Taipei, Taiwan

1/15㊁~1/17㊃ 2013

氣·候·變·遷·國·際·研·討·會

International Conference on CLIMATE CHANGE

Assessment of hydrologic projections under climate change

Ke-Sheng Cheng

Dept. of Bioenvironmental Systems Engineering

National Taiwan University

Background

- **Aiming to assess the impact of climate change on water resources management/planning and to formulate adaptation strategies, the Water Resources Agency (WRA) initiated a four-year (2010 – 2013) *Climate Change Impact and Adaptation program* (CCIAP) which is composed of fourteen subprojects.**
  - Due to the nature of water resources planning and design (for examples, flood prevention and mitigation, inundation mapping, etc.) for which WRA bears the administrative responsibility, it is imperative for CCIAP to consider the impact of climate change on **stormwater hydrology** which involve rainfalls in local and event scales.

Importance of climate change impacts on stormwater hydrology

- **Key factors in water resources management and design related to stormwater hydrology**
  - Design rainfall depth (e.g. rainfall depth of 24-hr duration and 100-year return period)
  - Design storm hyetograph
  - Flood of 100-year return period

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

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

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

Objectives

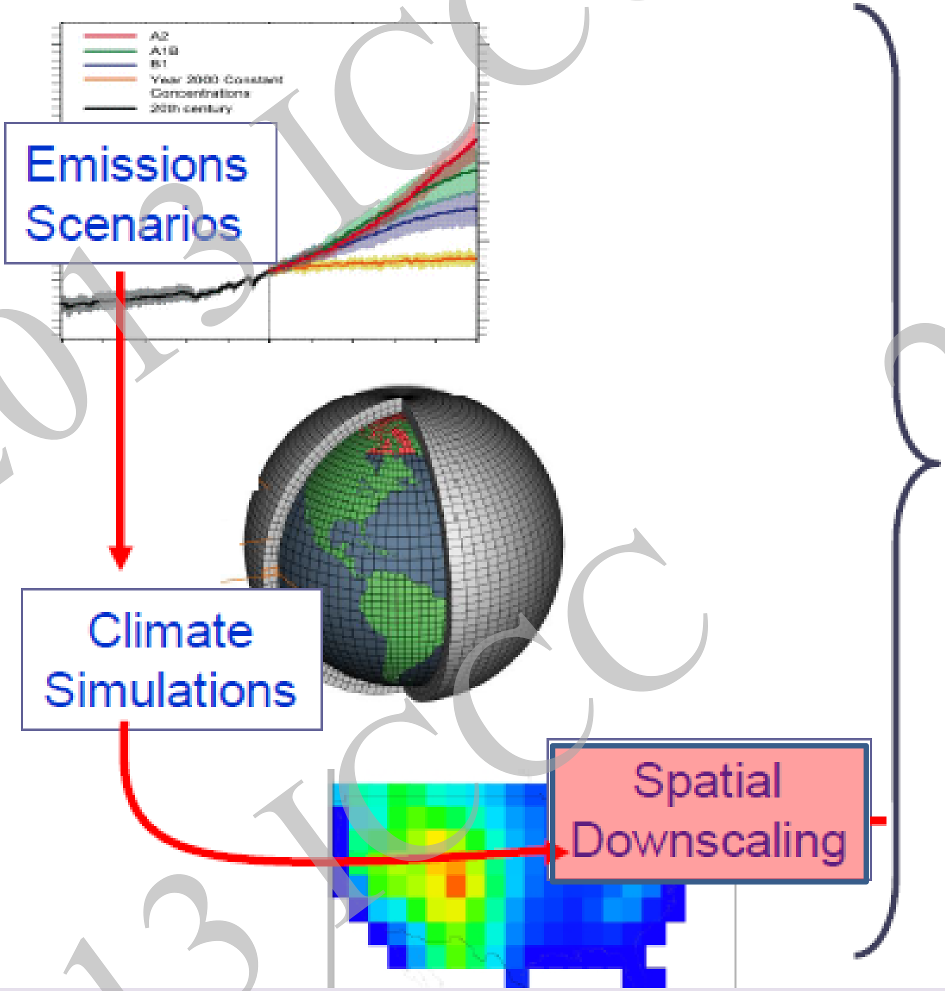
- **Among a group of CCIAP projects, this project aims to assess the impact of climate change on hydrologic projections.**
  - Characteristics of storm rainfall extremes
  - Considering physical storm parameters (number of occurrences, duration, total rainfall depths, etc.)
  - Stochastic modeling of storm occurrences and time variation of rainfall intensities.

A *GCM–stochastic model* integrated approach

Key concerns

- **From a hydrological perspective**
  - How do we bridge the gap between climate projections and hydrologic projections?
    - Downscaling (spatial and temporal)
    - weather generators (simulating daily precipitations)
  - What statistical properties need to be preserved in downscaled data?
    - Can the downscaled data preserve the spatiotemporal variation of the observed data?
    - Stormwater hydrology involves rainfall characteristics of daily and sub-daily scales.

Downscaling of GCM outputs



Emissions Scenarios

Climate Simulations

Spatial Downscaling

- 3 emissions scenarios
  - A1b, A2, B1
- Monthly P&T 1950-2099
- 1/8° (12 km) gridded data

Santa Clara Univ. (Maurer)
Reclamation
LLNL

Santa Clara University
RECLAMATION

Adapted from

Subhrendu Gangopadhyay
USBR, Technical Services Center, Denver
sgangopadhyay@usbr.gov

Statistical Downscaling Model (SDSM)

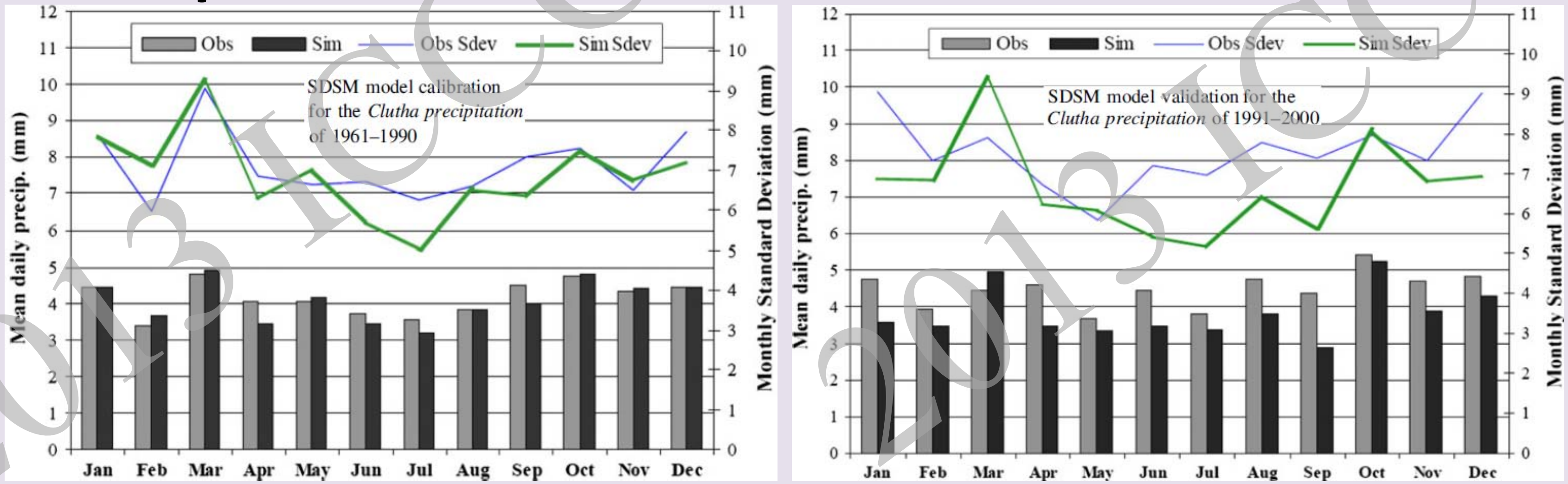
- **Multiple regression model**
  - Large-scale predictors: GCM or NCEP data
  - Local or station predictands: temperature or precipitation (almost exclusively in daily scale)
    - The predictor-predictand correlation is generally low. Predictors having correlation coefficient in the range of 0.13-0.25 are considered to be acceptable when dealing with precipitation downscaling (cf. Wilby et al., 2002).
- **Weather generator**

Weather generators

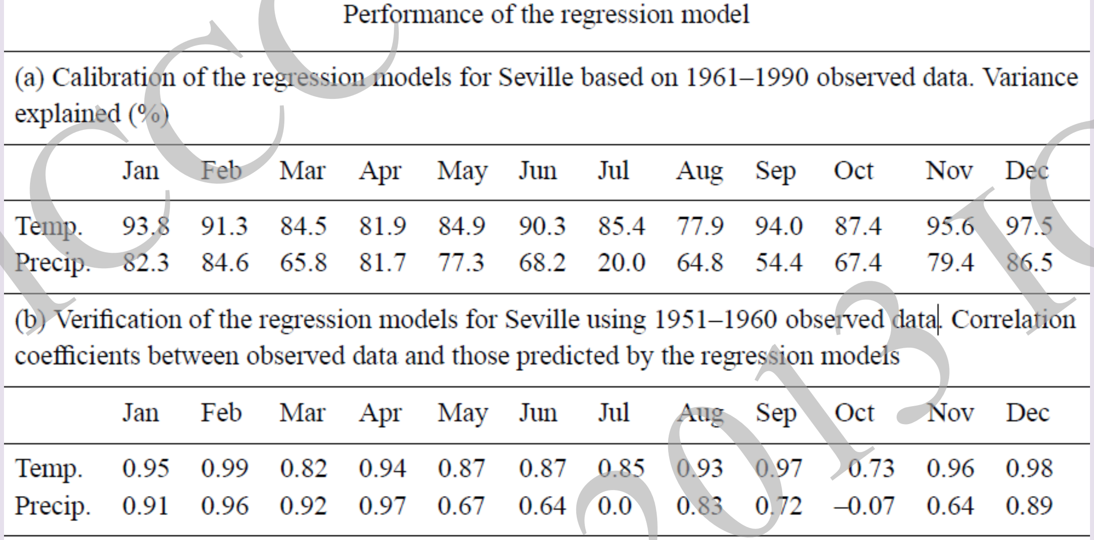
- **WGEN (Richardson & Wright, 1984)**
  - Dry/wet day transition probability matrix (Markov chain)
  - Exponential/gamma random number generation for wet-day daily rainfall simulation
- **LARS-WG (Racsko et al., 1991; Semenov & Barrow, 1997)**

- Generate daily precipitation series.
- Daily rainfalls are independently generated (serial correlation of daily rainfalls is not considered).
- Statistical property of wet/dry spells are not well preserved.
- Performance evaluation of the models were almost exclusively based on monthly scale statistics. [Monthly mean and standard deviation]

Examples of performance evaluation of downscaling techniques.



Comparisons of the observed and the SDSM-estimated month-wise mean daily precipitation and its standard deviation.



Performance of the regression model

(a) Calibration of the regression models for Seville based on 1961–1990 observed data. Variance explained (%)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp.	93.8	91.3	84.5	81.9	84.9	90.3	85.4	77.9	94.0	87.4	95.6	97.5
Precip.	82.3	84.6	65.8	81.7	77.3	68.2	20.0	64.8	54.4	67.4	79.4	86.5

(b) Verification of the regression models for Seville using 1951–1960 observed data. Correlation coefficients between observed data and those predicted by the regression models

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp.	0.95	0.99	0.82	0.94	0.87	0.87	0.85	0.93	0.97	0.73	0.96	0.98
Precip.	0.91	0.96	0.92	0.97	0.67	0.64	0.0	0.83	0.72	–0.07	0.64	0.89

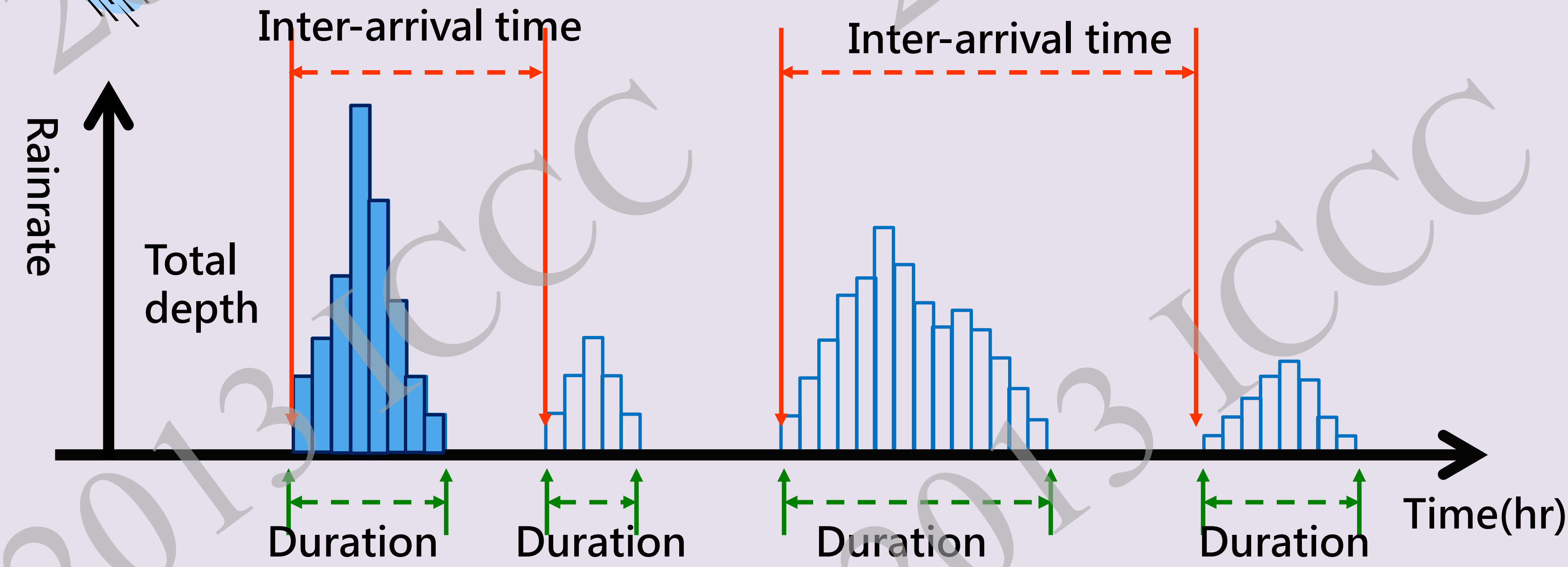
- **Storm characteristics are not considered in weather generator.** **Random in nature.**
  - Frequency and timing of storm occurrences
  - Storm duration
  - Total rainfall depth of a storm
  - Percentages of the total rainfall of individual intervals within the storm duration (dimensionless hyetograph)
- **The above characteristics need to be preserved in the downscaled data.**
- **The way out**
  - **Stochastic storm rainfall simulation model (SSRSM)**

- **Stochastic storm rainfall simulation model**
  - A stochastic model capable of representing all the above characteristics of storm rainfall process.
  - Physical storm parameters are considered as random variables in the model.
  - GCM outputs are used to assess changes in statistical properties of storm parameters under certain climate change scenarios.

Stochastic storm rainfall process

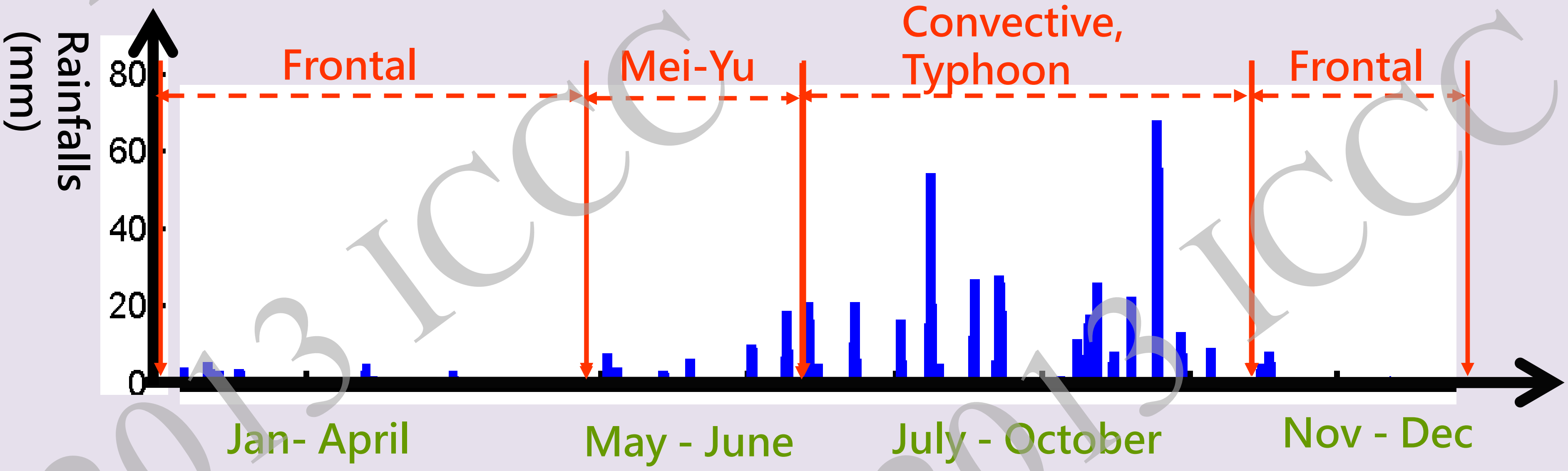
Storm characteristics

- Duration
- Event-total depth
- Inter-arrival time
- Time variation of rain-rates



Season-specific storm characteristics

Storm type	Period
Frontal	Nov - April
Mei-Yu	May - June
Convective	July - October
Typhoon	July - October

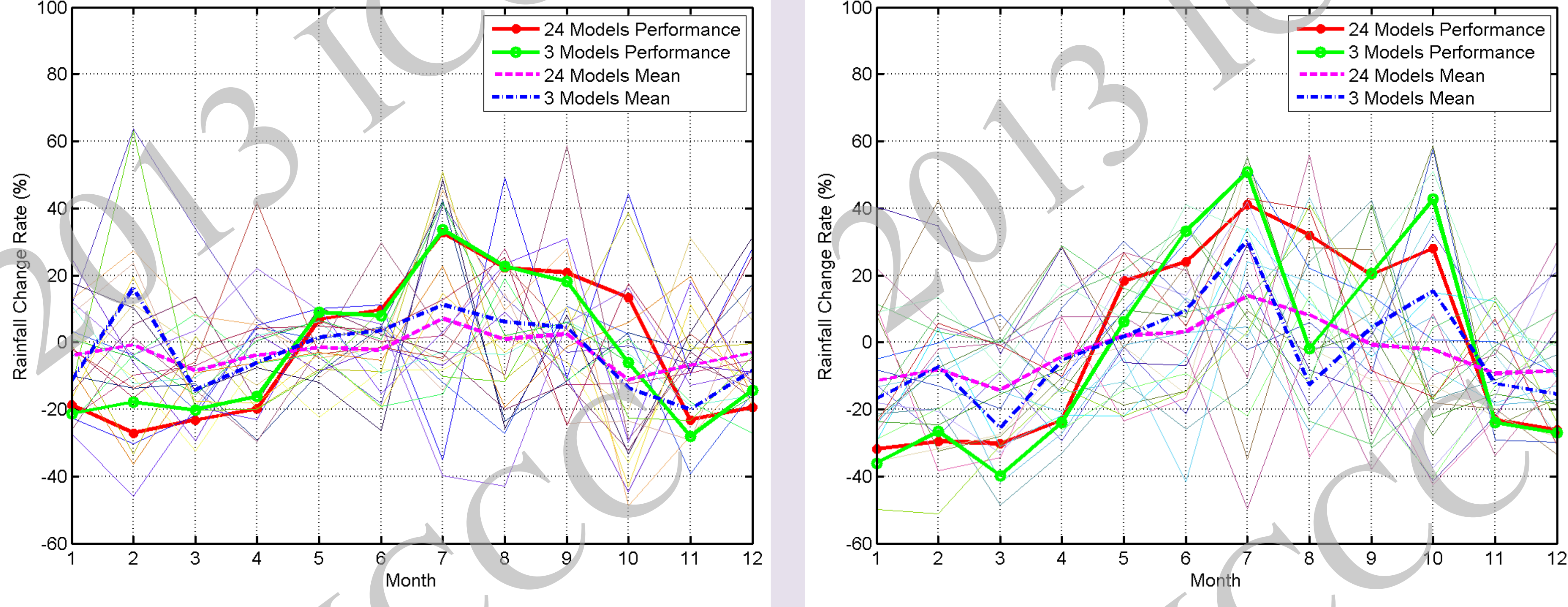


Climate change scenarios and GCM outputs (Case 1)

- **Emission scenario: A1B**
- **Baseline period: 1980 – 1999**
- **Projection period**
  - Near future: 2020 – 2039
  - End of century: 2080 – 2099
- **GCM models: change rates of monthly rainfalls (outputs of 24 GCMs provided by NCDR, statistical downscaling)**
- **Hydro-meteorological scenario: extreme situation**

Changes in monthly rainfalls (Statistical downscaling, Ensemble average with standard deviation adjustment)

Taipei area

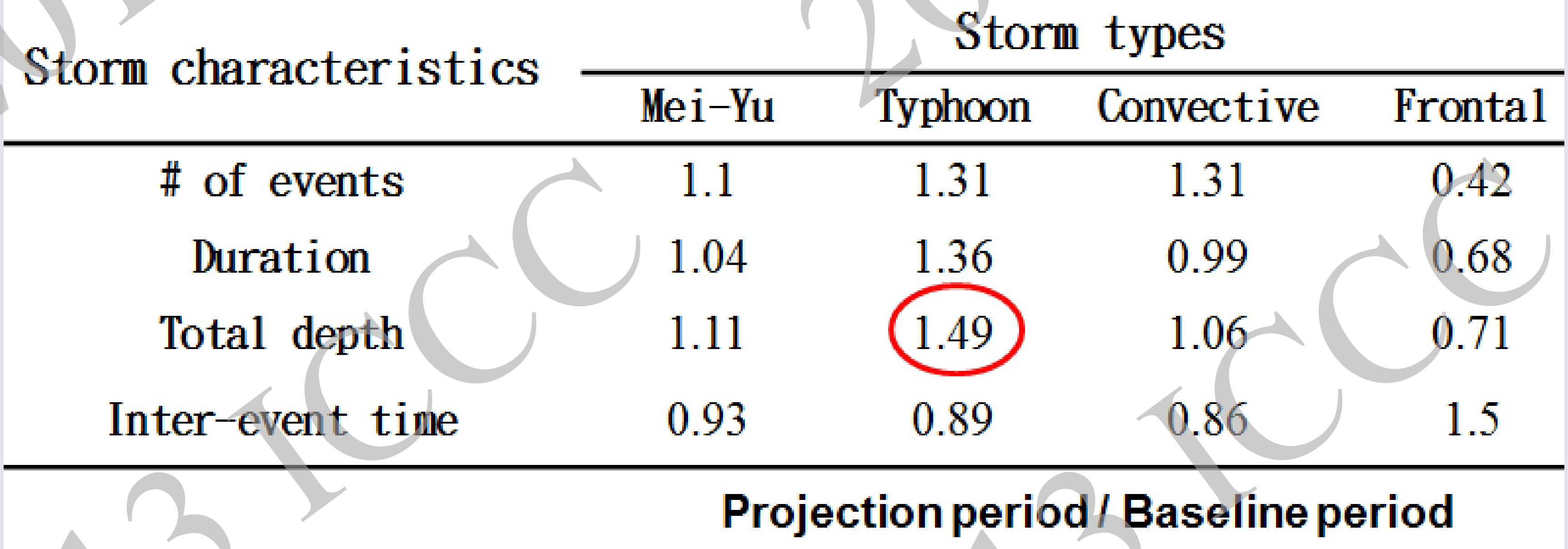


Near future (2020 – 2039)

End of century (2080 – 2099)

- A weather generator and ANN coupled algorithm was developed to determine changes in the mean and standard deviation of storm parameters under climate change.

- **An example of changes in means of storm parameters under climate change**



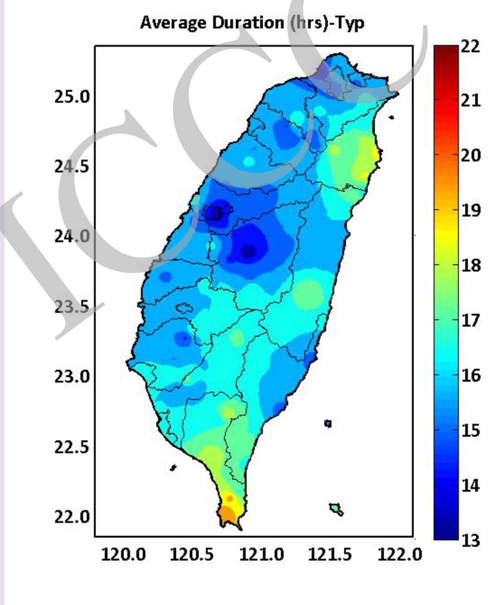
Storm characteristics	Storm types			
	Mei-Yu	Typhoon	Convective	Frontal
# of events	1.1	1.31	1.31	0.42
Duration	1.04	1.36	0.99	0.68
Total depth	1.11	1.49	1.06	0.71
Inter-event time	0.93	0.89	0.86	1.5

Projection period / Baseline period

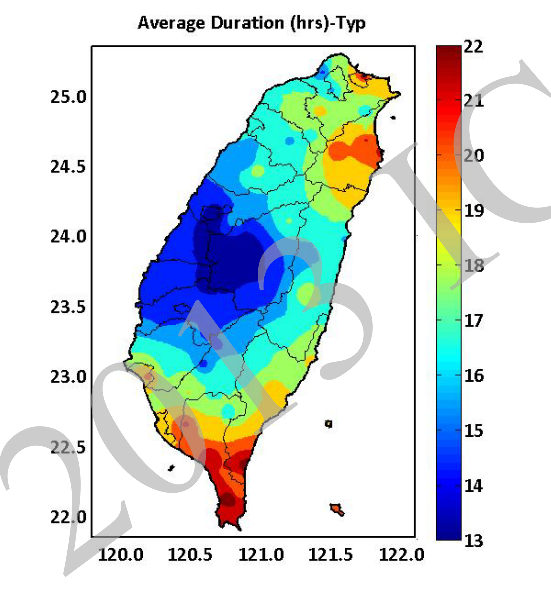
Climate change scenarios and GCM outputs (Case 2)

- **Emission scenario: A1B**
- **Baseline period: 1979 – 2003**
- **Projection period**
  - Near future: 2015 – 2039
  - End of century: 2075 – 2099
- **GCM model: MRI+WRF dynamic downscaling**
- **Hydrological scenario: changes in storm characteristics**

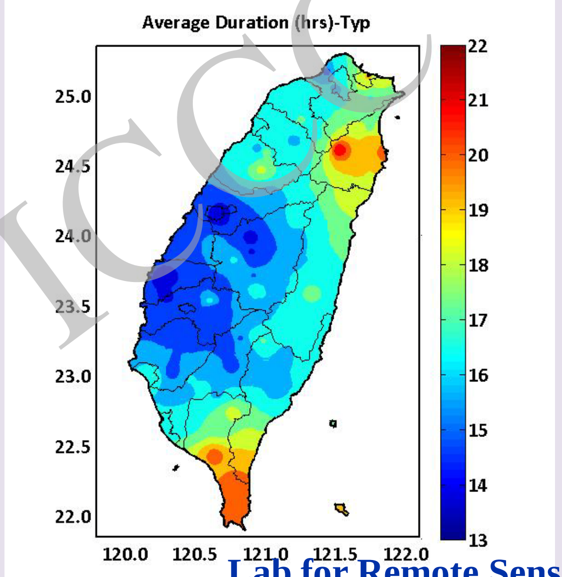
Storm characteristics (average duration of typhoon)



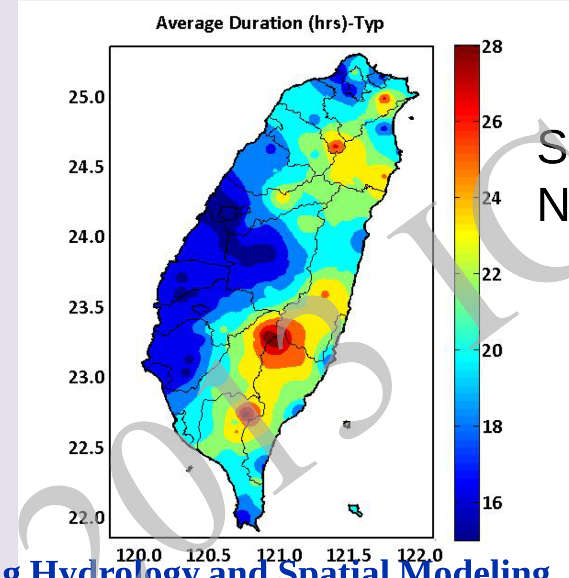
Gauge observations



MRI (1979 - 2003)



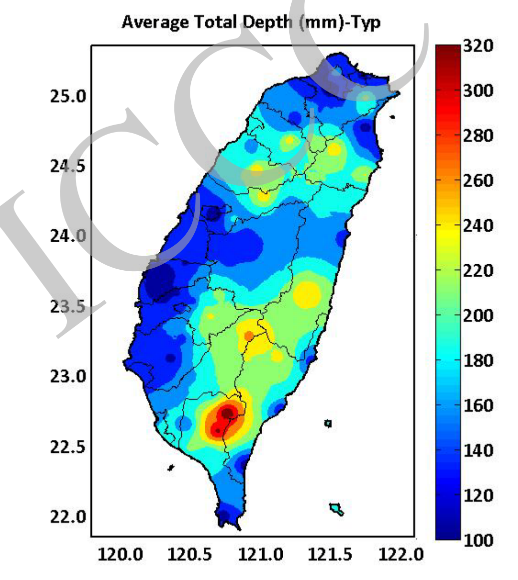
MRI (2015 – 2039)



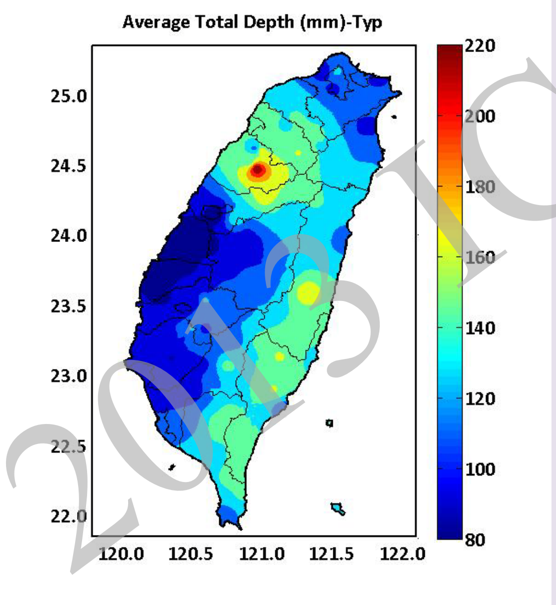
MRI (2075 - 2099)

Source: NCDR, Taiwan

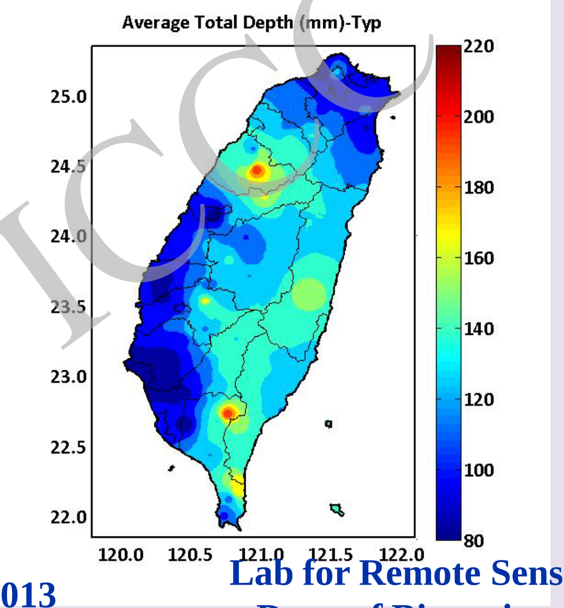
Storm characteristics (average event-total rainfalls of typhoon)



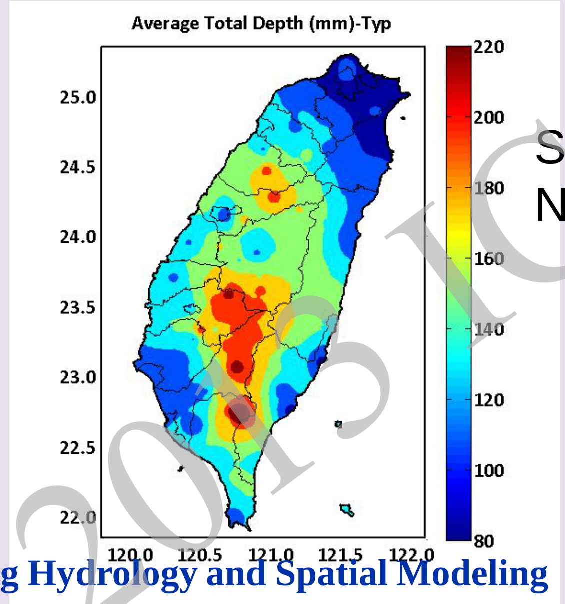
Gauge observations



MRI (1979 - 2003)



MRI (2015– 2039)



MRI (2075 - 2099)

Source:
NCDR, Taiwan

Stochastic Storm Rainfall Simulation Model (SSRSM)

- Simulating occurrences of storms and their rainfall rates
  - Preserving seasonal variation and temporal autocorrelation of rainfall process.
- Duration and event-total depth
  - Characterized by a bivariate gamma distribution (typhoons)
- Inter-event times
  - Gamma or log-normal distributions
- Percentage of total rainfalls in individual intervals (Storm hyetographs)
  - Modeled by a first-order Truncated Gamma-Markov process

- **Simulating occurrences of storm events of various storm types**
  - Number of events per year
    - Poisson distribution for typhoon and Mei-Yu
  - Inter-event time
    - Gamma or log-normal distributions

- **Simulating joint distribution of duration and event-total depth**
  - Bivariate gamma distribution (e.g. typhoons)
  - Log-normal-Gamma bivariate
  - Non-Gaussian bivariate distributions were transformed to a corresponding bivariate standard normal distribution with desired correlation matrix.

$\rho_{XY} \sim \rho_{UV}$ Conversion

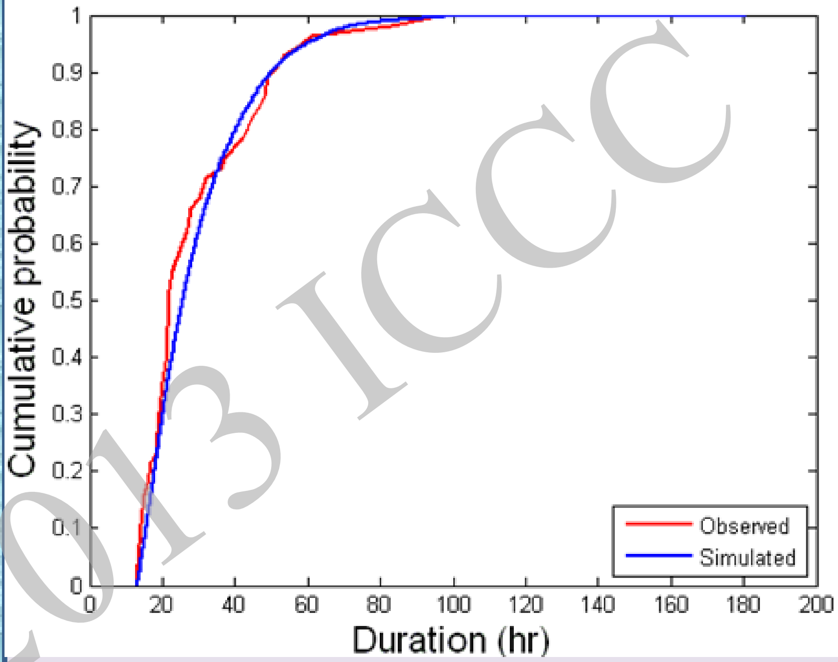
$$\rho_{XY} \approx \left(A_X A_Y - 3A_X C_Y - 3C_X A_Y + 9C_X C_Y\right)\rho_{UV}$$

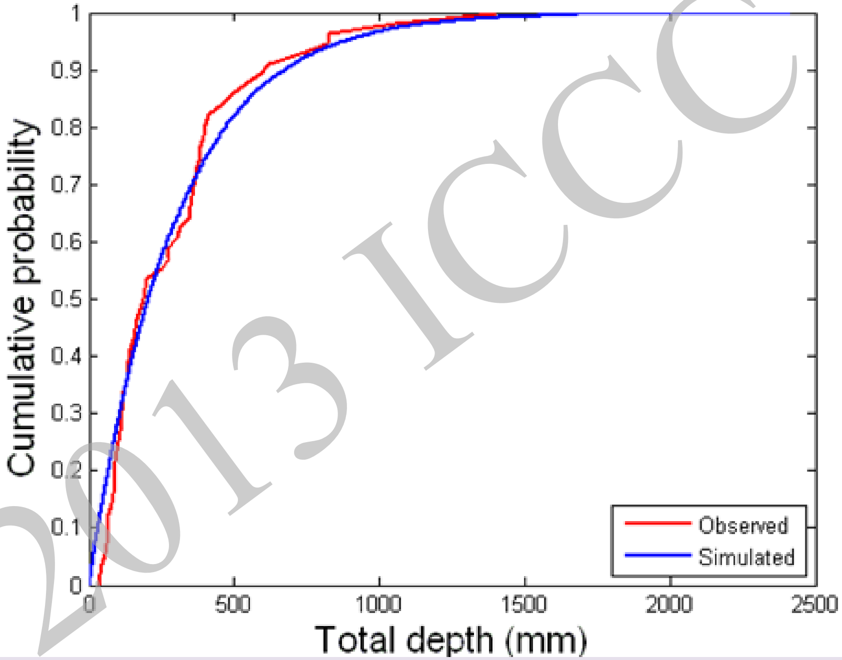
$$+2B_X B_Y \rho_{UV}^2 + 6C_X C_Y \rho_{UV}^3$$

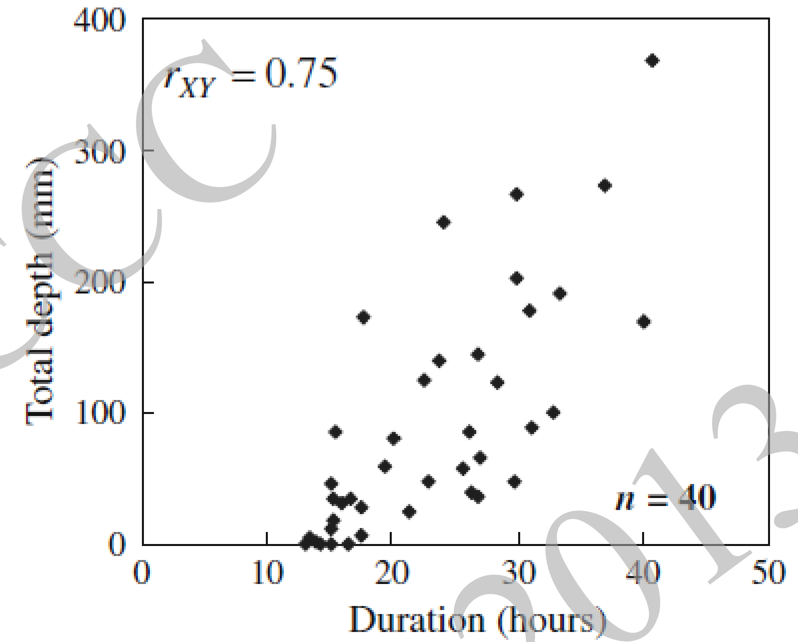
$$A_X = 1 + \left(\frac{\gamma_X}{6}\right)^4 \qquad B_X = \frac{\gamma_X}{6} - \left(\frac{\gamma_X}{6}\right)^3 \qquad C_X = \frac{1}{3}\left(\frac{\gamma_X}{6}\right)^2$$

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

Bivariate gamma (X,Y)


Cumulative probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
180
200
Duration (hr)
Observed
Simulated

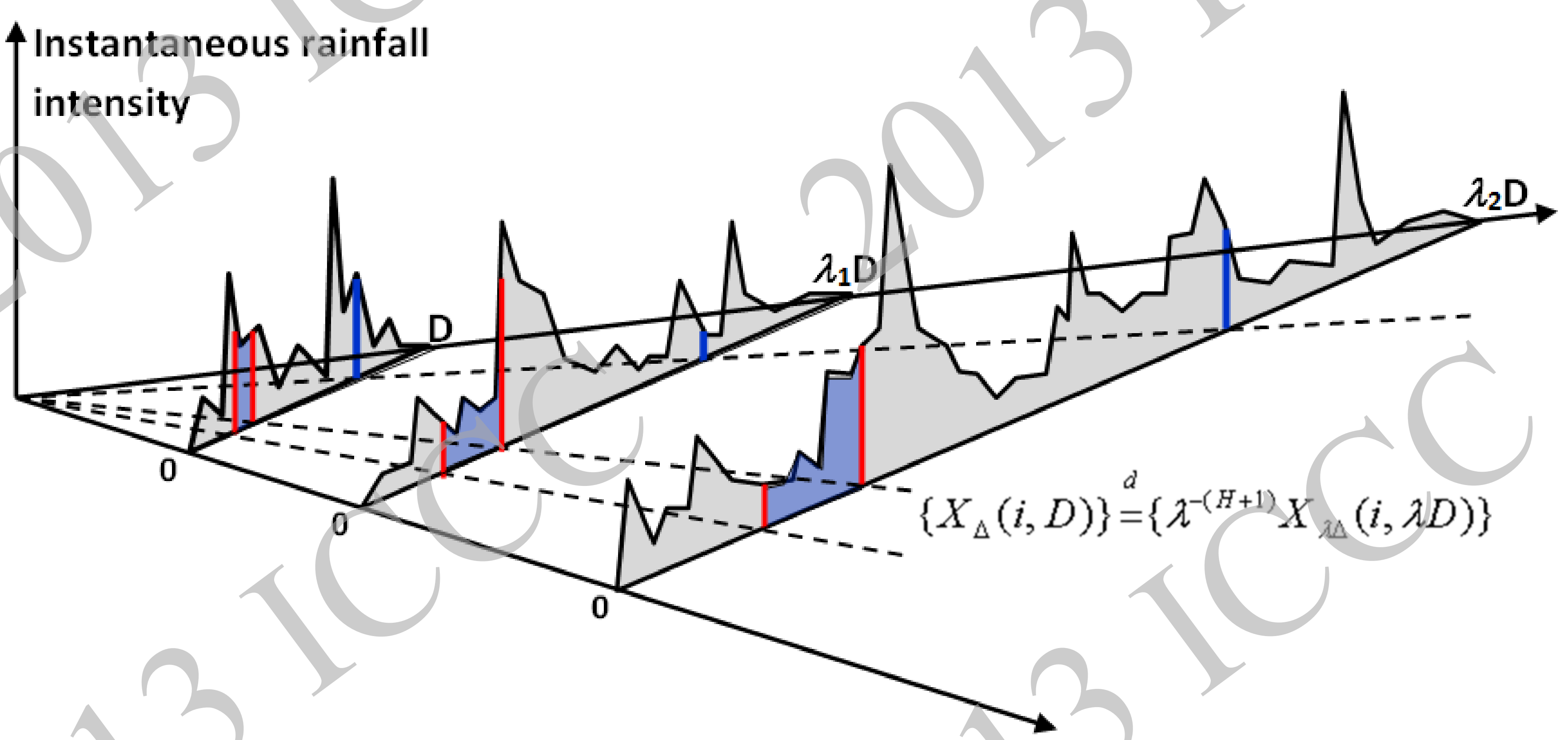

Cumulative probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
500
1000
1500
2000
2500
Total depth (mm)
Observed
Simulated


$r_{XY} = 0.75$
$n = 40$
Total depth (mm)
0
100
200
300
400
0
10
20
30
40
50
Duration (hours)

- **Simulating percentages of total rainfalls in individual intervals (Simulation of storm hyetographs)**
  - Based on the **simple scaling property**
    - Durations of all events of the same storm types are divided into a fixed number of intervals (e.g. 24 intervals).
    - For a specific interval, rainfall percentages of different events are identically and independently distributed (IID).
    - Rainfall percentages of adjacent intervals are correlated.

    - **The simple scaling is supported by Horner equation fitting of the IDF curves.**

Simple scaling



$$\{X_{\Delta}(i,D)\} \overset{d}{=} \{\lambda^{-(H+1)} X_{\lambda\Delta}(i,\lambda D)\}$$

- **Simulating percentages of total rainfalls in individual intervals (Simulation of storm hyetographs)**
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IDF Curves and the Scaling Property

- **Horner's Equation:**

$$\bar{i}_T(D) = \frac{aT^m}{(D+b)^c}$$

***D* >> *b* , particularly for long-duration events.**

- **Neglecting *b***

$$\bar{i}_T(D) = \lambda^c \bar{i}_T(\lambda D)$$

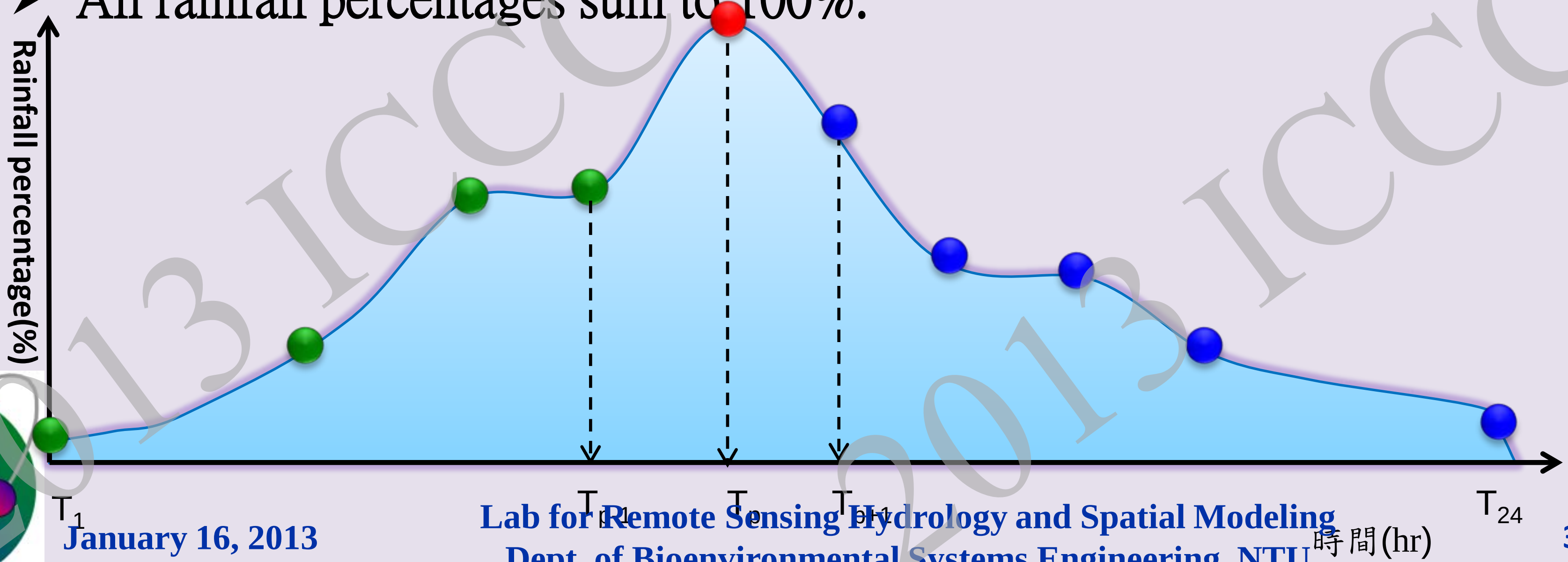
Simple scaling

$$\bar{i}_T(D) = \lambda^{-H} \bar{i}_T(\lambda D)$$

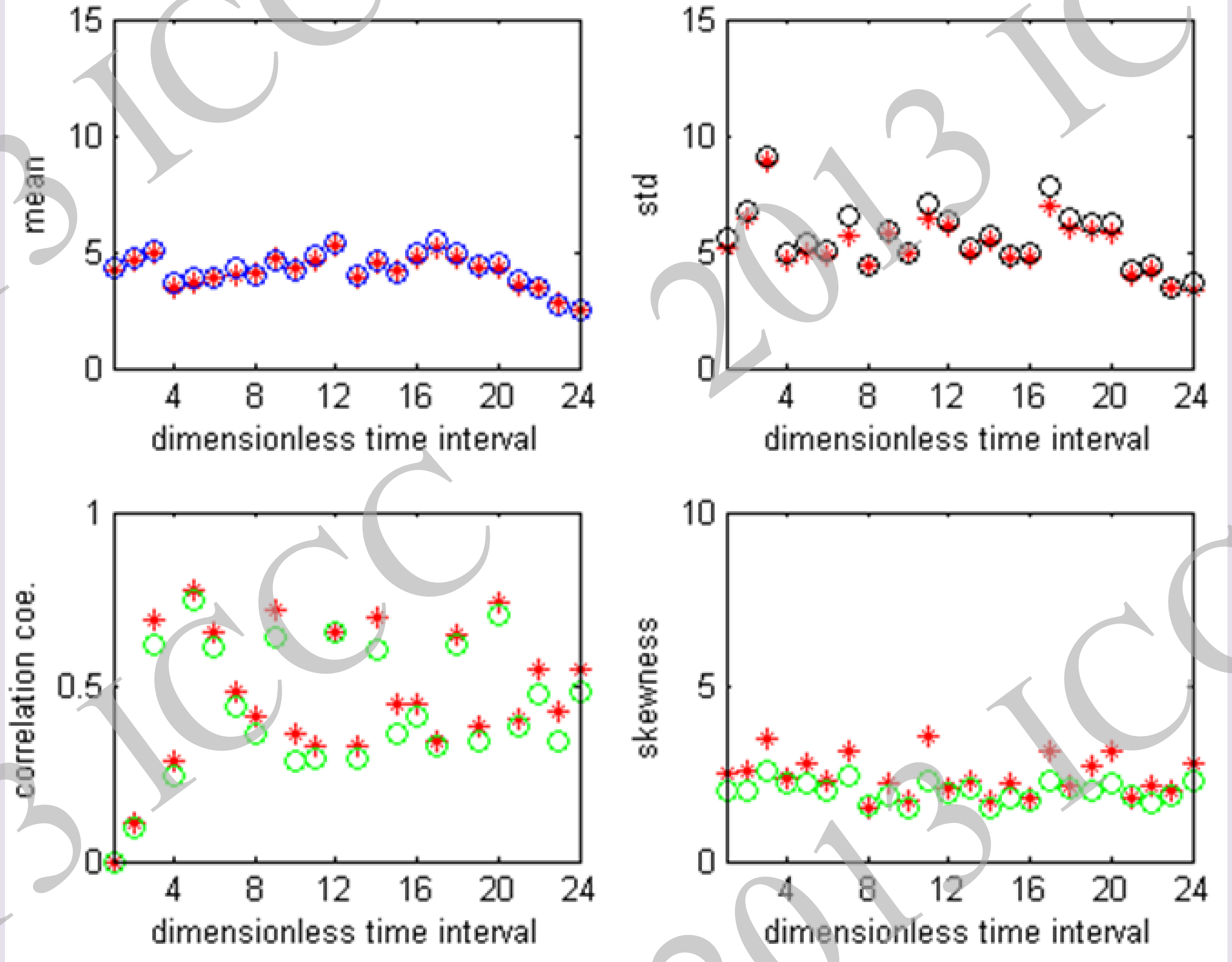
- ***C = - H***

Hyetograph simulation

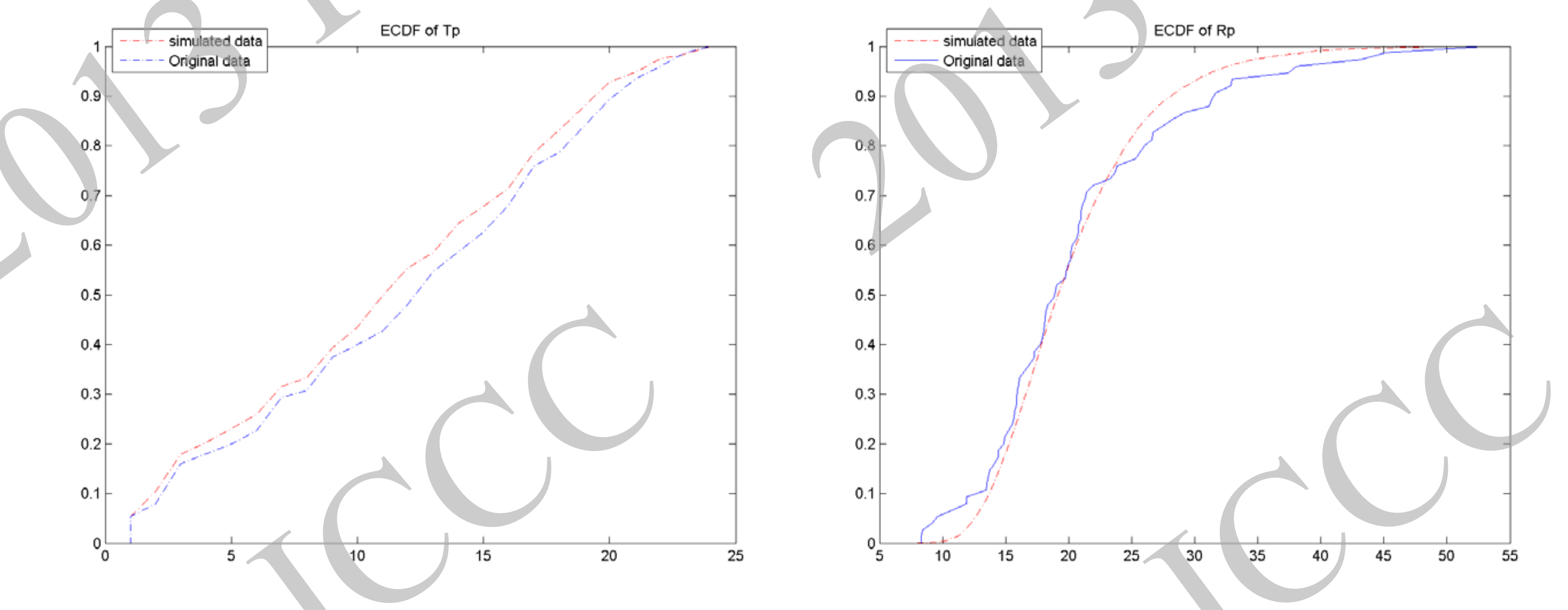
- Rainfall percentage of each individual interval is modeled by a truncated gamma distribution. (Rainfall percentage of each individual interval is bounded from above. For example, peak rainfall percentage is less than 40%.)
- Time-to-peak and peak percentage are simulated firstly.
- Rainfall percentages of neighboring intervals are correlated and can be modeled by a bivariate truncated gamma distribution.
- 1st order Markov process simulation for rainfall percentages of other intervals.
- All rainfall percentages sum to 100%.



Hyetograph Simulation results (Typhoons)



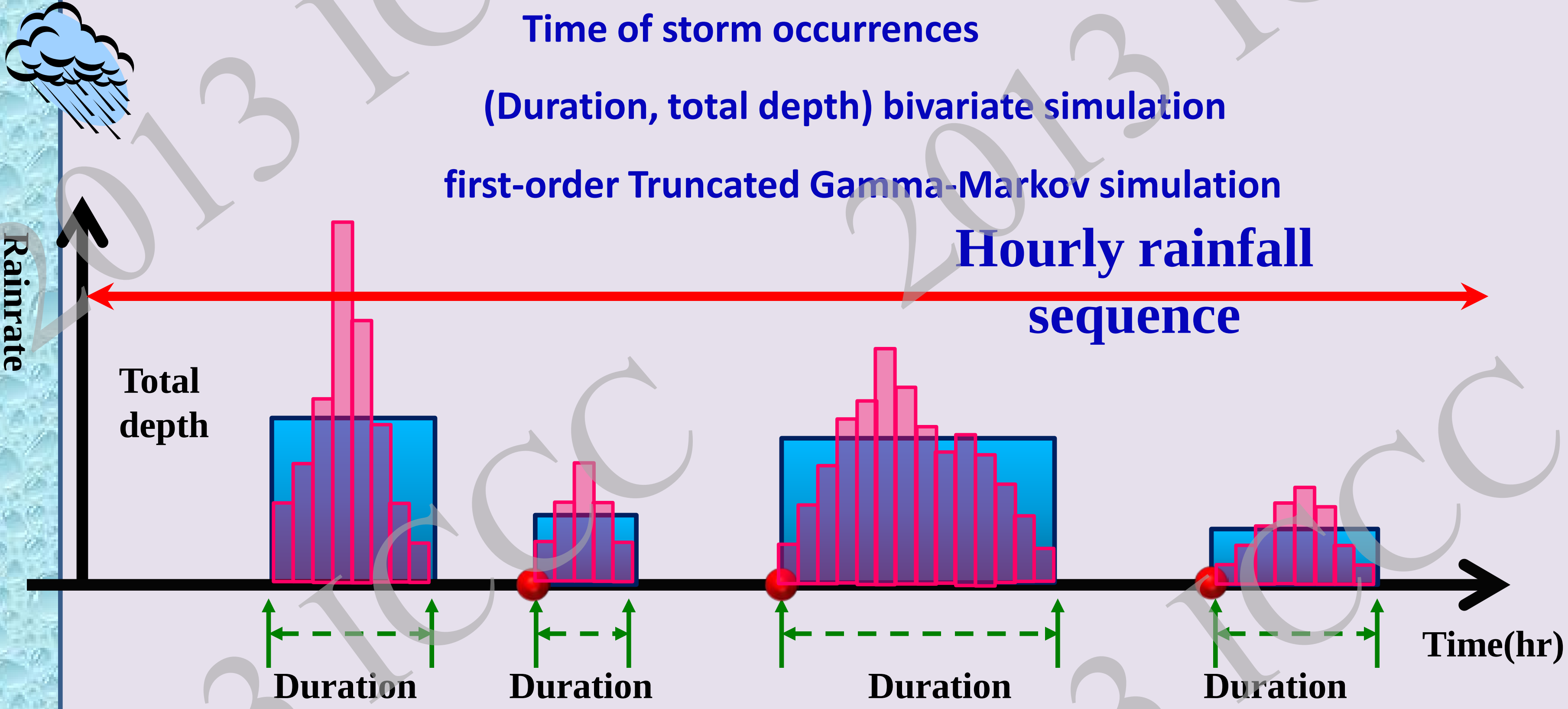
Kaoshiung



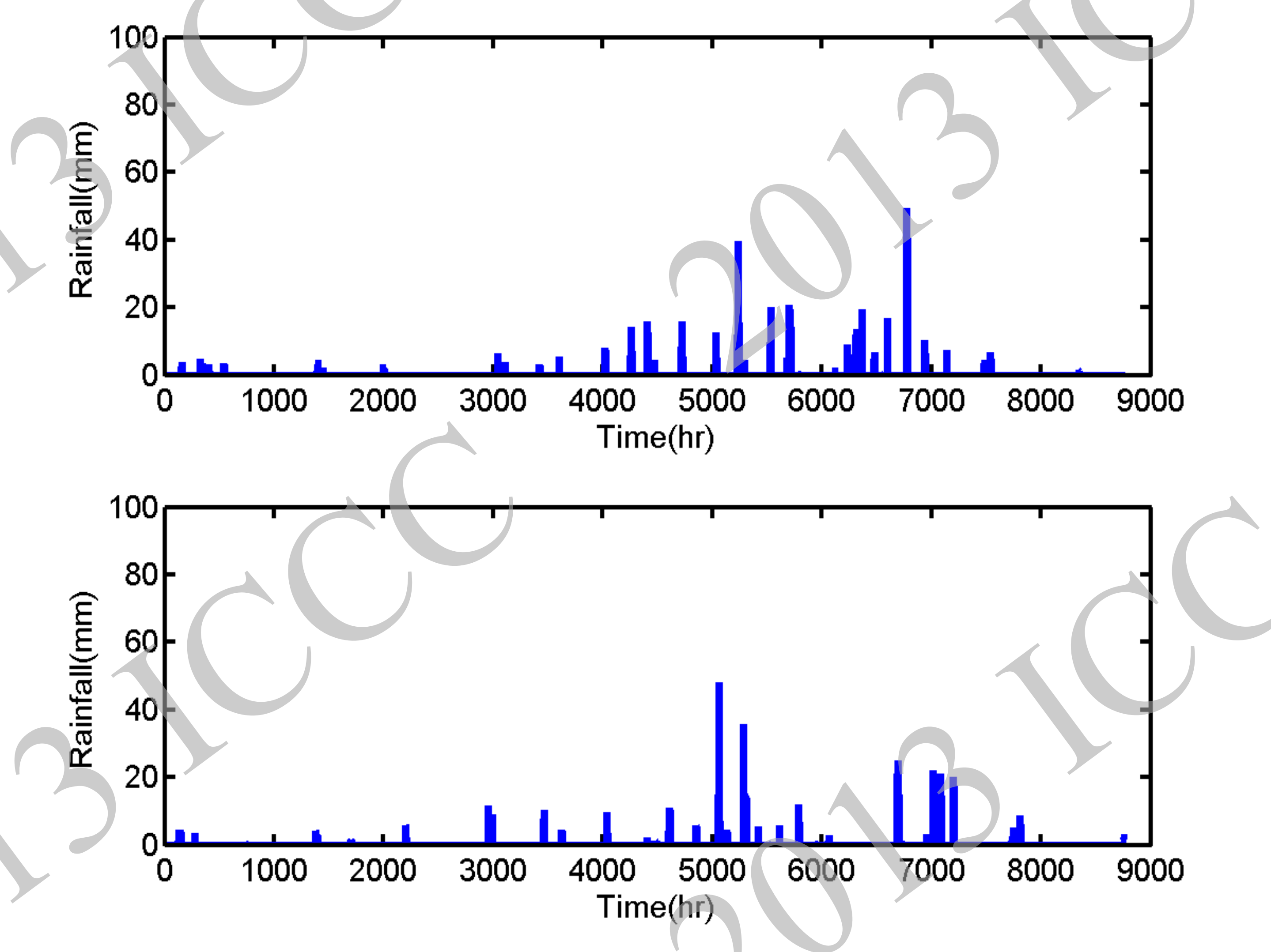
Time-to-peak

Peak rainfall percentage

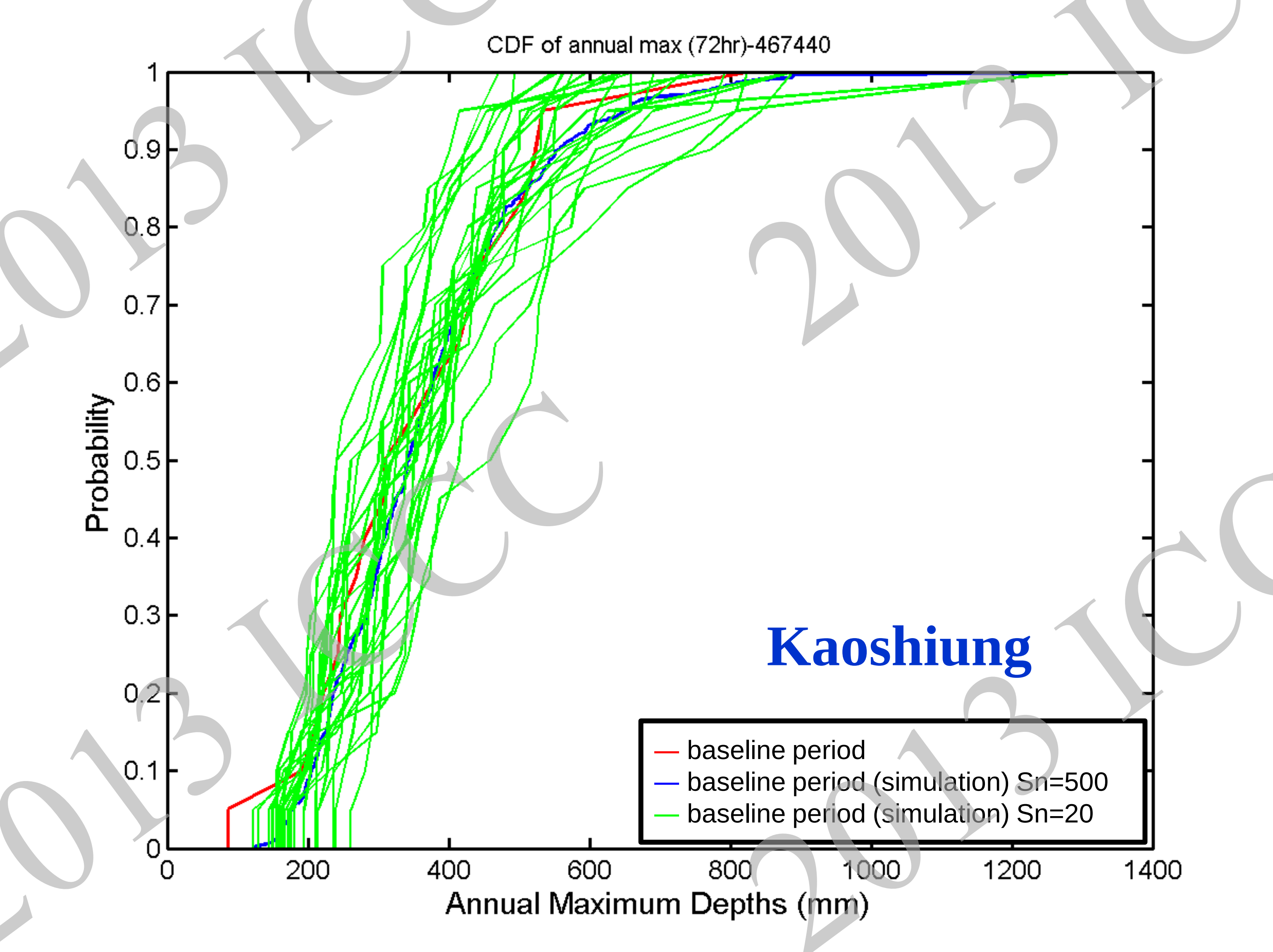
Each simulation run yields an annual sequence of hourly rainfalls. 500 runs were generated for each rainfall station.



Examples of hourly rainfall sequence (Kaoshiung)



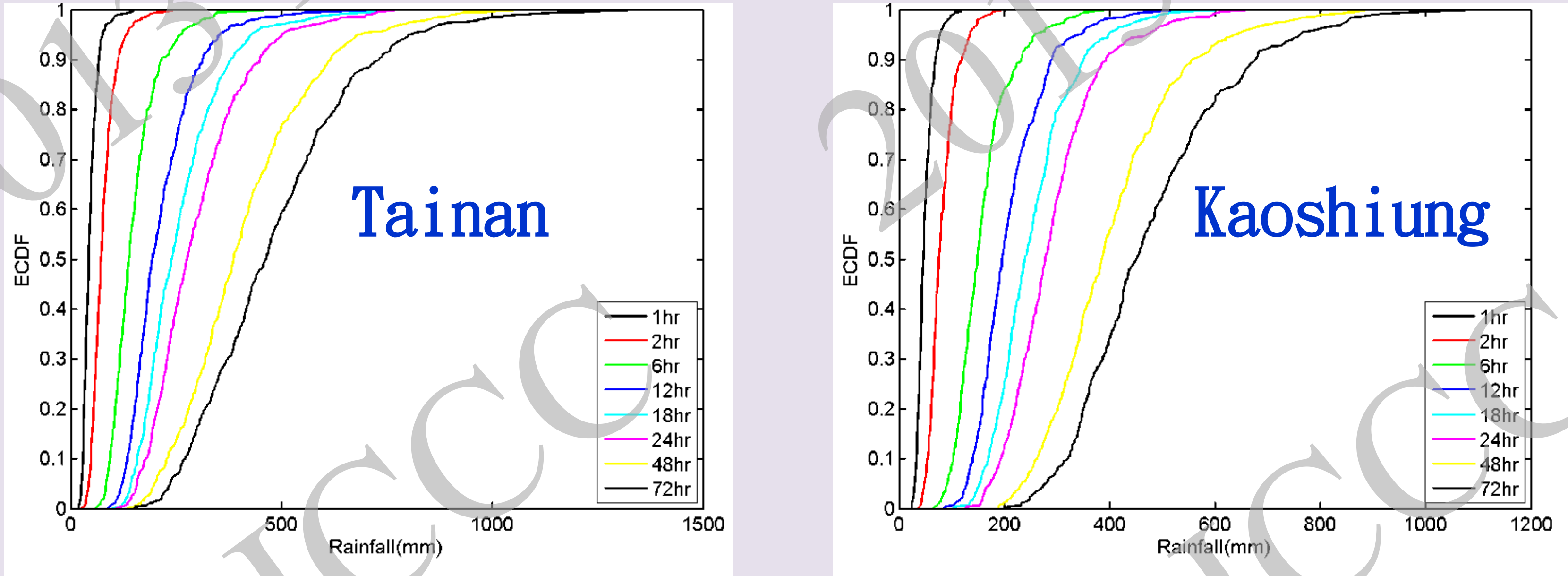
ECDF of Annual Max. Rainfalls
Observed data vs simulated data (25 sets of 20-year period)
(Baseline period: 1980-1999)



Application of simulation results

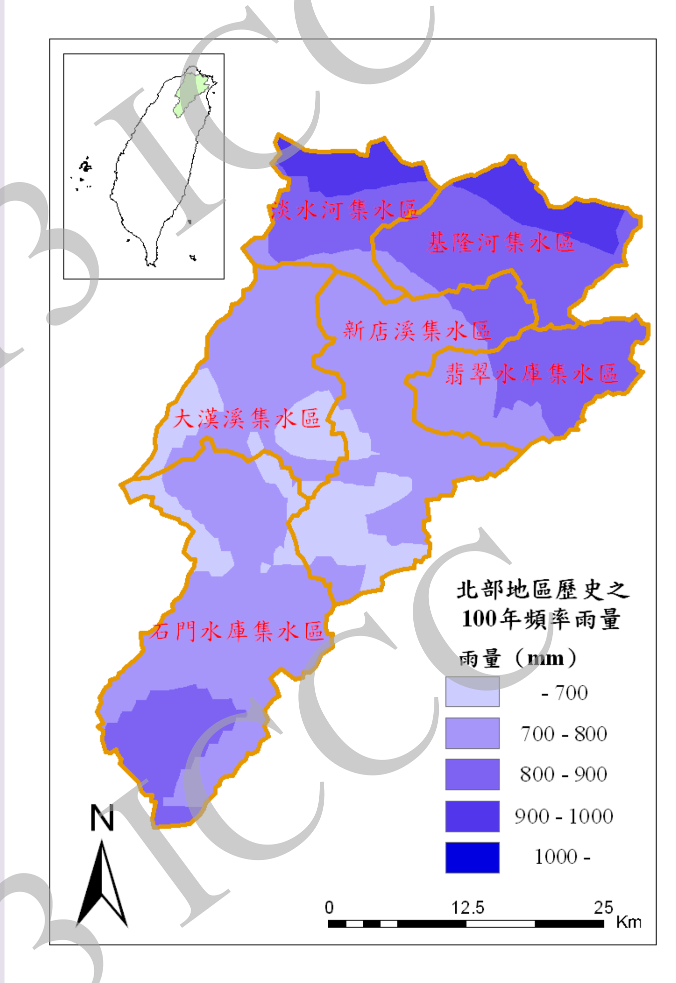
- Extreme rainfall assessment
  - Annual maximum rainfall depth
  - Hydrological frequency analysis
- Seasonal rainfall assessment
  - Water resources management

Impact on design storm depths

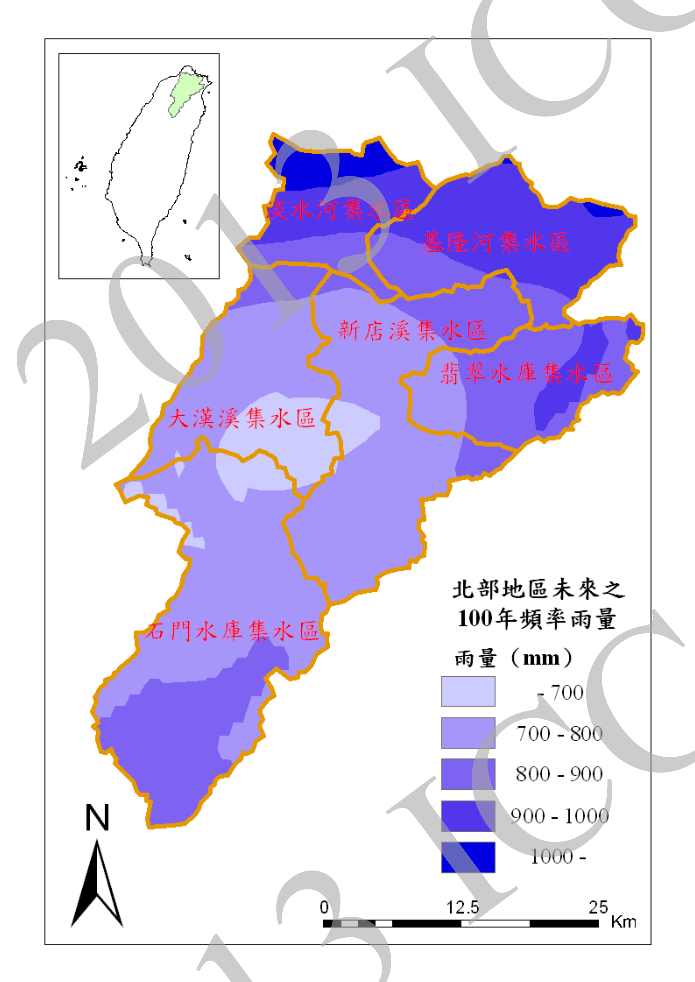


（2020-2039）

Rainfall of 24-hour, 100-year return period (Statistical Downscaling scenario) in Tanshui River Basin



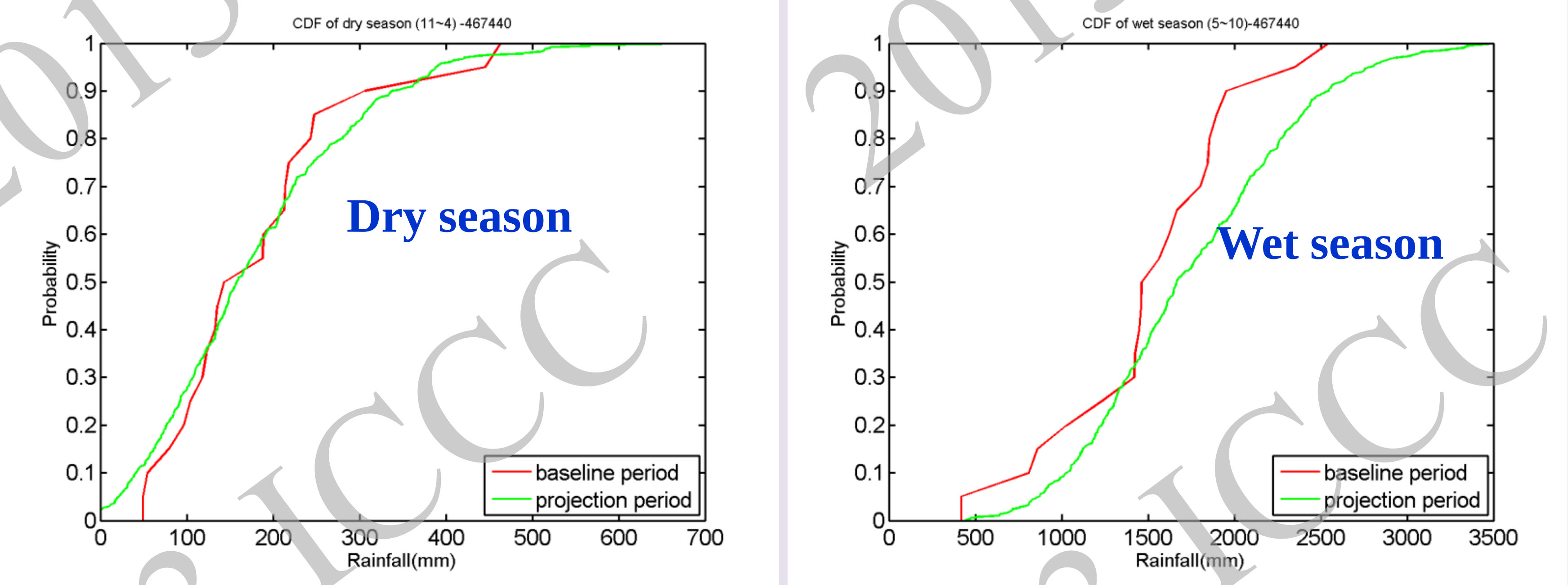
Baseline period
(1980~1999)



Projection period
(2020~2039)

Impact on seasonal rainfalls

Kaoshiung



Conclusions

- **The SSRSM is highly versatile.**
  - Can provide rainfall data of different temporal scales (hourly, daily, TDP, monthly, yearly)
  - Can facilitate the data requirements for various applications (disaster mitigation, water resources management and planning, etc.)
  - Based on assumptions of changes in **storm physical parameters**.

- **Uncertainty is an essential component in all climate change studies.**
- **Scenario setting is crucial and may be mission-oriented.**
- **Be proactive in taking progressive (if possible, no-regret) adaptation measures. Don’t be reactive.**

- # References

Wu, Y.C., Hou, J.C., Liou, J.J., Su, Y.F., Cheng, K.S., 2012. Assessing the impact of climate change on basin-average annual typhoon rainfalls with consideration of multisite correlation. *Paddy and Water Environment*, DOI 10.1007/s10333-011-0271-5.

Liou, J.J. Su, Y.F., Chiang, J.L., Cheng, K.S., 2011. Gamma random field simulation by a covariance matrix transformation method. *Stochastic Environmental Research and Risk Assessment*, 25(2): 235 – 251, DOI: 10.1007/s00477-010-0434-8.

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Acknowledgements

- Financial supports by the National Science Council, Water Resources Agency, Council of Agriculture of Taiwan.
- GCM outputs provided by NCDR, Taiwan.

各氣候模式月降雨量變化量結果評估

- 評估準則

  挑選模擬東亞季風較佳的GCM模式

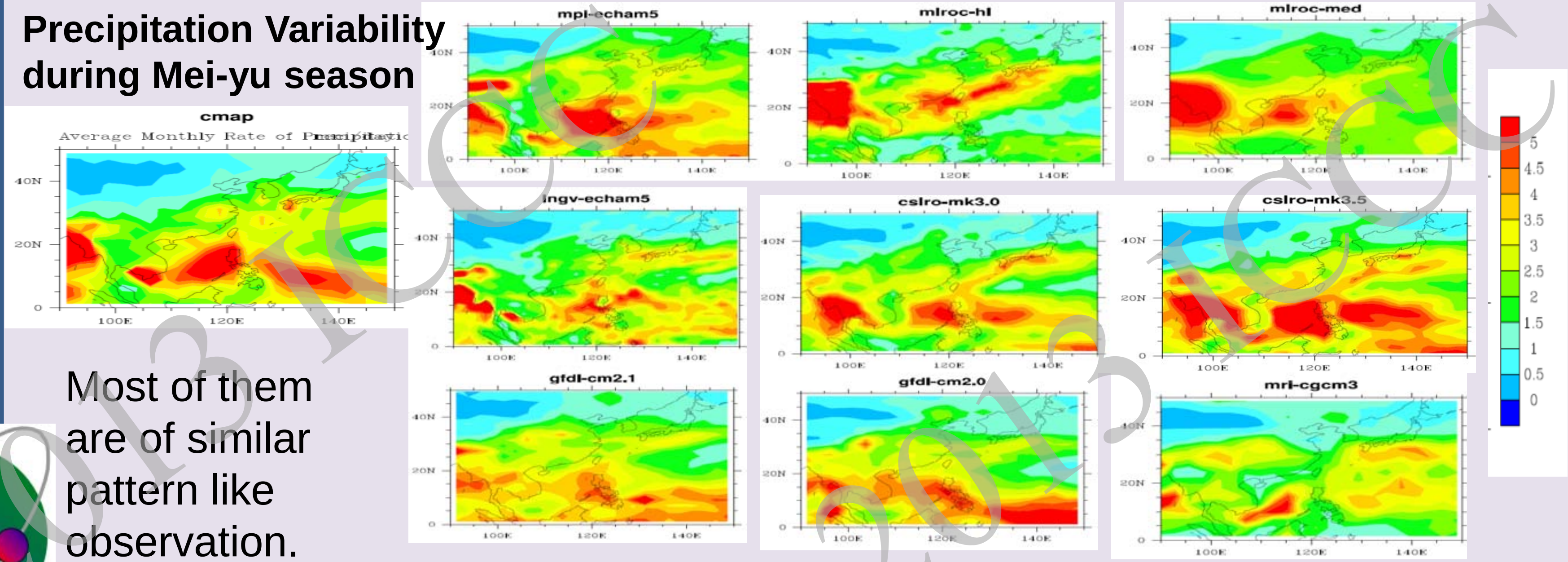
  依據豐枯水期降雨改變率變化挑選GCM模式

方法I：依據東亞季風表現挑選GCM模式

Source: NCDR TCCIP Project

Mean precipitation of MJ	**Mean temperature of JAS**	**Temperature Variability during MJ season**
Mean temperature of MJ	Mean MSLP of JAS	Temperature Variability during JAS season
Mean MSLP of MJ	Precipitation Variability during MJ season	Monthly average rainfall distribution through latitude (25N-40N)averaged over (100-160E)
Mean precipitation of JAS	Precipitation Variability during JAS season	

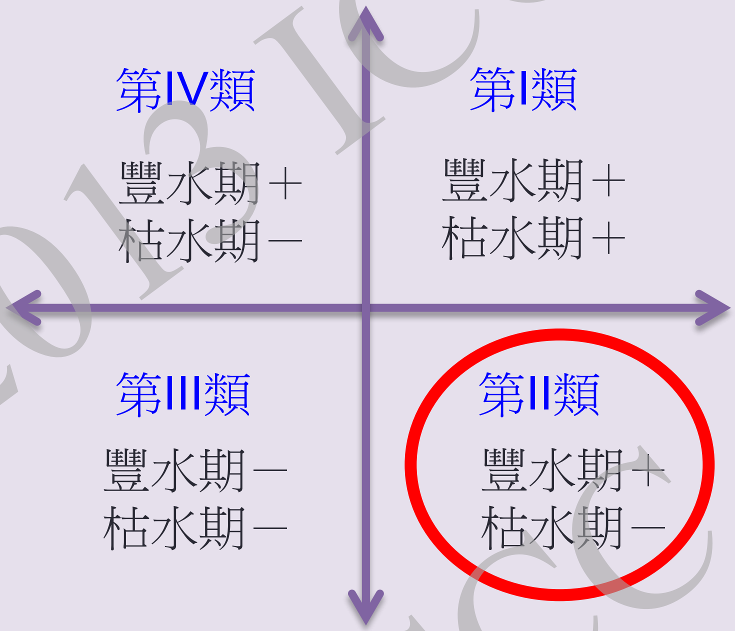
Precipitation Variability during Mei-yu season



Most of them are of similar pattern like observation.

方法II：依據豐枯水期降雨變化挑選模式

Source: NCDR TCCIP Project

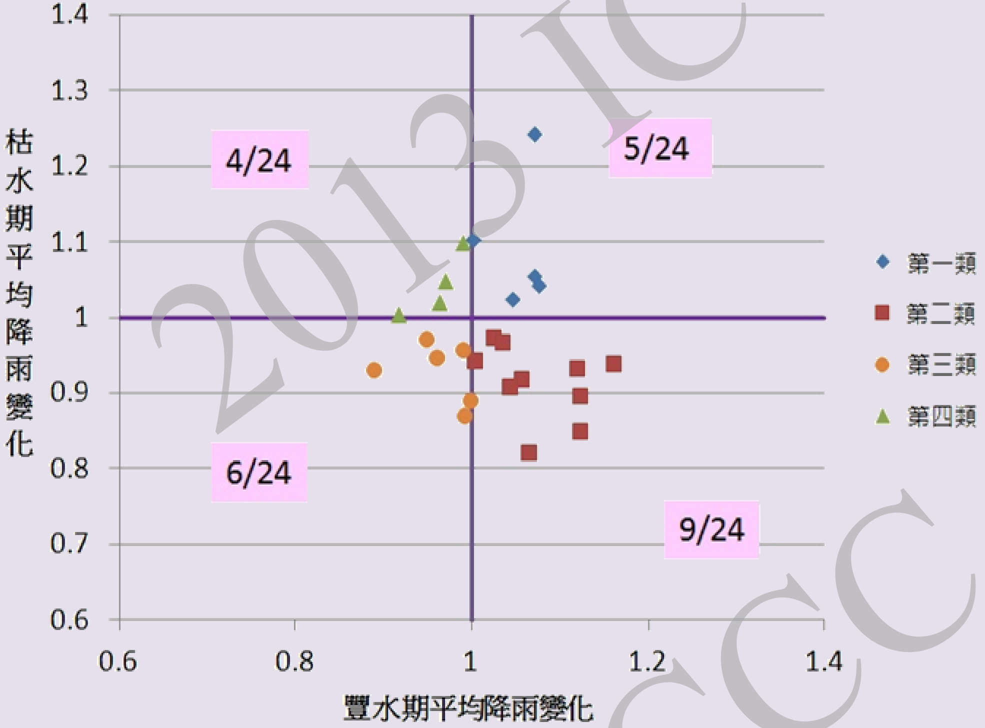


第IV類
豐水期＋
枯水期－

第I類
豐水期＋
枯水期＋

第III類
豐水期－
枯水期－

第II類
豐水期＋
枯水期－



挑選結果：同屬於第二類的GCM模式(9個)

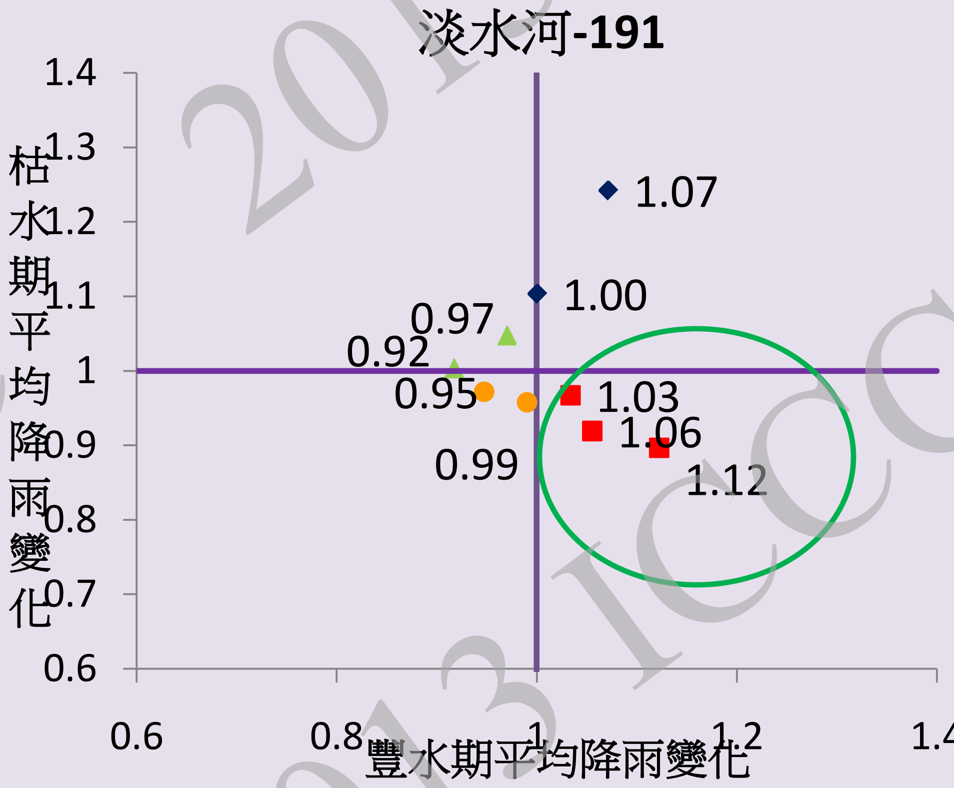
1.bccr_bcm2_0
2.cccma_cgcm3_1
3.csiro_mk3_5
4.iap_fgoals1_0
5.ingv_echam4
6.inmcm3_0
7.ipsl_cm4
8.mri_cgcm2_3_2a
9.ukmo_hadgem1

符合兩種評估準則之GCM模式

依東亞季風表現挑選GCM模式

-a1b_2020-2039_csiro_mk3_0	1.07	1.24	1
-a1b_2020-2039_gfdl_cm2_0	1.00	1.10	1
-a1b_2020-2039_csiro_mk3_5	1.06	0.92	2
-a1b_2020-2039_ingv_echam4	1.03	0.97	2
-a1b_2020-2039_mri_cgcm2_3_2a	1.12	0.90	2
-a1b_2020-2039_miroc3_2_hires	0.99	0.96	3
-a1b_2020-2039_miroc3_2_medres	0.95	0.97	3
-a1b_2020-2039_gfdl_cm2_1	0.92	1.00	4
-a1b_2020-2039_mpi_echam5	0.97	1.05	4

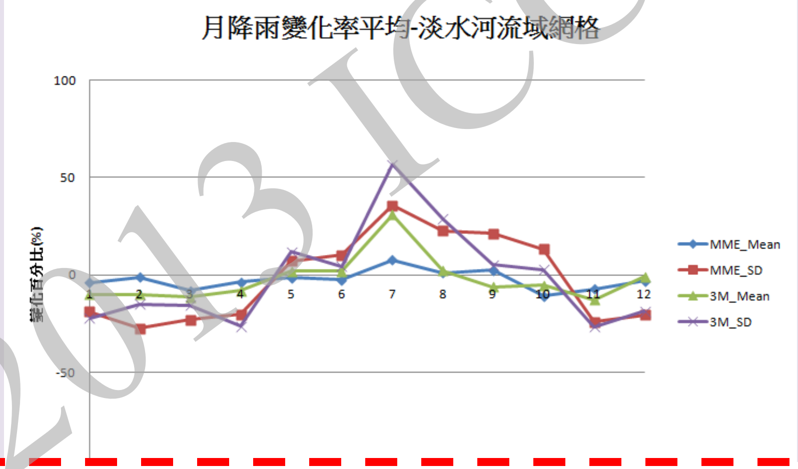
依豐枯水期降雨變化挑選模式

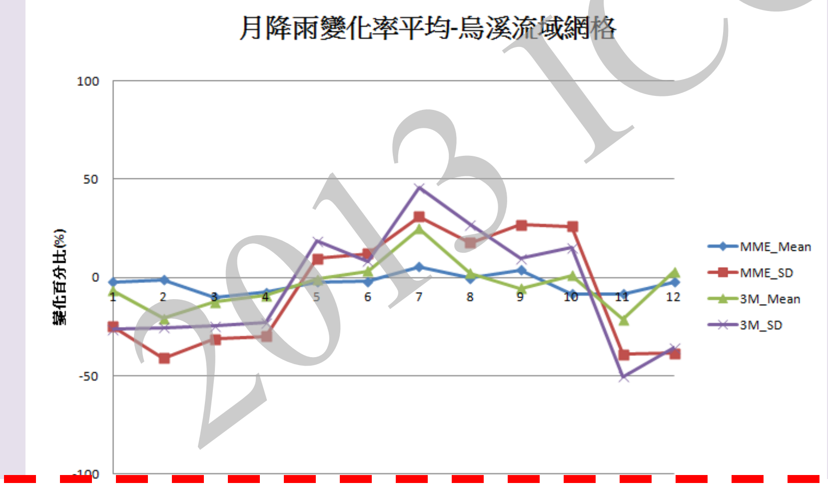


水文氣象情境設定評估

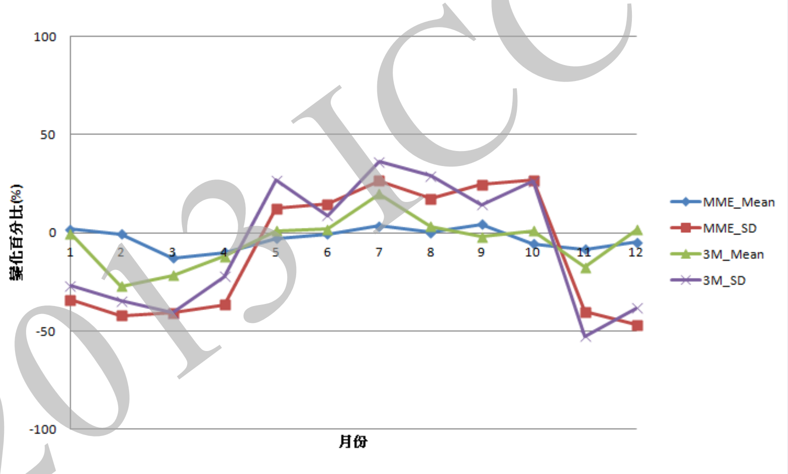
- MME_Mean：A1B情境下24個GCMs的系集平均值。
- MME_SD：24個GCMs的平均值依豐枯水期加減一倍標準偏差。
- 3M_Mean：3個較適合台灣GCMs(csiro_mk3_5, ingv_echam, mri_cgcm2_3_2a)的平均值。
- 3M_SD：將3個較適合台灣GCM的平均值依豐枯水期加減一倍標準偏差。

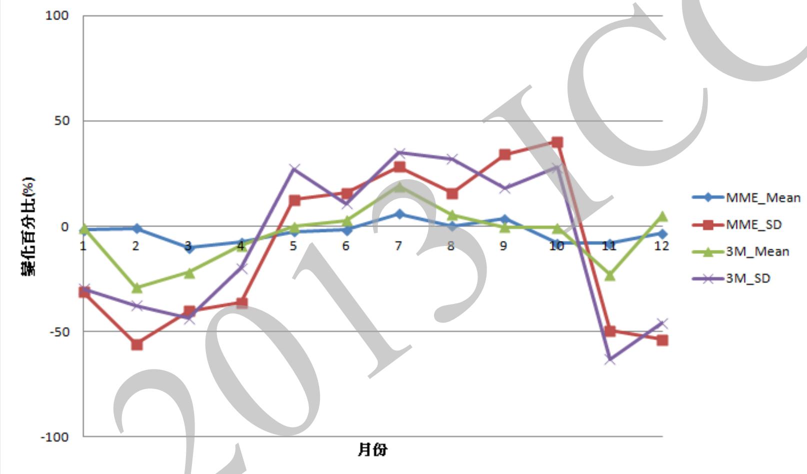
月降雨量變化率情境設定


月降雨變化率平均-淡水河流域網格

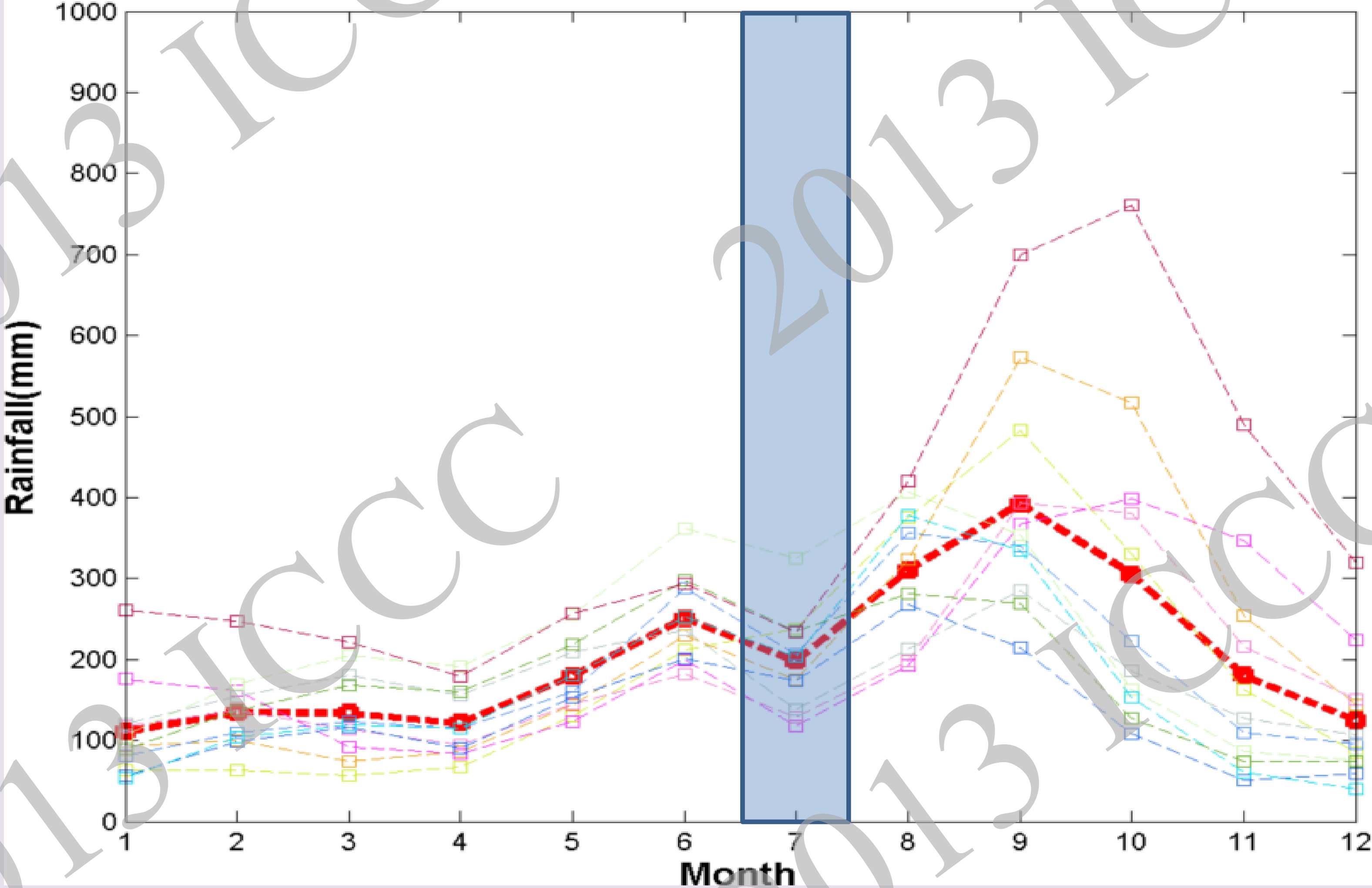

月降雨變化率平均-烏溪流域網格

使用「24個GCM模式月雨量變化率之平均值依豐枯水期加減一倍標準差」做為本計畫之變遷情境。

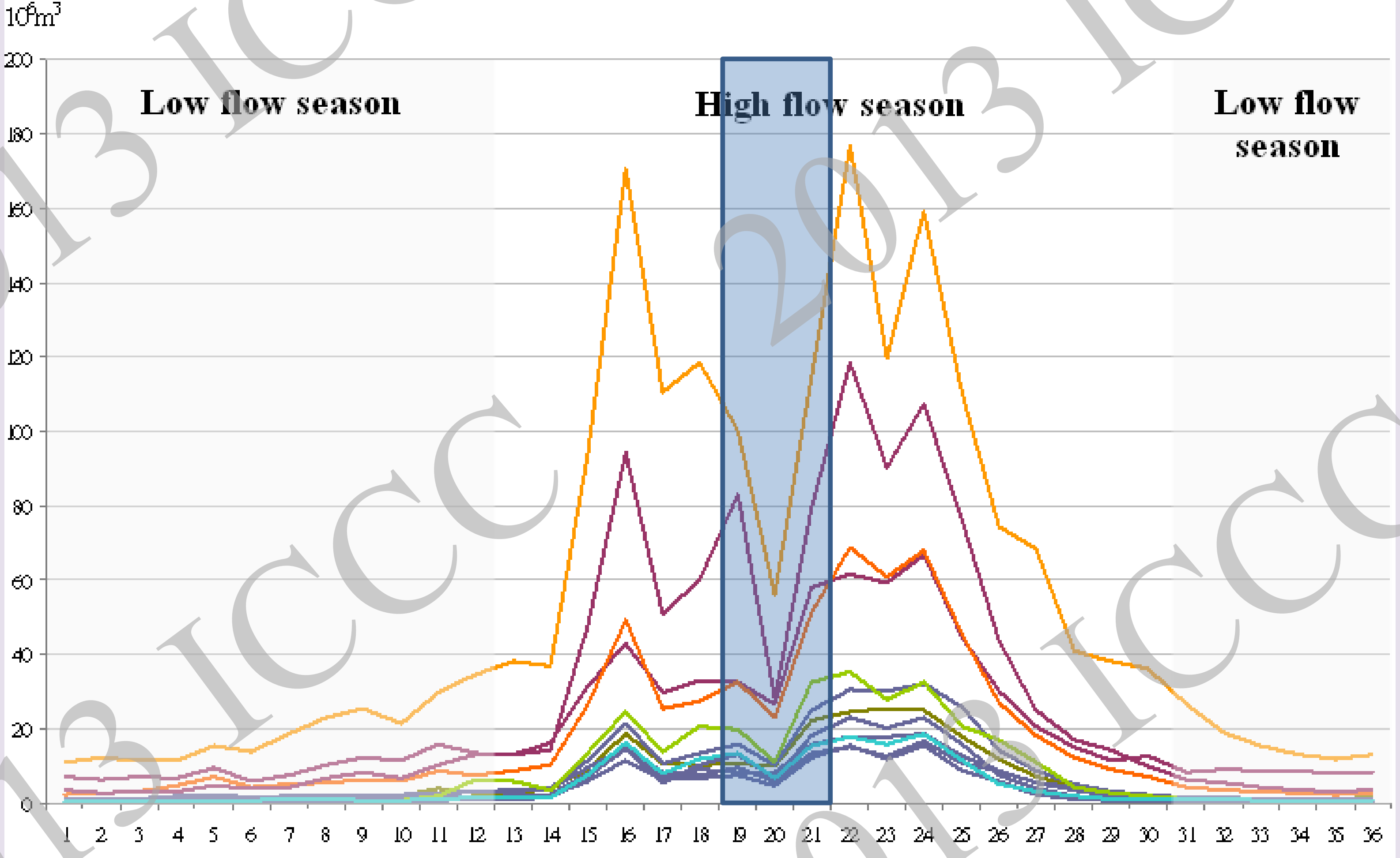




Temporal variation of monthly rainfalls (Dan-Shuei River Watershed)



Temporal variation of TDP flows (Southern Taiwan)



Seasonal variation of TDP flows at different flow stations.