日降雨資料序列，輸出項則為水文情境參數。
  - 類神經網路建立日資料判讀模式之示意圖：

訓練階段 (a)



驗證階段 (b)



輸入項	$R(t\text{-}1)$, $R(t)$, $R(t+1)$
輸出項	1. 發生次數 2. 事件總降雨量 3. 事件降雨延時 4. 各事件降雨間距

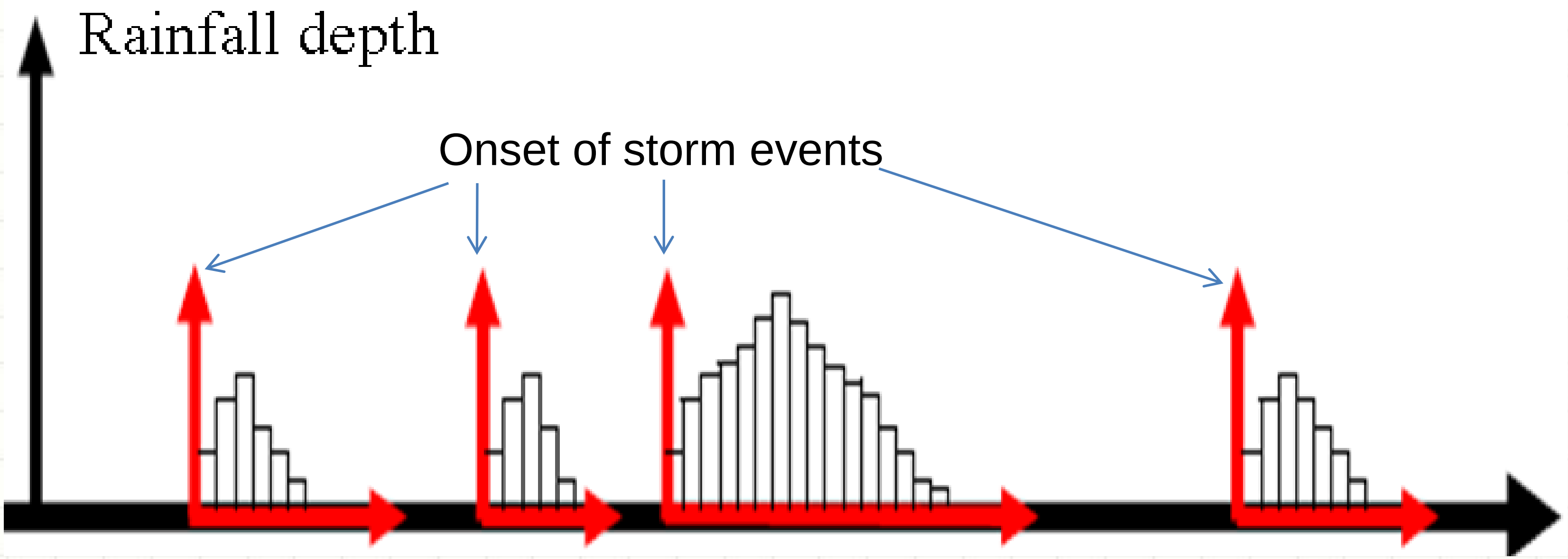
Stochastic storm-rainfall simulation approach

- Simulation of occurrences and rain rates of individual storm events.
- Stochastic storm rainfall simulation model (SSRSM)
  - Parametric
  - Multivariate
  - Storm-type-specific

Mei-Yu (synoptic-scale cloud band with embedded mesoscale convective systems, May, June)
Convective storm (July – October)
Typhoon (July – October)
Frontal rainfall (Nov. – April)

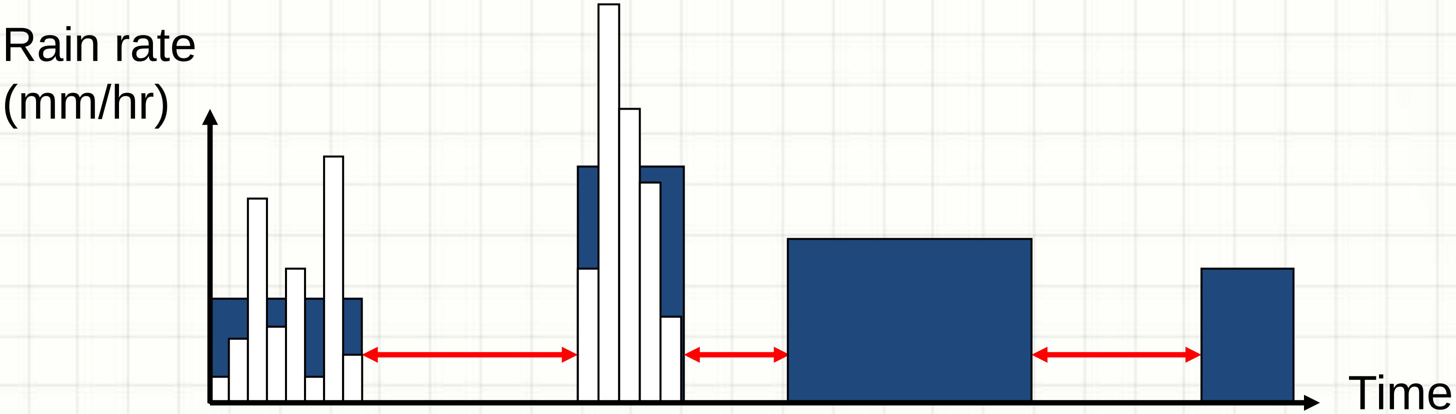
A Random Sample of the Storm Rainfall Process

- **Occurrences of storm events – a Poisson process for typhoon occurrences.**
- **Temporal variation of storm rainfalls can also be modeled as a random process.**



Characterizing storm rainfall processes

- Inter-arrival time or inter-event time
- Storm duration
- Total rainfall depths of storm events
- Time variation of the total depth



Simulation of discrete storm events

- Modeling of the inter-arrival time or the inter-event time.
  - Inter-event times of rare events (typhoons) can be modeled by exponential distribution.
  - Inter-event times for events of other storm types are better characterized by the log-normal distribution.
- Joint distribution of the total depth and storm duration.

Stochastic simulation of the joint distribution of total depth and storm duration

- In general, storm events with longer duration yield larger amount of total rainfall depths.
- Duration and total depth are correlated and form a bivariate distribution.
  - e.g. bivariate gamma, gamma - log normal, etc.
- A frequency-factor based approach for stochastic simulation of bivariate distributions has been developed (Cheng et al., 2010).

Bivariate distributions of duration and total depth for various types of storms

Type of storm	Duration	Total depth
Typhoon	Gamma	Gamma
Convective storm	Gamma	Log-normal
梅雨	Log-normal	Log-normal
鋒面雨	Log-normal	Gamma

- A ***bivariate gamma distribution*** was adopted in this study to simulate (total rainfall, duration) data pairs of typhoon events.
- Frequency factor of the gamma distribution involves a standard normal distribution.

$$X_T = \mu_X + K_T \sigma_X$$

$$K_T \approx z + \left(z^2 - 1\right)\frac{\gamma_X}{6} + \frac{1}{3}\left(z^3 - 6z\right)\left(\frac{\gamma_X}{6}\right)^2 - \left(z^2 - 1\right)\left(\frac{\gamma_X}{6}\right)^3 + z\left(\frac{\gamma_X}{6}\right)^4 - \frac{1}{3}\left(\frac{\gamma_X}{6}\right)^5$$

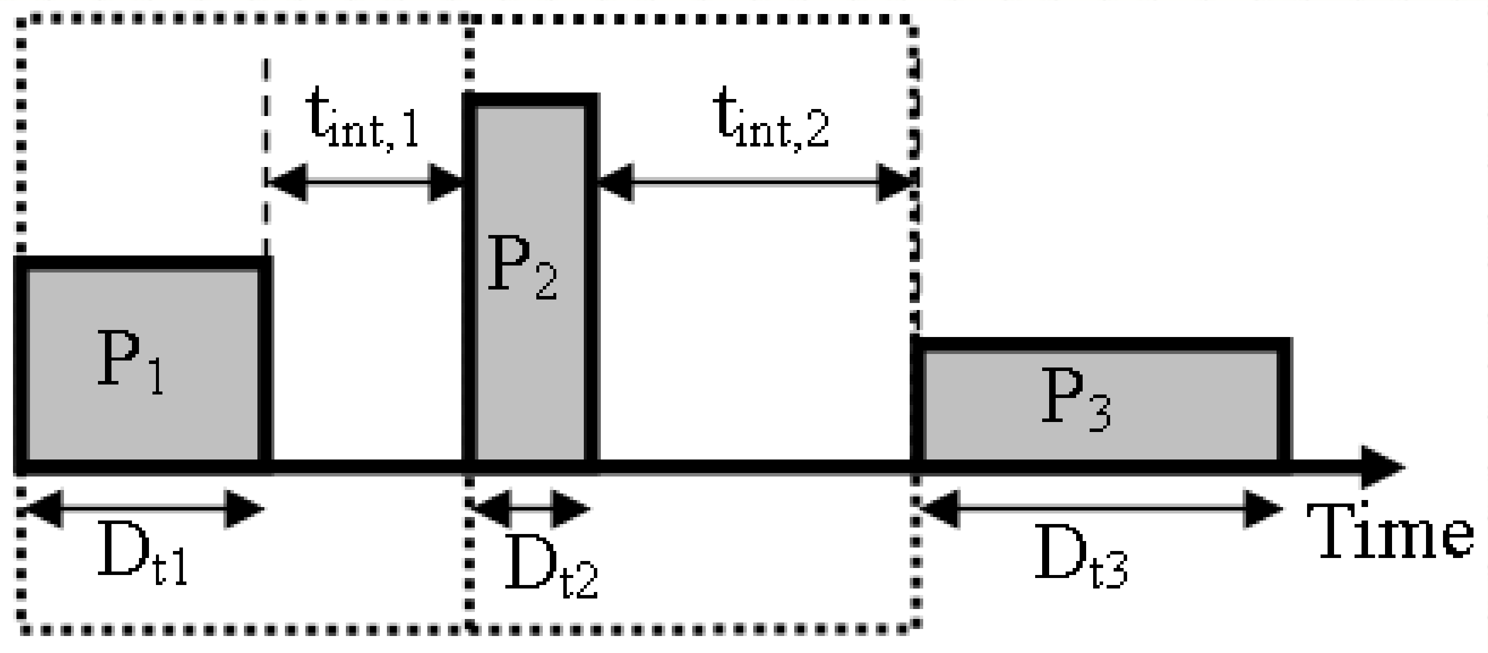
Bivariate gamma simulation

- Conversion between BVG and BVN
- Conversion of the correlation coefficients

$$\rho_{XY} \approx \left(A_X A_Y - 3A_X C_Y - 3C_X A_Y + 9C_X C_Y\right)\rho_{UV}$$
$$+ 2B_X B_Y \rho_{UV}^2 + 6C_X C_Y \rho_{UV}^3$$

$$A_X = 1 + \left(\frac{\gamma_X}{6}\right)^4 \quad B_X = \frac{\gamma_X}{6} - \left(\frac{\gamma_X}{6}\right)^3 \quad C_X = \frac{1}{3}\left(\frac{\gamma_X}{6}\right)^2$$

$$A_Y = 1 + \left(\frac{\gamma_Y}{6}\right)^4 \quad B_Y = \frac{\gamma_Y}{6} - \left(\frac{\gamma_Y}{6}\right)^3 \quad C_Y = \frac{1}{3}\left(\frac{\gamma_Y}{6}\right)^2$$


$t_{int,1}$
$t_{int,2}$
P_1
P_2
P_3
D_{t1}
D_{t2}
D_{t3}
Time

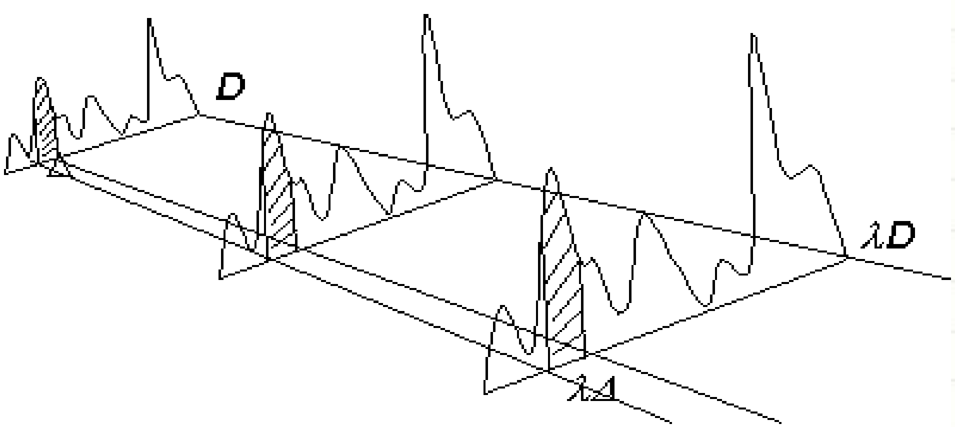
Time distribution of event total rainfall

- The temporal variation of event-total rainfall is considered as a random process.
- A previous study (Cheng et al., 2001) has shown that, under simple scaling assumption, a scale-invariant Gauss-Markov process can be used for time distribution of total rainfalls of annual maximum events.
- A scale-invariant gamma-Markov process was used in this study for disaggregation of event-total rainfalls.

Theoretical Basis for Using Dimensionless Hyetographs

- In view of the simple scaling characteristics, the normalized rainfall rates of storms of different event durations are identically distributed.

$$\left\{\frac{X_{\Delta}(i,D)}{h(D,D)}\right\} \overset{d}{=} \left\{\frac{X_{\lambda\Delta}(i,\lambda D)}{h(\lambda D,\lambda D)}\right\}$$



$$Y_{\Delta}(i,D)=\frac{X_{\Delta}(i,D)}{h(D,D)}$$, then

$$\{Y_{\Delta}(i,D)\}\overset{d}{=}\{Y_{\lambda\Delta}(i,\lambda D)\}$$

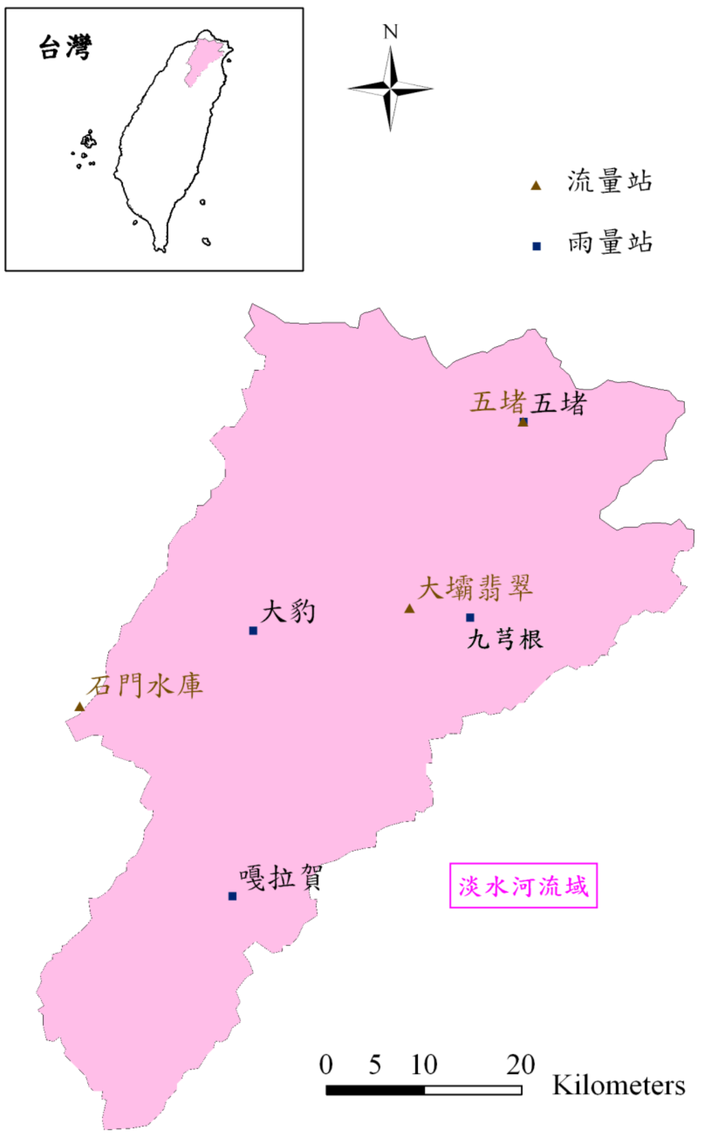
The *i*-th incremental rainfall percentages of storms of durations D and λD are ***identically distributed*** if the time intervals are Δ and $\lambda\Delta$, respectively.

The annual maximum events are ***mutually independent***.

The ***IID*** property allows us to combine the *i*-th incremental rainfall percentages of any storm durations to form a ***random sample***.

研究區域與測站 (淡水河流域)

1. 本計畫最終所選用之雨量及流量測站：



(a) 雨量測站

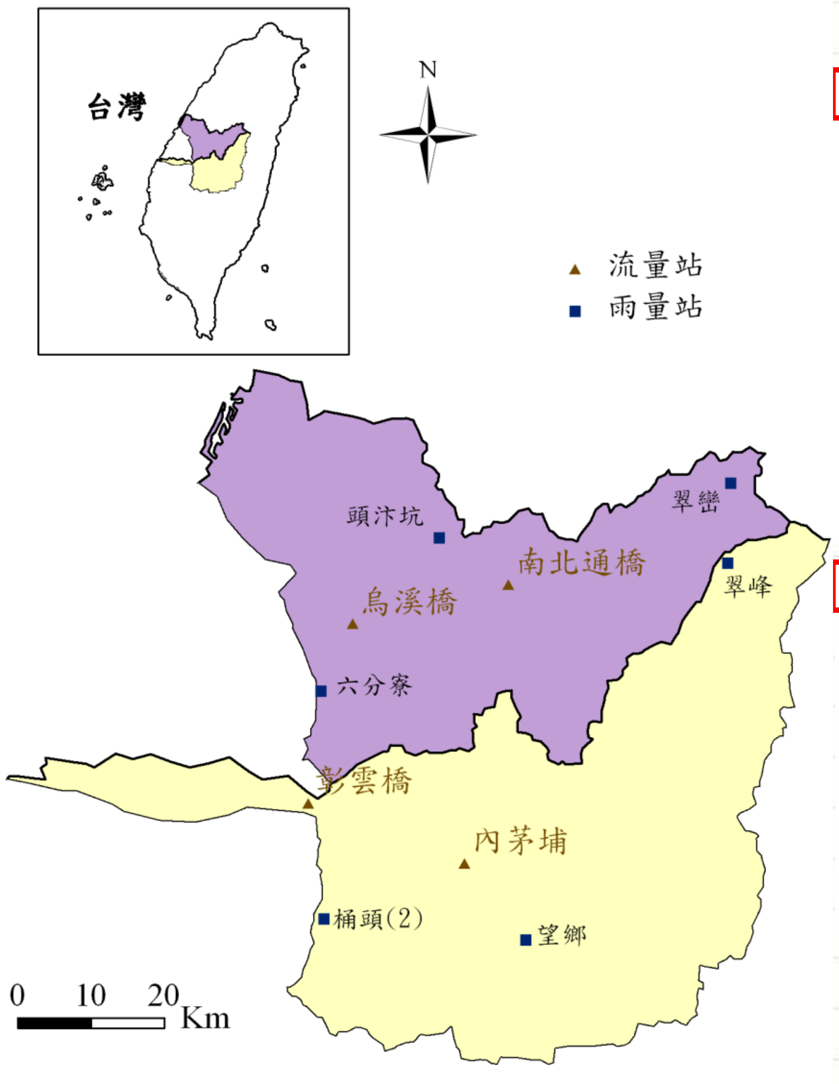
站名	站號	所屬單位	流域	UTM X 座標(m)	UTM Y 座標(m)
大豹	01A210	水利署	淡水河	291744.10	2753559.70
五堵	01B030	水利署	淡水河	319447.50	2774911.40
嘎拉賀	21C090	水利署	淡水河	289655.70	2726339.50
九芎根	1140P156	水利署	淡水河	313981.39	2754859.91

(b) 流量測站

站名	站號	流域	UTM X 座標(m)	UTM Y 座標(m)
五堵	1140H058	淡水河	319419.40	2774923.70
石門水庫	21C050	淡水河	273987.00	2745789.00
大壩翡翠	1140P154	淡水河	307775.40	2755817.00

研究區域與測站(烏溪、濁水溪流域)

1. 本計畫最終所選用之雨量及流量測站：



(a) 雨量測站

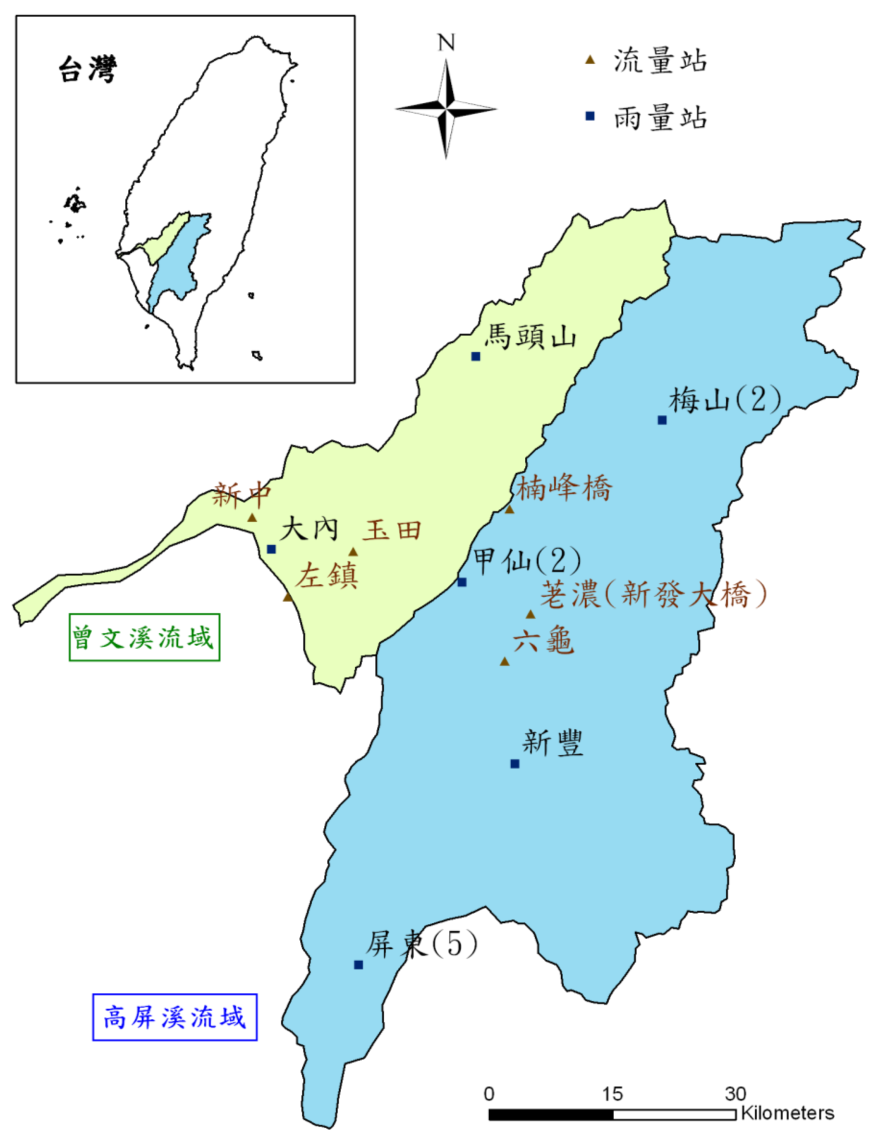
站名	站號	所屬單位	流域	UTM X座標(m)	UTM Y座標(m)
翠巒	01H210	水利署	烏溪	269847.40	2675462.70
頭汴坑	01F680	水利署	烏溪	229970.60	2667989.50
六分寮	01H590	水利署	烏溪	212320.60	2647102.30
桶頭(2)	01H110	水利署	濁水溪	214240.50	2615918.50
翠峰	01H310	水利署	濁水溪	269429.60	2667093.20
望鄉	01H390	水利署	濁水溪	241806.10	2613068.00

(b) 流量測站

站名	站號	流域	UTM X座標(m)	UTM Y座標(m)
烏溪橋	1430H030	烏溪	218205.00	2656247.00
南北通橋	1430H032	烏溪	239454.00	2661580.00
內茅埔	1510H049	濁水溪	233493.20	2623505.00
彰雲橋	1510H057	濁水溪	212103.20	2631755.00

研究區域與測站(曾文、高屏溪流域)

1. 本計畫最終所選用之雨量及流量測站：



經分析後，發現玉山站因地勢過高，較不能代表整個高屏溪上游雨量情況，故改用梅山(2)站代表之。

(a) 雨量測站

站名	站號	所屬單位	流域	UTM X座標(m)	UTM Y座標(m)
馬頭山	H1M250	水利署	曾文溪	208615.00	2581785.00
大內	C1O860	氣象局	曾文溪	183767.00	2557942.00
屏東(5)	00Q070	水利署	高屏溪	194329.90	2506375.20
甲仙(2)	01P660	水利署	高屏溪	206926.70	2553841.20
新豐	01Q160	水利署	高屏溪	213346.00	2531343.00
梅山(2)	01V060	水利署	高屏溪	231253.40	2573907.10

(b) 流量測站

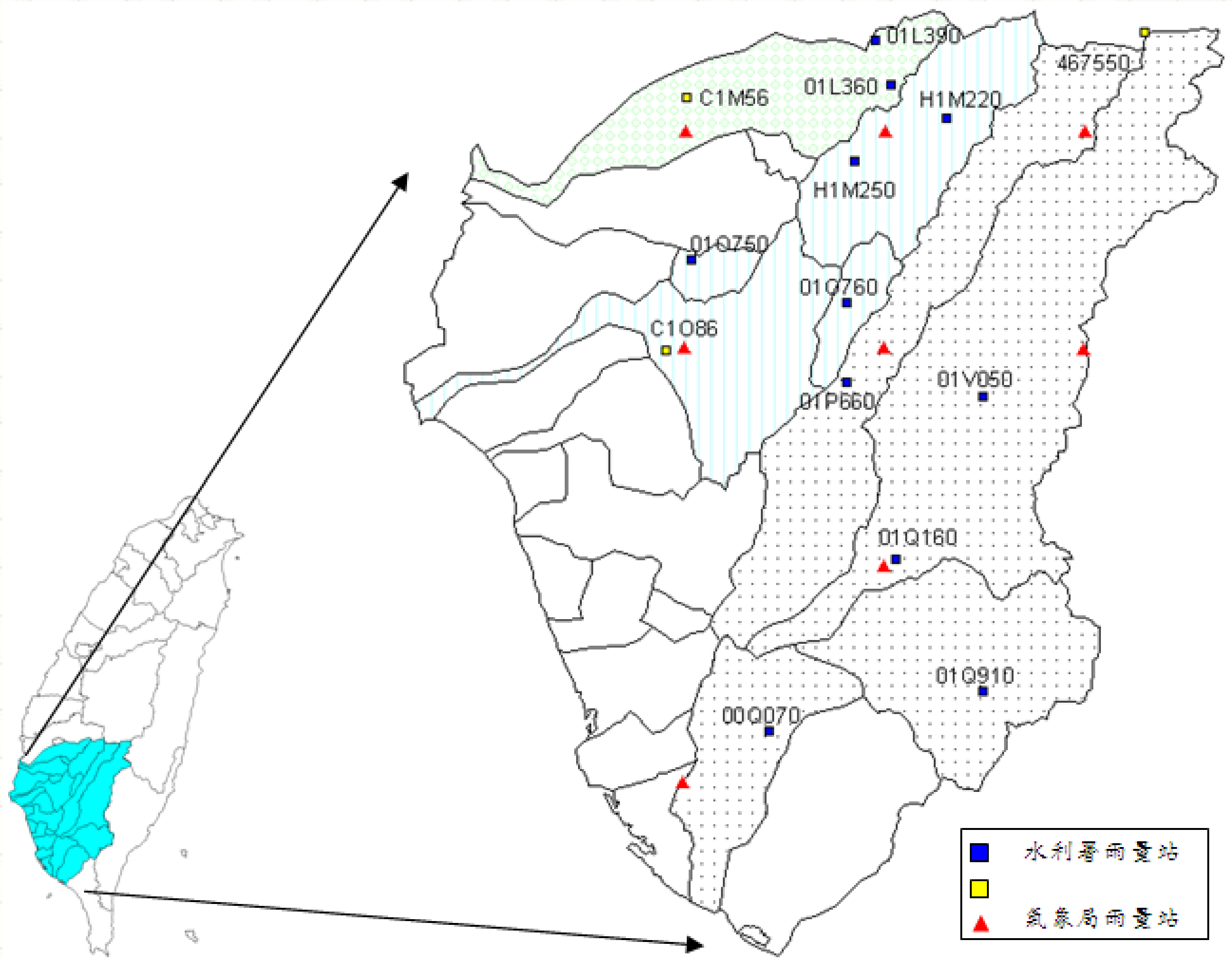
站名	站號	流域	UTM X座標(m)	UTM Y座標(m)
玉田	1630H005	曾文溪	193691.40	2557641.00
左鎮	1630H013	曾文溪	185724.90	2552024.00
新中	1630H019	曾文溪	181375.00	2561875.00
荖濃(新發大橋)	1730H031	高屏溪	215269.80	2549904.00
六龜	1730H039	高屏溪	212084.40	2544033.00
楠峰橋	1730H046	高屏溪	212678.60	2562916.00

Setting climate change scenarios

- **GCM Scenarios**
- Parameter scenarios of SSRSM
  - inter-event time
  - Total depth
  - Duration
  - Time variation

Downscaled from GCM outputs using an ANN approach (SVM)

GCM grids (25km) and rainfall stations



GCM scenarios and outputs

- 24 GCMs
- A1B (2010), A1B, A2, B1 (2011) scenarios
- Statistical downscaling by NCDR (25 km x 25 km)
- Monthly rainfalls of the projection period (2020 – 2039)
- Ensemble average of 24 GCMs (single run, multi-model ensemble)

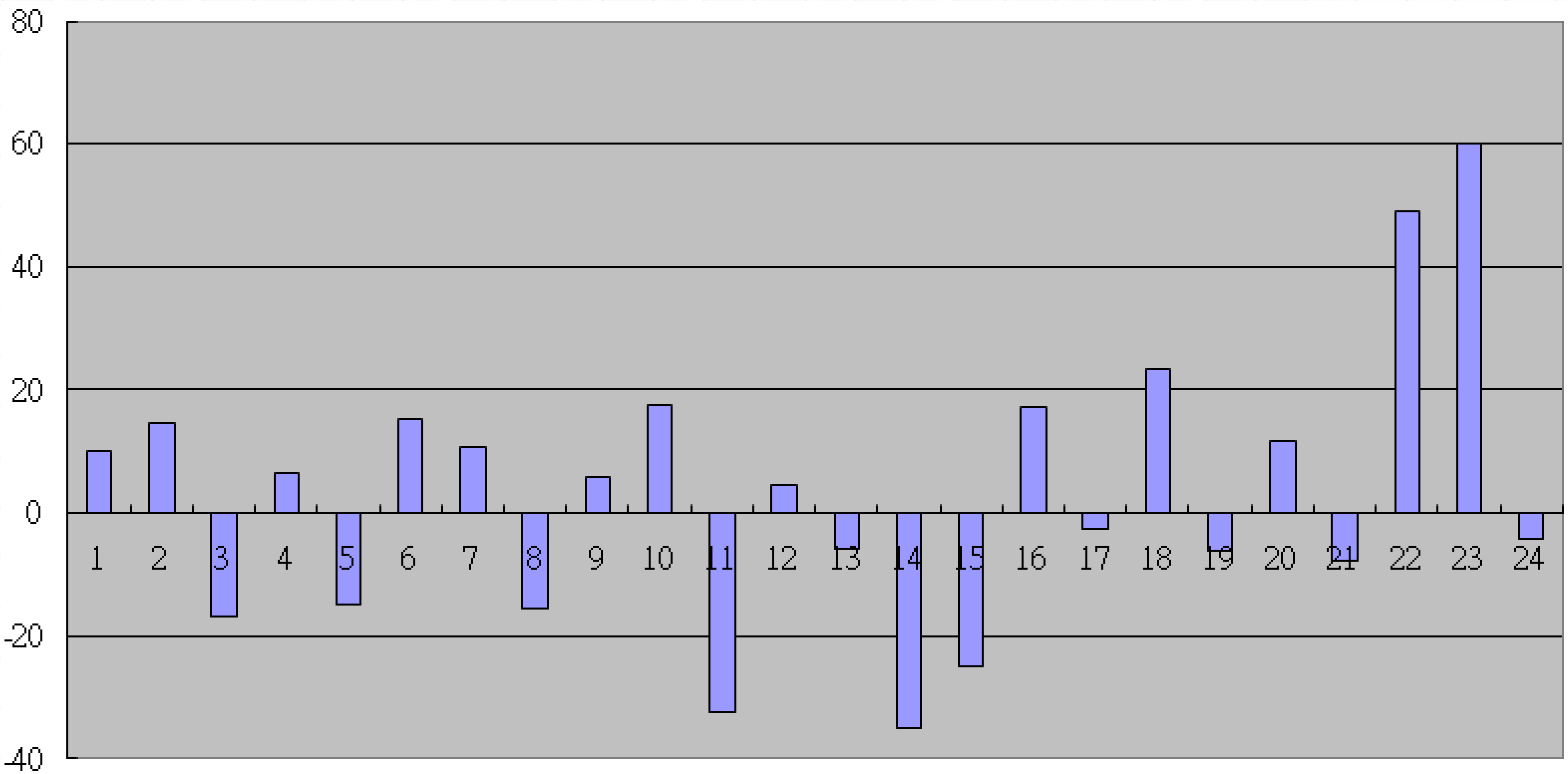
GCMs used by NCDR

Model	Center	Center Acronym
BCM2	Bjerknes Centre for Climate Research, Norway	BCCR
CGCM3 1-T47	Canadian Center for Climate Modelling and Analysis, Canada	CCCMA
CGCM3 1-T63		
CM3	Centre National de Recherches Meteorologiques, France	CNRM
ECHO-G	Meteorological Institute, Univ. of Bonn, Germany Meteorological Research Institute of KMA, Korea	CONS
MK3	Australia's Commonwealth Scientific and Industrial. Research Organization, Australia	CSIRO
MK3 5		
CM2	Geophysical Fluid Dynamics Laboratory, USA	GFDL
CM2 1		
CM3	Institute of Numerical Mathematics, Russia	INM
CM4	Institut Pierre Simon Laplace, France	IPSL
FGOALS-G1 0	Institute of Atmospheric Physics, China	LASG
ECHAM5	Max Planck Institute for Meteorology, Germany	MPIM
ECHAM4		
CGCM2 3 2	Meteorological Research Institute, Japan	MRI
GISS-AOM	Goddard Institute for Space Studies (GISS), NASA, USA	NASA
GISS-EH		
GISS-ER		
CCSM3	National Center for Atmospheric Research, USA	NCAR
PCM		
MIROC3 2-HI	National Institute for Environmental Studies, Japan	NIES
MIROC3 2-MED		
HADCM3	Hadley Centre for Climate Prediction and Research, Met Office, UK	UKMO
HADGEM1		

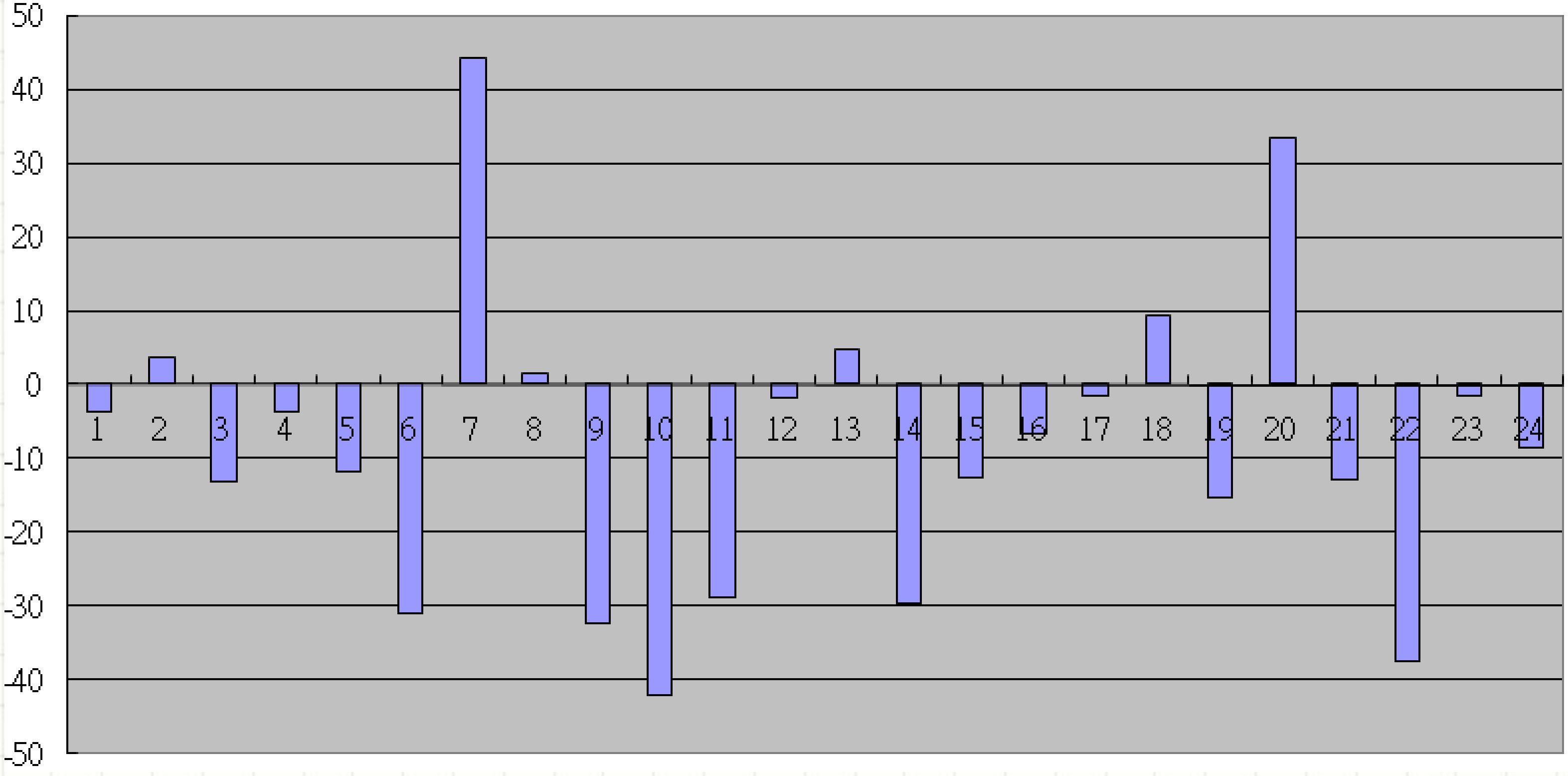
Outputs of different GCMs (projection period)

Single initial condition, single-run outputs (no parameter perturbation)

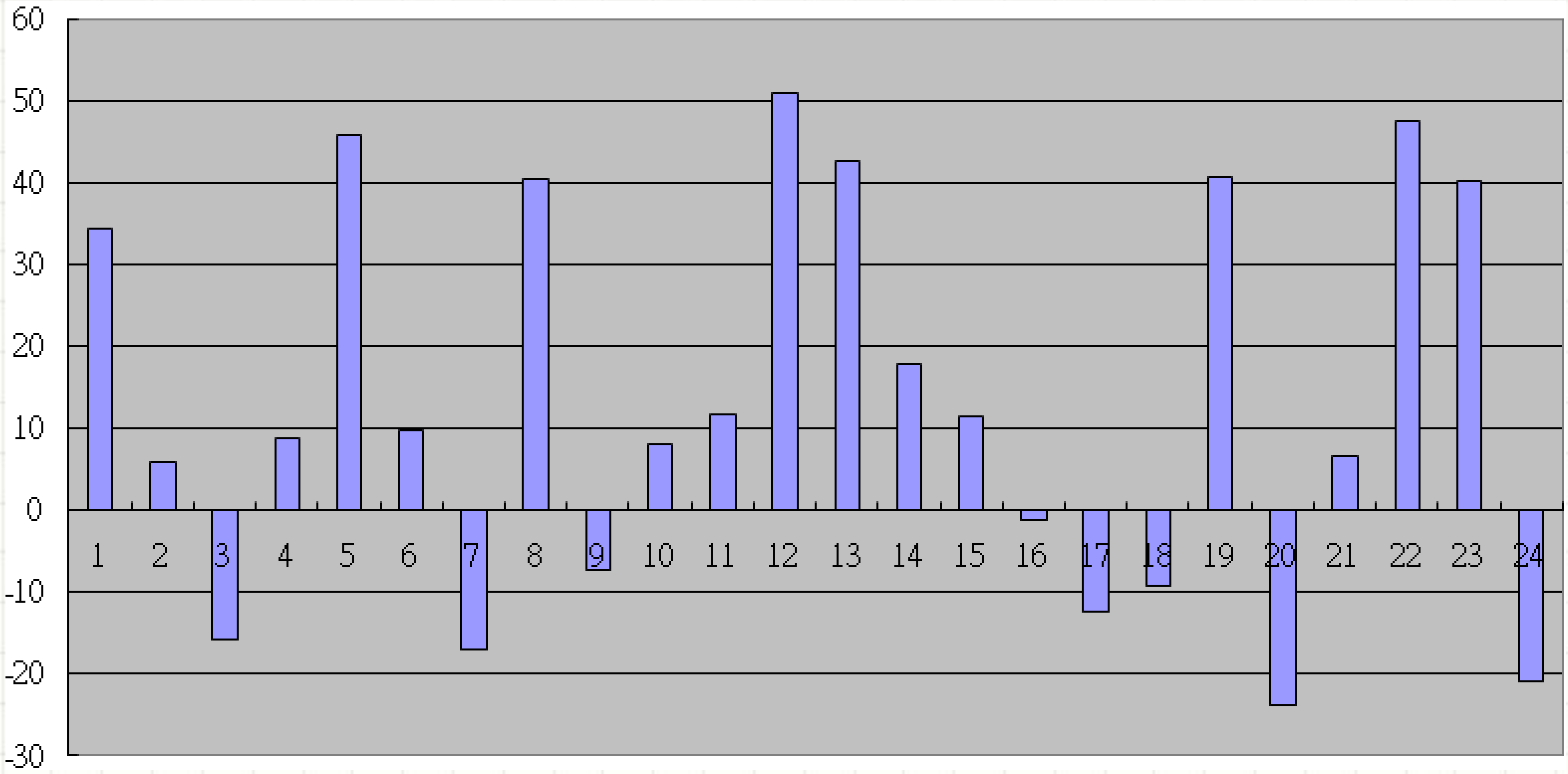
- Grid_70, January Monthly Rainfall



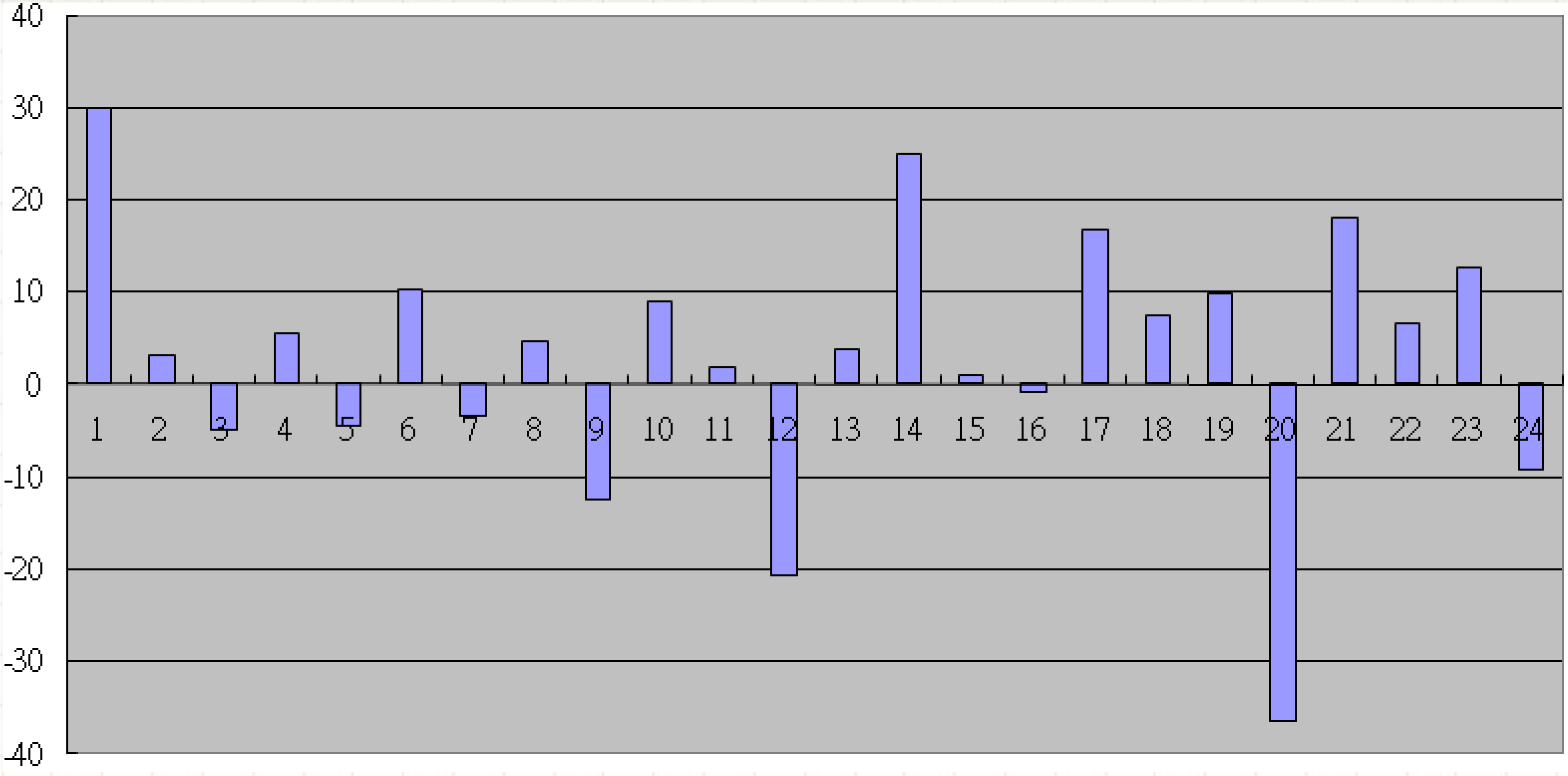
- Grid_70, April Monthly Rainfall



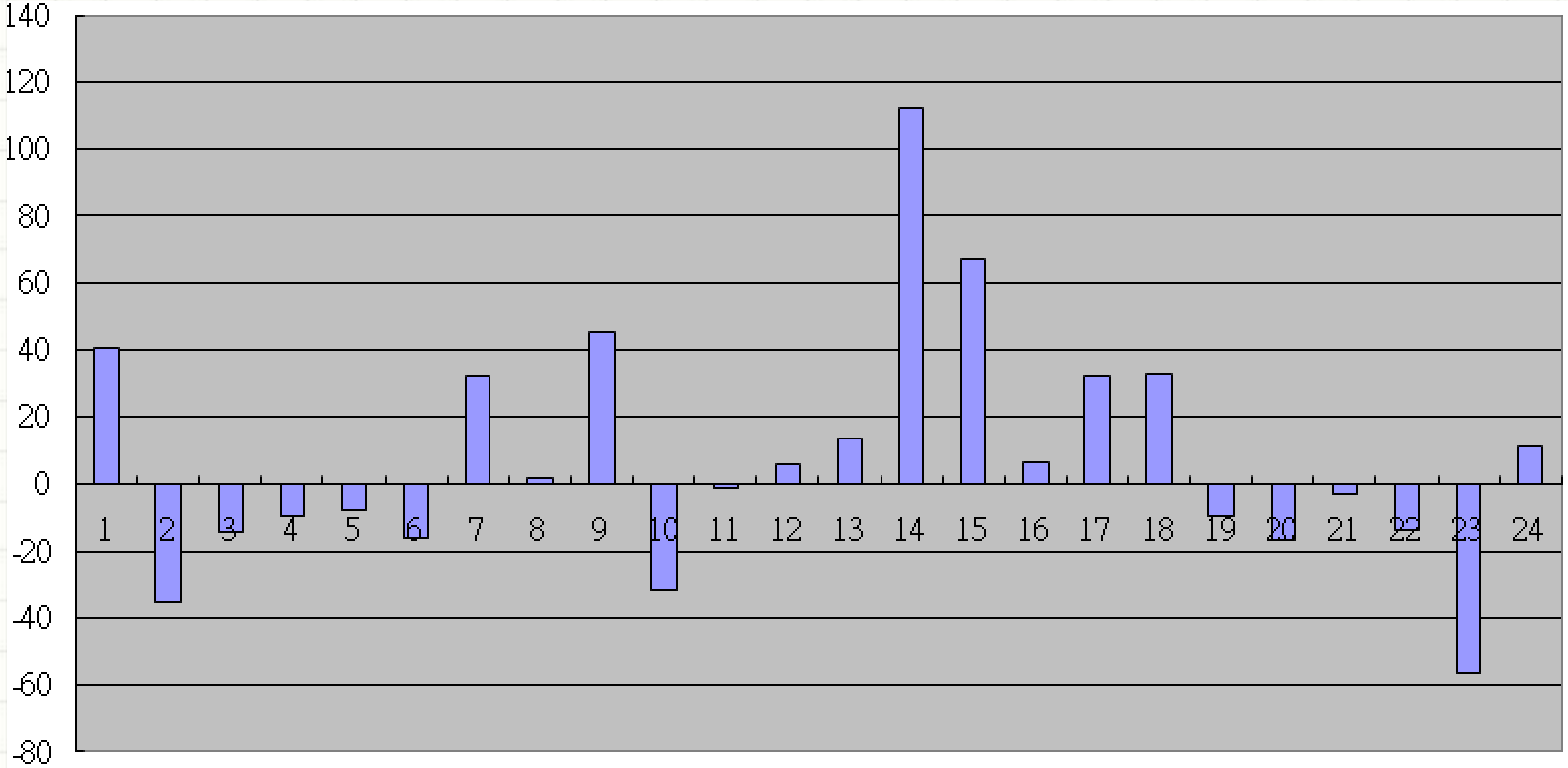
- Grid_70, July Monthly Rainfall



• Grid_70, August Monthly Rainfall

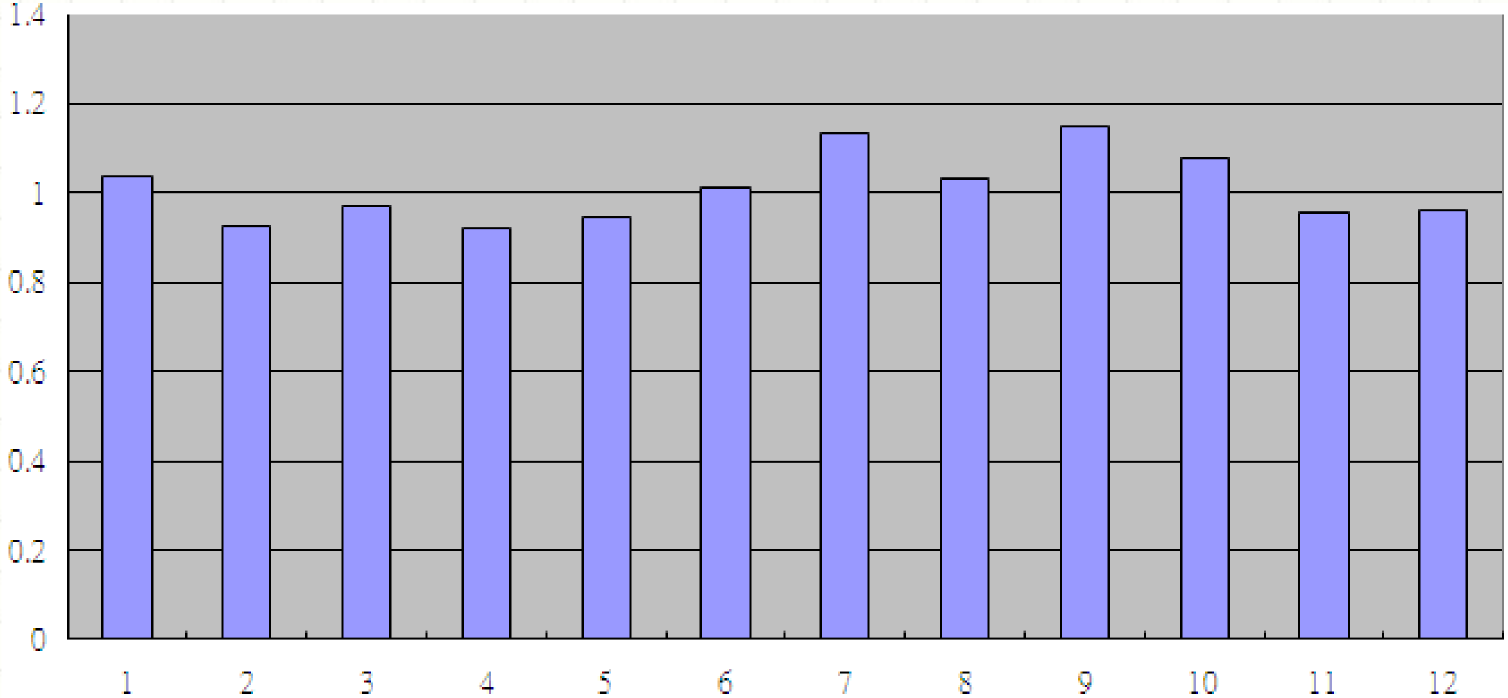


- Grid_70, October Monthly Rainfall



Changes in monthly rainfall (Multi-model ensemble average)

- Baseline period (1980 – 1999), Projection period (2020-2039)
  - **A1B, Grid_70**

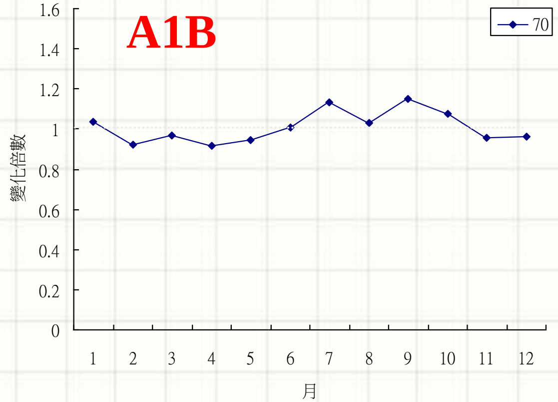


Changes in monthly rainfalls at different GCM grid points

	GCM Grid Points						
月份	70	84	96	97	109	110	111
1	1.03	1.03	1.03	1.02	1.02	1.01	1.01
2	0.92	0.93	0.93	0.94	0.93	0.94	0.94
3	0.97	0.97	0.97	0.96	0.96	0.96	0.95
4	0.92	0.92	0.93	0.93	0.93	0.94	0.94
5	0.95	0.95	0.96	0.96	0.97	0.97	0.98
6	1.01	1.01	1	1.01	1	1.01	1.01
7	1.13	1.13	1.12	1.13	1.12	1.13	1.13
8	1.03	1.03	1.03	1.03	1.03	1.04	1.04
9	1.15	1.14	1.14	1.13	1.13	1.12	1.12
10	1.08	1.07	1.07	1.06	1.06	1.05	1.04
11	0.96	0.96	0.96	0.96	0.96	0.97	0.97
12	0.96	0.96	0.96	0.96	0.96	0.96	0.96

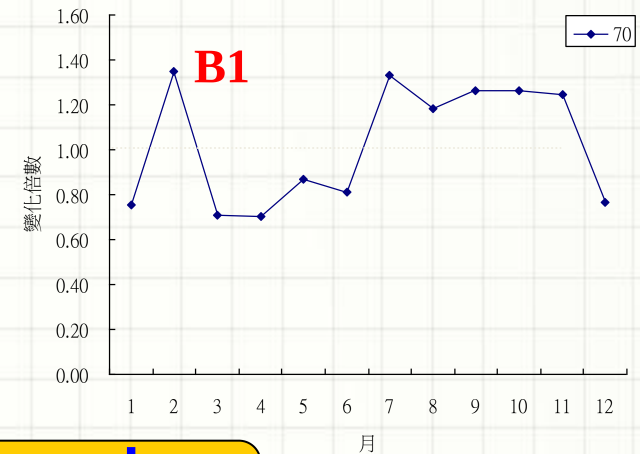
Climate change scenarios (2011 Project)

1. 去年度使用A1B情境下，24個GCMs之系集平均（ensemble mean）月降雨量變化。

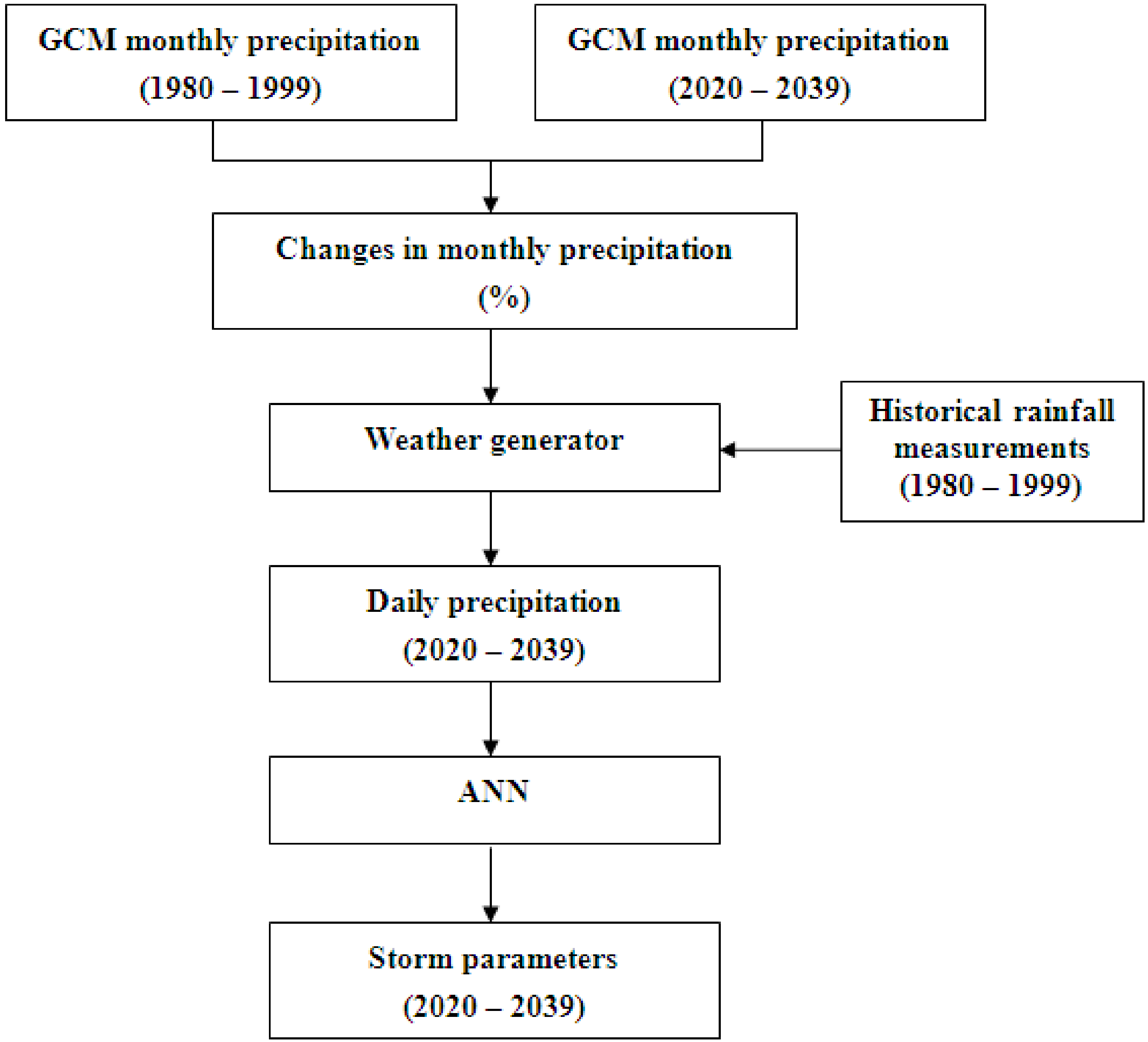


以GCM降尺度點位70為例

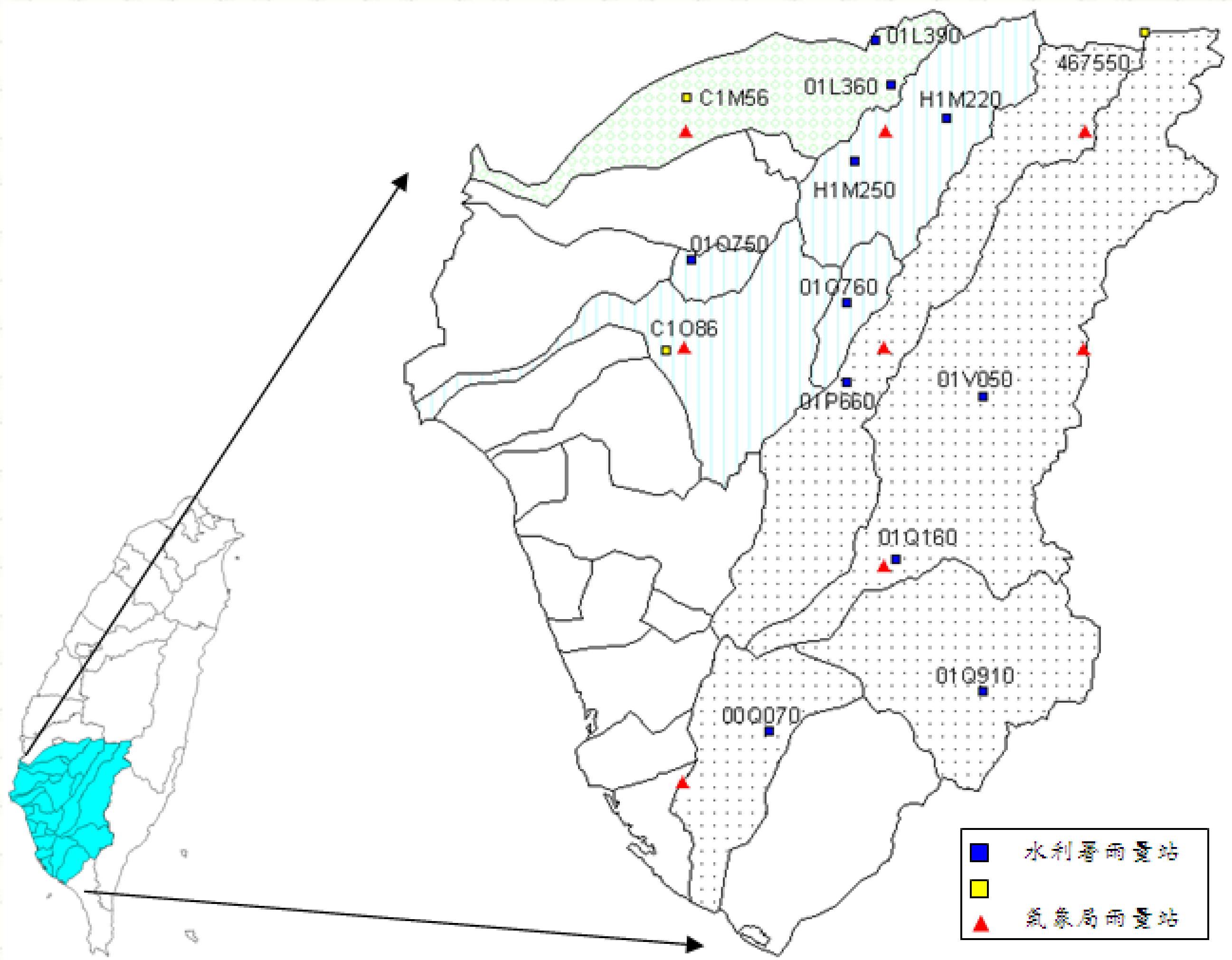
2. 本年度使用A1B、A2及B1情境，24個GCMs之系集平均加減一倍標準偏差之月降雨量變化。



More extreme situations and conservative attitude


GCM monthly precipitation (1980 – 1999)
GCM monthly precipitation (2020 – 2039)
Changes in monthly precipitation (%)
Weather generator
Historical rainfall measurements (1980 – 1999)
Daily precipitation (2020 – 2039)
ANN
Storm parameters (2020 – 2039)

Exemplar Demonstration



Statistical properties of duration, total depth, and inter-event time of typhoon events (baseline period 1980 – 1999)

流域	編號	站號	Duration (hr)			Total depth (mm)			Int event time (hr)			*r*
			Mean	Std.	Skew	Mean	Std.	Skew	Mean	Std.	Skew	
八掌溪	1	01L360	31.51	14.33	0.64	306.58	243.83	1.63	344.54	386.3	1.03	0.69
	2	01L390	26.81	13.02	1.00	236.31	263.97	2.62	276.39	373.74	1.60	0.70
	3	C1M560	23.54	9.50	0.86	121.69	79.82	1.36	525.38	563.40	1.45	0.88
曾文溪	4	H1M220	35.73	21.51	1.15	334.97	393.73	2.37	325.45	331.02	1.50	0.65
	5	H1M250	33.42	19.16	0.83	274.97	352.05	3.02	323.74	385.00	1.46	0.74
	7	01O750	28.18	16.94	1.99	154.74	120.74	1.50	338.04	444.97	1.79	0.87
	7	01O760	33.29	20.22	1.25	274.40	232.50	1.67	292.03	360.05	1.31	0.69
	8	C1O860	26.72	12.59	0.95	148.58	85.88	0.68	337.78	461.17	1.86	0.62
高屏溪	9	01P660	31.63	17.21	1.12	253.92	187.58	1.39	310.73	366.74	1.16	0.75
	10	00Q070	29.29	14.69	0.60	199.37	152.97	1.36	358.00	418.02	1.08	0.76
	11	01Q160	31.02	15.76	1.23	245.38	172.18	1.13	233.54	318.04	1.52	0.79
	12	01Q910	42.10	22.60	1.47	418.89	371.91	2.16	394.38	417.83	1.18	0.81
	13	01V050	33.68	17.14	1.15	300.10	256.74	1.21	338.32	431.34	1.45	0.79
	14	467550	34.16	19.1	1.30	173.5	162.29	1.79	471.74	450.69	1.16	0.81

Statistical properties of duration, total depth, and inter-event time of Mei-Yu events (baseline period 1980 – 1999)

流域	編號	站號	Duration (hr)			Total depth (mm)			Int event time (hr)			r
			Mean	Std.	Skew	Mean	Std.	Skew	Mean	Std.	Skew	
八掌溪	1	01L360	12.48	12.13	2.84	71.11	70.94	2.72	109.01	166.16	2.12	0.86
	2	01L390	11.01	8.78	2.05	63.53	52.09	1.55	139.99	237.87	2.74	0.68
	3	C1M560	8.46	5.03	2.83	39.04	36.28	1.56	88.90	125.84	1.72	0.60
曾文溪	4	H1M220	11.39	13.42	4.29	58.54	97.10	4.25	63.52	119.65	5.20	0.82
	5	H1M250	11.63	12.76	4.13	58.18	90.16	4.12	78.44	136.93	4.21	0.85
	7	01O750	12.95	9.79	1.84	60.01	53.40	1.71	106.55	166.96	1.77	0.81
	7	01O760	14.16	15.54	3.59	81.82	103.72	3.76	95.24	172.19	3.31	0.89
	8	C1O860	9.37	6.59	2.36	41.77	44.66	2.73	93.14	138.27	2.05	0.76
高屏溪	9	01P660	13.40	13.13	2.81	80.40	94.58	3.50	90.55	159.04	2.66	0.87
	10	00Q070	14.53	17.21	4.35	82.99	106.33	3.72	87.05	152.63	2.52	0.94
	11	01Q160	15.65	14.86	3.20	89.27	108.47	4.51	114.94	176.17	1.77	0.88
	12	01Q910	20.58	21.10	2.66	139.89	187.63	3.11	110.26	164.35	1.77	0.87
	13	01V050	15.98	13.25	1.82	106.43	121.61	2.66	107.15	189.93	2.27	0.85
	14	467550	13.54	13.85	2.50	42.81	67.51	3.31	55.36	79.51	2.75	0.86

Deriving parameters of SSRSM through ANN

Monthly rainfall of the projection period
(From GCMs)

↓

Weather Generator
(Reference to rainfall pattern of the baseline period)

↓

Daily rainfall of the projection period

↓

ANN

↓

Parameters of SSRSM

Mean values of SSRSM parameters (Projection period: 2020 – 2039)

Storm type	Statistic	Station ID 玉山 (467550)	新豐 (01Q160)	甲仙(2) (01P660)	屏東(5) (00Q070)	馬頭山 (H1M250)	大內 (C1O860)	南靖 (C1M560)
梅雨 MY	Duration (hour)	12.16	11.39	12.01	15.32	11.69	10.05	9.44
	Depth (mm)	53.38	61.41	64.12	85.65	59.27	52.68	42.41
	Int E time (hour)	66.56	66.21	67.26	77.43	87.34	92.84	79.72
颱風 Typh	Duration (hour)	34.00	37.01	38.47	30.61	33.67	25.57	31.91
	Depth (mm)	186.09	387.49	390.02	240.93	290.08	152.04	85.56
	Int E time (hour)	510.17	321.03	330.49	316.78	288.35	566.43	776.55
對流 Conv	Duration (hour)	6.42	6.04	6.19	6.19	5.75	6.53	5.80
	Depth (mm)	23.54	41.61	46.09	32.70	42.95	45.90	41.02
	Int E time (hour)	227.62	150.79	208.83	233.90	156.43	193.97	220.79
鋒面 Front	Duration (hour)	12.12	6.39	7.61	6.00	6.97	4.32	5.13
	Depth (mm)	41.88	25.35	32.36	26.59	33.05	19.30	21.42
	Int E time (hour)	312.65	880.78	451.58	607.25	296.32	456.84	343.06

Changes in storm parameters

符號	意義
●	增加
○	略增
○	略減
●	減少

- **Number of occurrences**

SRES 情境	降雨類型	區域		
		北部	中部	南部
A1B	梅雨	○	○	○
	颱風雨	●	●	●
	對流雨	●	●	●
	鋒面雨	●	●	●
A2	梅雨	●	●	●
	颱風雨	●	●	●
	對流雨	○	○	○
	鋒面雨	●	●	●
B1	梅雨	●	●	●
	颱風雨	●	●	●
	對流雨	○	○	○
	鋒面雨	●	●	●

Total depth

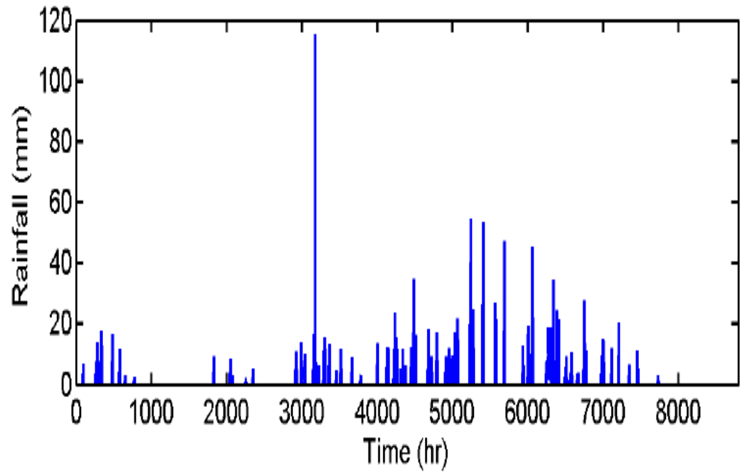
SRES 情境	降雨類型	區域		
		北部	中部	南部
A1B	梅雨	○	○	○
	颱風雨	●	●	●
	對流雨	●	●	●
	鋒面雨	●	●	●
A2	梅雨	●	●	●
	颱風雨	●	●	●
	對流雨	○	○	○
	鋒面雨	●	●	●
B1	梅雨	○	○	○
	颱風雨	●	●	●
	對流雨	○	○	○
	鋒面雨	●	●	●

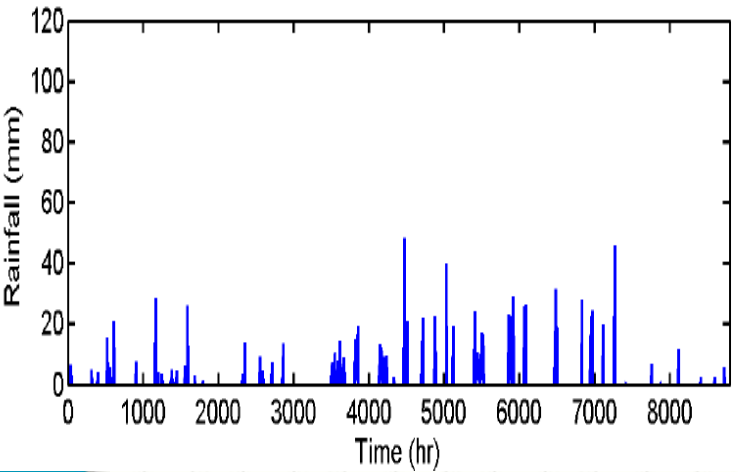
Stochastic simulation of hourly rainfall series

- Each simulation run consists of different storm types.
- Each run yields a sample series of one-year hourly rainfall data.
- A total of 100 runs were conducted for each station.
- Annual max rainfalls of specific durations (1, 2, 6, 12, 18, 24, 48 and 72 hours) were extracted from each of the 100 sample series.

An exemplar result of SSRSM

Baseline period（1980~1999年）simulated hourly rainfall series





甲仙(2)站

- Station: 甲仙(2)站
- Storm parameters extracted from simulated series

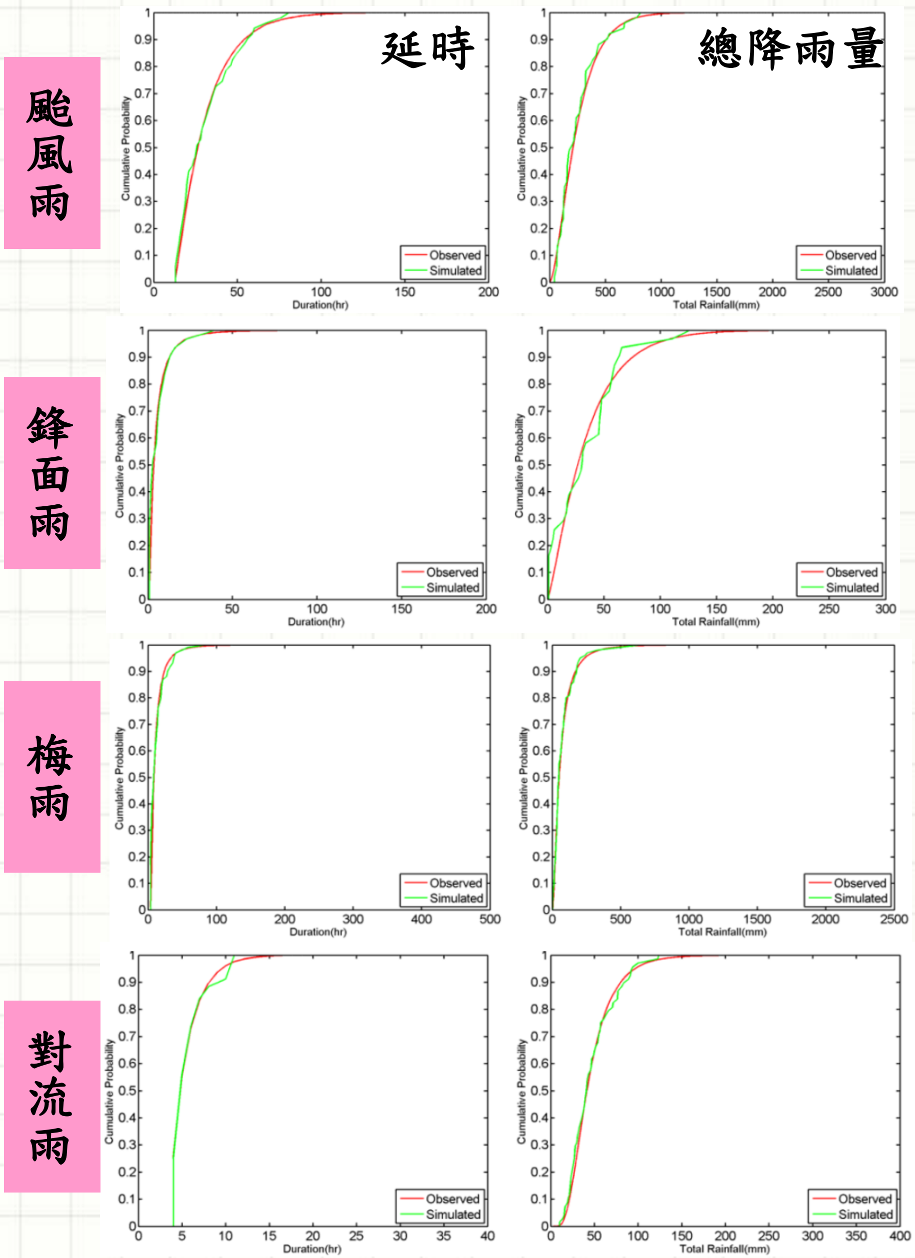
Storm type	延時(小時)		總降雨量(mm)		相關係數
	Mean	Std.	Mean	Std.	ρ
Typhoon	31.6499	17.3186	254.3826	188.6108	0.7402
Mei-Yu	13.4374	13.1138	80.5561	93.8202	0.8579
onvective	5.9016	2.0877	47.2196	25.7145	0.3328
Frontal	6.4627	8.3817	35.3875	30.9446	0.7241

註：相關係數指事件延時與事件總雨量之相關係數。

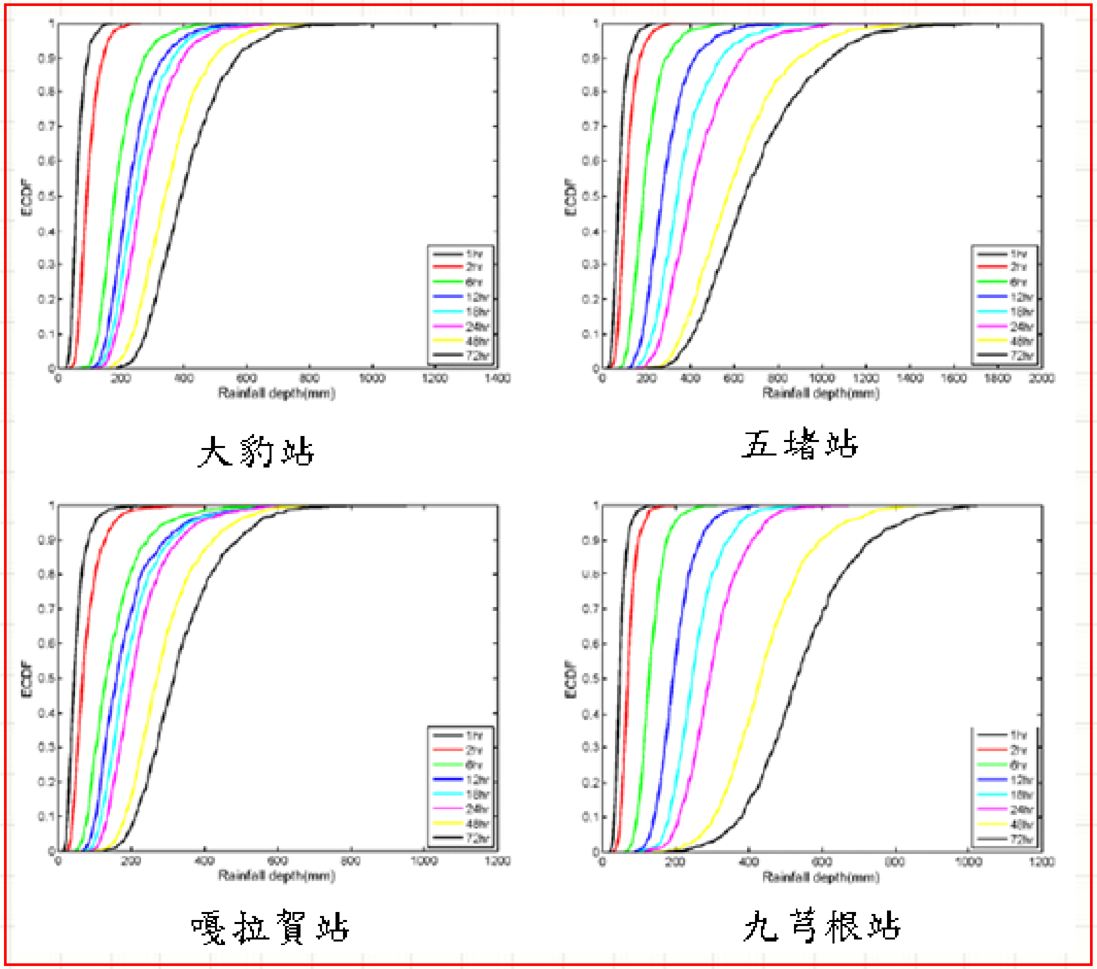
Verification of ECDF

- 以甲仙(2)站為例。
- 原始與模擬雙變量隨機樣本延時與總降雨量之ECDF與CDF套配圖。

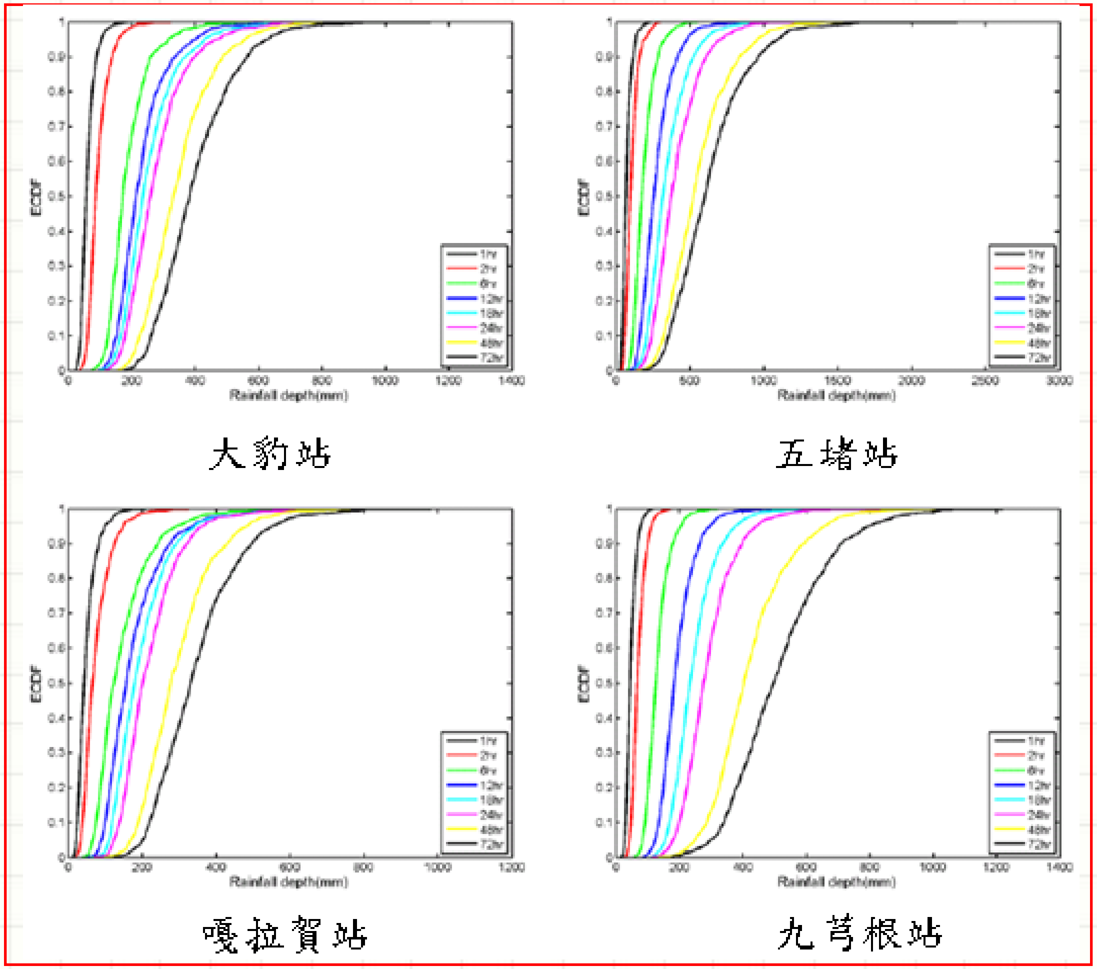
1. **模擬結果均符合原始資料分布形式**
2. **模擬結果良好，亦即模式可反應真實情況**



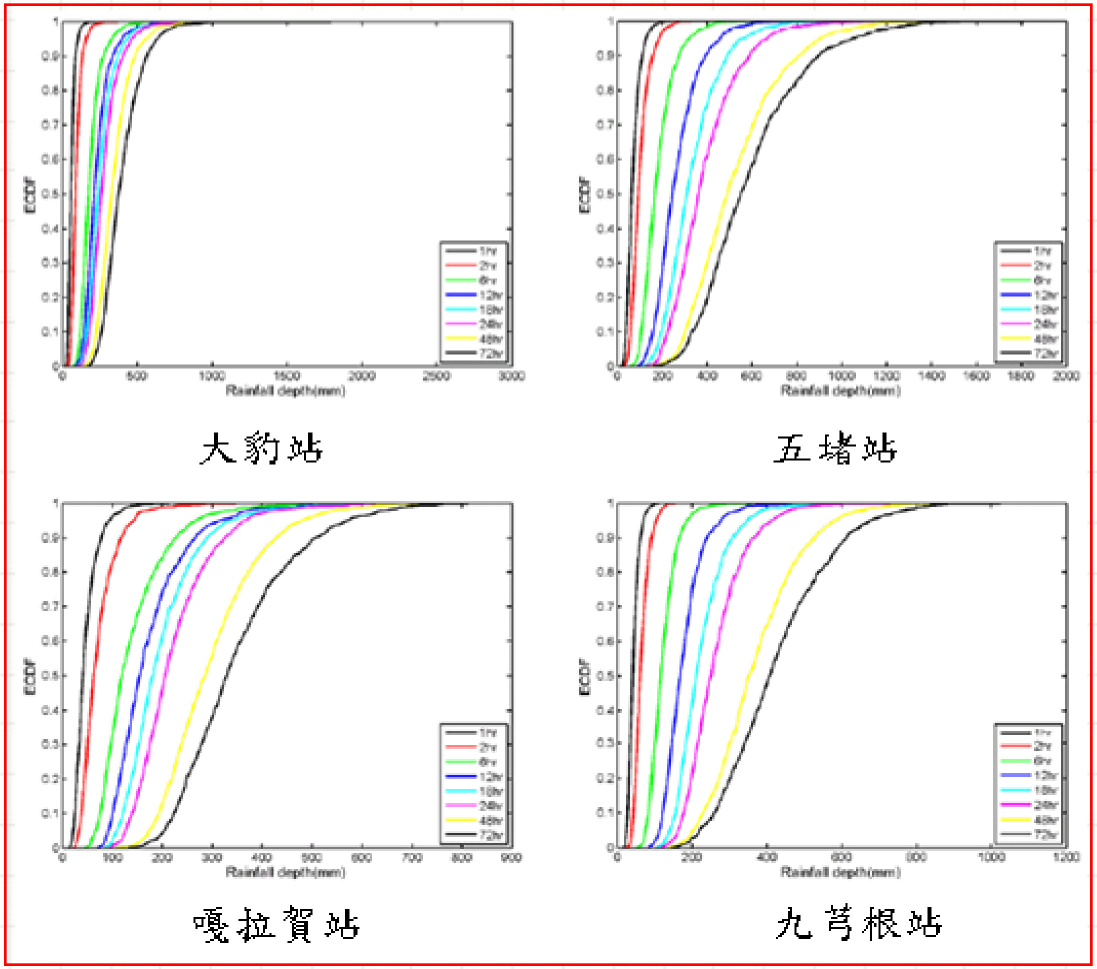
CDF of annual maximum rainfalls of various design durations (**A1B, North**)



CDF of annual maximum rainfalls of various design durations (**A2, North**)

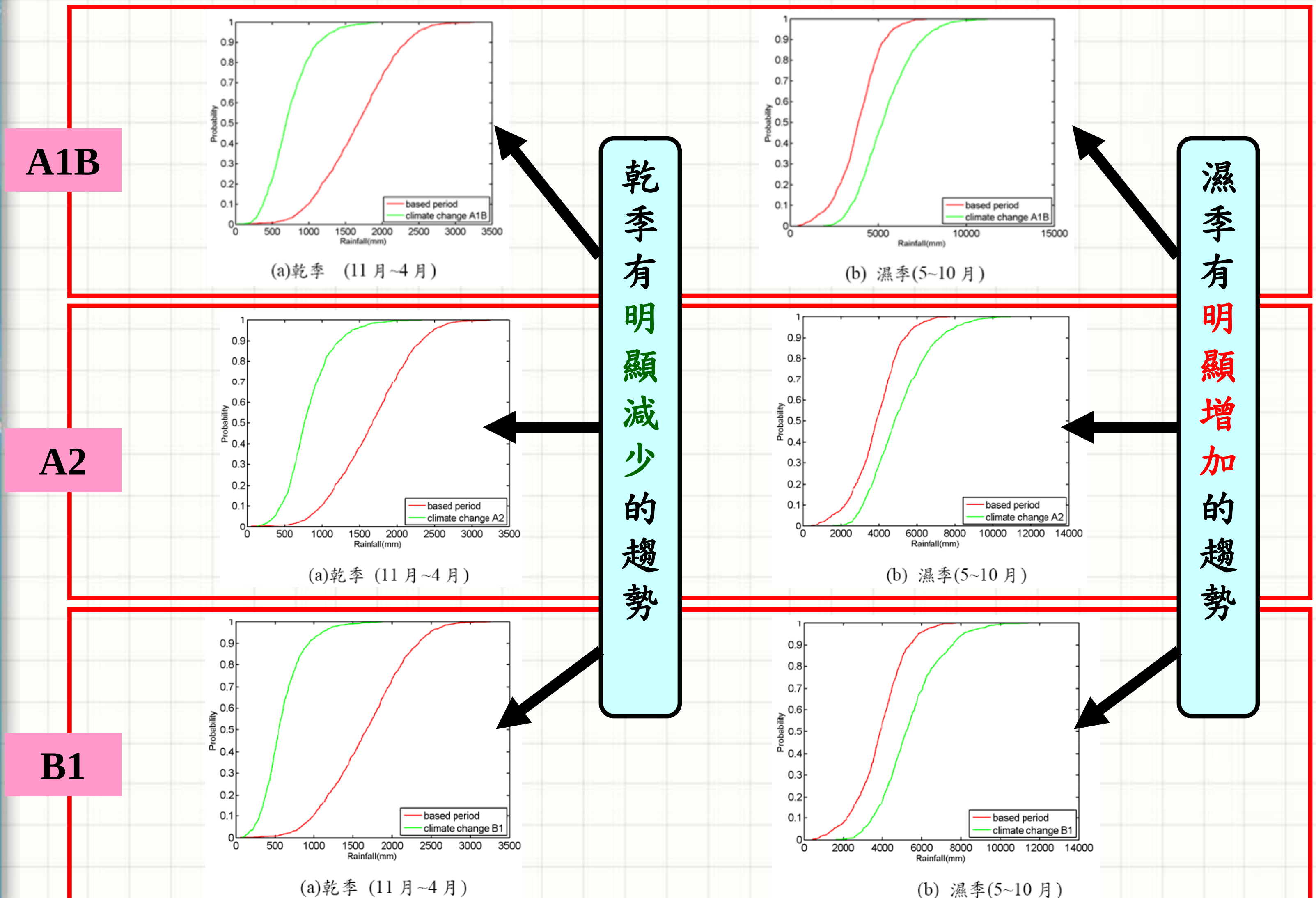


CDF of annual maximum rainfalls of various design durations (**B1, North**)



Assessing changes in seasonal rainfalls

- 未來各情境乾季與濕季的雨量變化情況 - 以甲仙(2)站為例。



Concluding remarks

- We have demonstrated the feasibility of using SSRSM with parameters derived from GCMs through an ANN for assessing the impacts of climate change on stormwater hydrology.
- Scenario setting is crucial and requires good judgements and decisions.

Further Considerations

- Ensemble projection is important
- Ensemble projection takes into account uncertainties involved in different stages of the "estimation" process.
- Multi-site joint storm rainfall simulation