

Program of the AWCI training course for the Climate Change Assessment and Adaptation Study

1. Overview of Climate Change Impact Assessment on Water Resources

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Contents

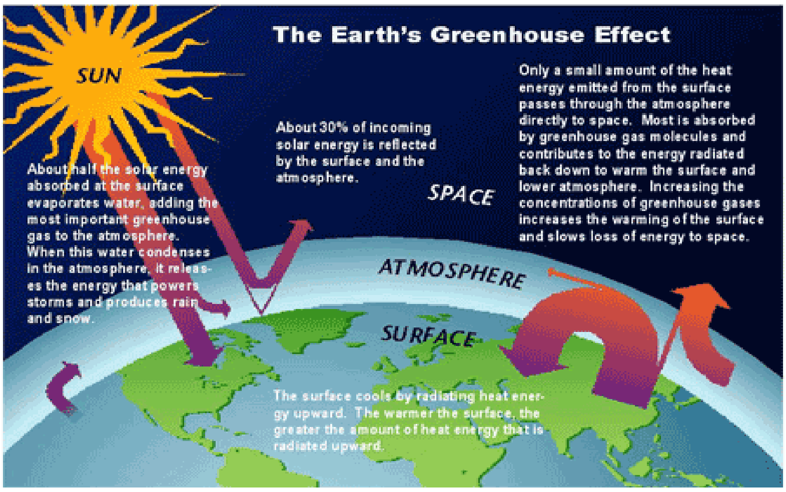
- eneral approaches for climate change impact assessment
- ncertainties of climate change impact assessment
- ME-based climate change impact assessment
- oncluding remarks

General Approaches for Climate Change Impact Assessment

The Climate System

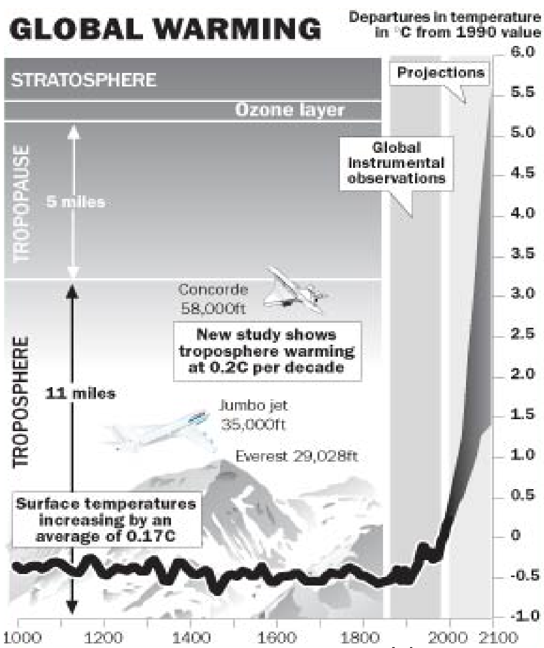
- **The climate is the "average weather" (it is a statistical description of weather, including variability and extremes as well as averages)**
- **The Earth's climate results from interactions between many processes in the various components of the climate system:**

- **The atmosphere**
- **The ocean**
- **The land surface,**
- **The biosphere**
- **an anthropogenic system, (human activities)**



Climate Change ?

- **Refers to statistically significant variations that persist for an extended period, typically decades or longer**
- **Slow continuous rise in global mean surface temperature**
- **The mean annual global surface temperature has increased by about 0.3 - 0.6℃ since the late 19th century**
- **It is anticipated to further increase by 1.4 – 4.0 ℃ in this century (IPCC, 2007)**



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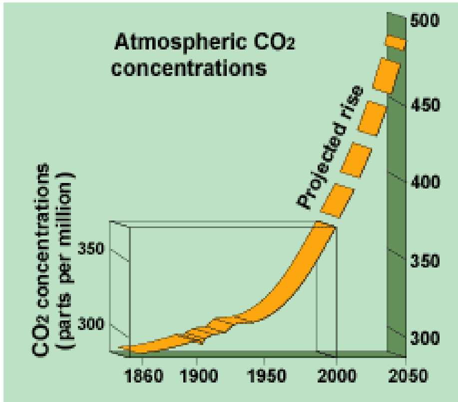
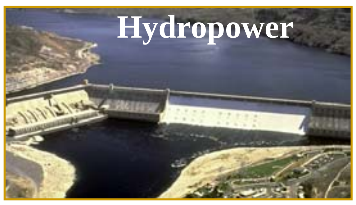
Cause of Climate Change

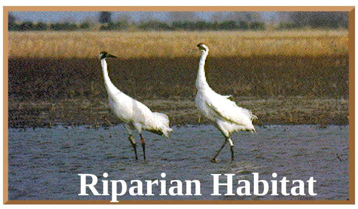
- **Emission of greenhouse gases and aerosols and their increasing concentration in the atmosphere**
- **Carbon dioxide (CO_2) and methane (CH_4) are the most important radiative forcings by greenhouse gases emitted through human activity**
- **The increase in atmospheric CO_2:**
  - fossil-fuel burning and land use change including deforestation
- **The increase in CH_4:- emissions from energy use, livestock, rice agriculture and landfill**



Hydrologic Impacts of Climate Change

- **Changes in global climate will have significant impacts on local hydrological regimes**
  - **Changes in stream flows**
  - **Significant change in the frequency and severity of floods and droughts**

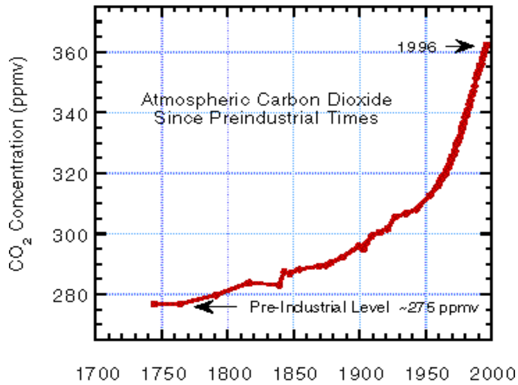


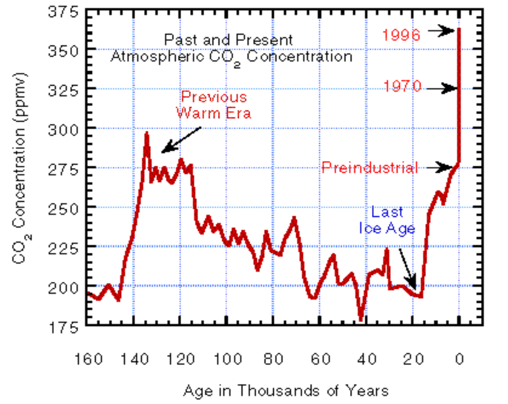


- **Need to be taken into consideration by policy and decision makers when managing water recourses and making plans for the future**

Chronicle of Climate Change and Their Impact Analysis on Water Resources

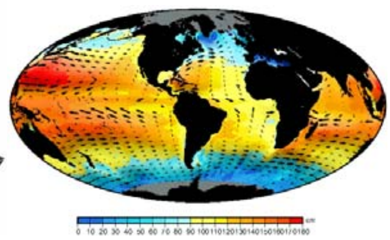
- **1985 : Global warming ?**
- **1995 : Is global warming real ?**
- **~1997 : What are the expected impacts of climate change for our region and our water system ?**
- **~2004 : How do we include climate change and climate uncertainty in long-term planning to reduce risks ?**





Approaches for Climate Change and Water Resources Study

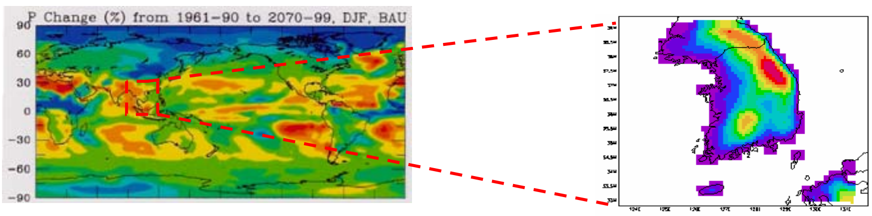
- **GCMs [Global Climate Models]**
  - **GCMs are computer modeling tools for understanding the global climate system and for projecting the effects of changing conditions forward in time.**
  - **The 3-D model formulation is based on the fundamental laws of physics consisting of:**
    - **conservation of energy;**
    - **conservation of momentum;**
    - **conservation of mass; and**
    - **the Ideal Gas Law.**



- **Why GCMs ?**
  - **GCMs simulate the radiative balance of the atmosphere in great detail by human activities, account for complex interactions between the atmosphere and oceans, and are capable of simulating the broad features of atmospheric and oceanic circulation that ultimately determine regional climate.**

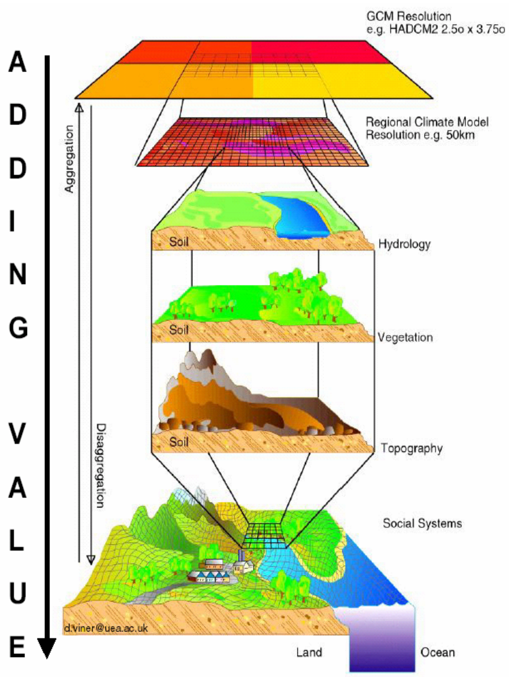
Limitation of GCMs

- Climate models **simplify** what is **a very complex climate system**
  - limited understanding of the climate system
  - computational constraints
- Typical horizontal grid resolution of **2° to 4°** latitude and longitude,
- Limited spatial resolution in the vertical dimension (with **10 to 20 layers** in the vertical)
- GCMs are unable to represent **local subgrid-scale features and dynamics**, such as:
  - **local topographical features** and **Convective cloud processes**
- GCMs does not give a good estimation of **hydrological responses to climate change**



Downscaling GCM outputs

- Downscaling is **a means of relating the large scale atmospheric predictor variables to local or station-scale meteorological series** that can be used as input to hydrological models
- Downscaling techniques are used to **convert GCM outputs into local meteorological variables** that are required for reliable hydrological modeling

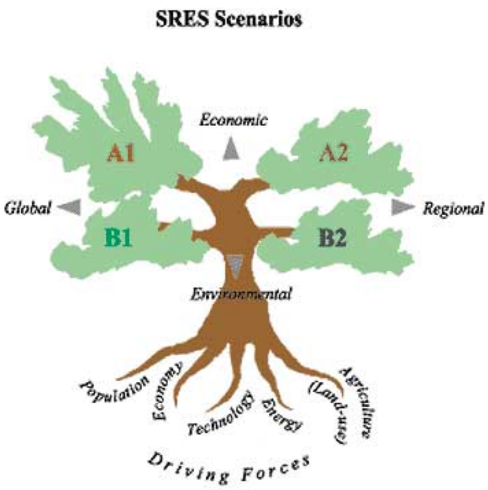


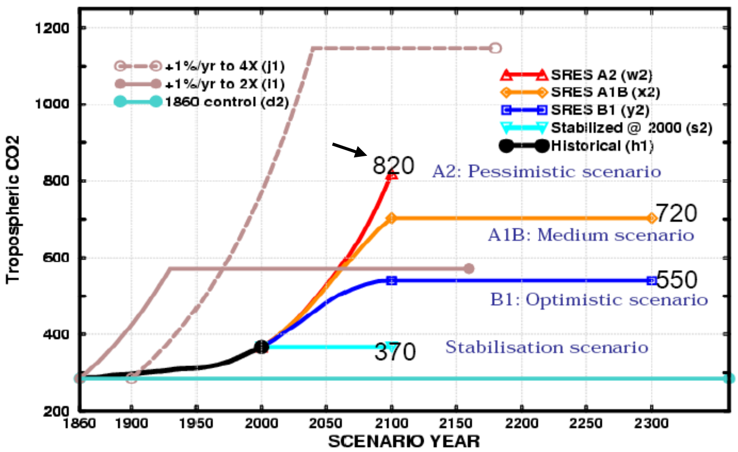
Consideration of Climate Change Impact Assessment on Water Resources

- **Choice of greenhouse gas emission scenario**
- **Choice of GCMs Model & Climate scenario development**
- **Choice of Downscaling method**
- **Uncertainty of Runoff model**
- **Uncertainties Assessment**
- **Data generation period**

Greenhouse Gas Emission Scenarios

- **Special Report on Emission Scenario (SRES)**
  - **The SRES scenarios were used for the AR4 (4th Assessment Reports) in 2007, and have been subject to discussion about whether emissions growth since 2000 makes these scenarios obsolete.**

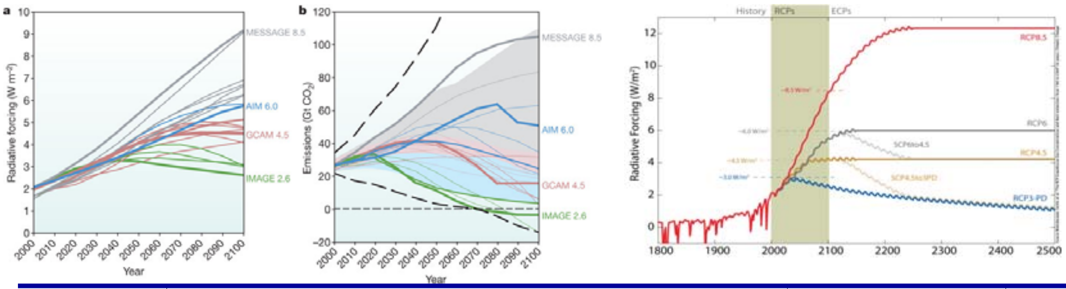




➢ CMIP5 (Coupled Model Intercomparison Project 5)

- **The purpose of CMIP5 experiments is to address outstanding scientific questions that arose as part of the IPCC AR4 process, improve understanding of climate, and to provide estimates of future climate change that will be useful to those considering its possible consequences.**

➢ Representative Concentration Pathways (RCPs)



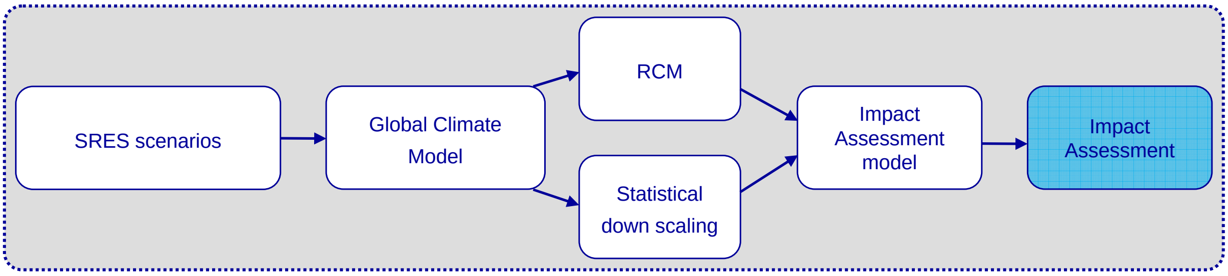
Name	Description	Shape of Pathway	Comparing with SRES
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	Rising	A2~A1FI
RCP6	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100	Stabilization	A1B
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100	Stabilization	B1
RCP3-PD	Peak in radiative forcing at ~ 3 W/m^2 before 2100 and Decline	Peak, decline	-

Global Climate Models

No.	ID	Model (agency: version)	Country	Resolution	
				Atm.	Ocn.
1	a	BCC: CM1	China	128X96	128X96
2	b	BCCR: BCM2	Norway	128X64	360X180
3	c	CCCMA: CGCM3_1-T47	Canada	96X48	192X96
4	d	CCCMA: CGCM3_1-T63	Canada	128X64	256X192
5	e	CNRM: CM3	France	128X64	180X170
6	f	CSIRO: MK3	Australia	192X96	192X189
7	g	GFDL: CM2	USA	144X90	360X200
8	h	GFDL: CM2_1	USA	144X90	360X200
9	i	NASA: GISS-AOM	USA	90X60	90X60
10	j	NASA: GISS-EH	USA	72X46	360X180
11	k	NASA: GISS-ER	USA	72X46	72X46
12	l	LASG: GFOALS-G1_0	China	128X60	360X170
13	m	INM: CM3	Russia	72X45	144X84
14	n	IPSL: CM4	France	96X72	180X170
15	p	NIES: MIROC3_2_HI	Japan	320X160	320X320
16	q	NIES: MIROC3_2_MED	Japan	128X64	256X192
17	r	CONS: ECHO-G	Germany/Korea	96X48	128X117
18	s	MPIM: ECHAM5	Germany	192X96	360X180
19	t	MRI: CGCM2_3_2	Japan	128X64	144X111
20	u	NCAR: CCSM3	USA	256X128	320X395
21	v	NCAR: PCM	USA	128X64	360X180
22	w	UKMO: HADCM3	UK	96X73	288X144
23	x	UKMO: HADGEM1	UK	192X144	360X216

Uncertainties of Climate Change Impact Assessment on Water Resources

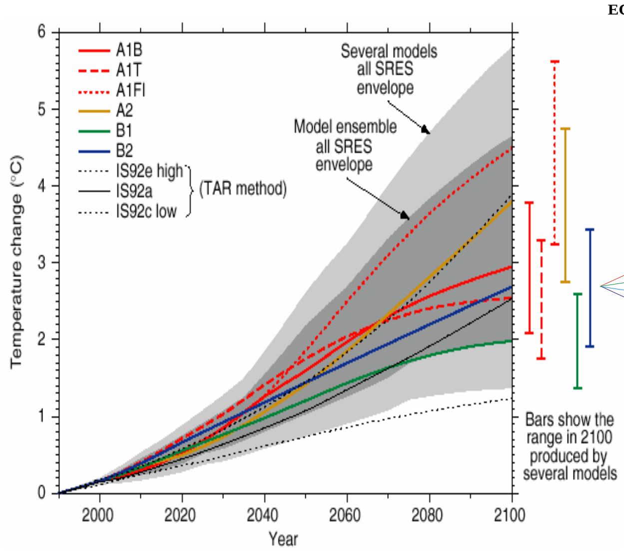
- **Uncertainties of SRES scenario**
- **Uncertainties of GCMs**
- **Uncertainties of downscaling**
- **Uncertainties of Impact assessment model**

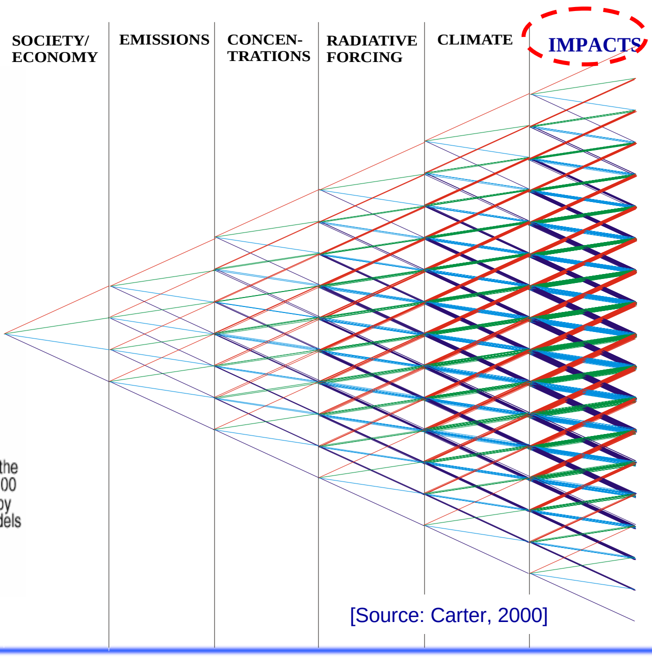


General Processing of climate change impact assessment on water resources

Uncertainties of Climate Scenarios

- **There are a great many sources of uncertainty inherent in the modeling and prediction of a complex process**





[Source: Carter, 2000]

Uncertainties of Climate Change Impact Assessment

The Necessity of the Study

- **The reliability of hydrologic projections obtained from only one hydrological application for the climate change impact assessment on water resources is not quantified.**
- **Quantifying the uncertainties existing within the whole process is difficult.**
- **The public decision maker rarely reflect the results of climate change impacts assessment on water resources due to the existence of various uncertainties with in there.**

The objective of the Study

- **Quantify the magnitudes of uncertainties existing the process.**

Scenario & GCM

- Used IPCC AR4 13 out of 23 GCMs simulation
- Data period : 200yr (1900-2099)
- IPCC SRES A2, A1B, B1
- Variables : precipitation, temperature, humidity et al.
- Data storage : approximately 1tera bite

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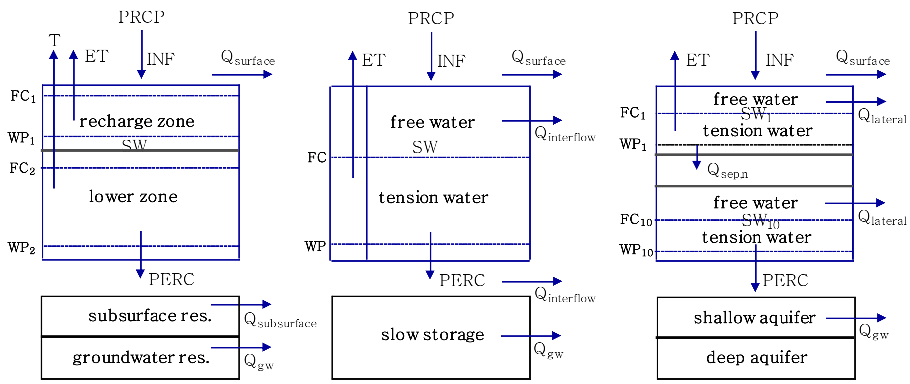
Weather Generator – WXGEN

- WXGEN (Sharply and Williams, 1990), a well-known and popularly used weather generator for climate study
- Daily precipitation, maximum temperature and minimum temperature, relative humidity, wind speed

Weather status	WXGEN (Sharpley & Williams, 1990)
Precipitation status	
Definition of wet day	Precipitation > 0mm
Determination of precip. status a given day	Transition probabilities of a first-order Markov chain applied to the previous day's status
Precipitation	
Daily distribution	Skewed distribution
parameters	Separate parameters are calculated for each month
Correlation	None.
Max. & Min. temperature	
Daily distribution	Normal distribution
Parameters	Mean and standard deviation of the normal vary daily
Conditioned on precip.	Yes
Correlation	Constant lag auto-correlation Constant cross-correlation between Tmax, Tmin, and radiation
Radiation	
Daily distribution	Normal distribution
Parameters	Mean and standard deviation of the normal vary daily
Wind & Relative humidity	
Daily distribution	Normal distribution
Parameters	Mean and standard deviation of the normal vary daily

Hydrological Models – 8 case

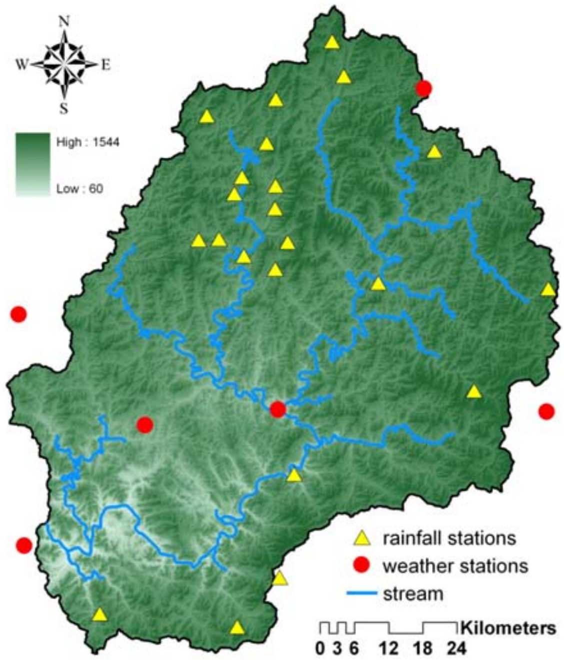


PRMS SLURP SWAT

Model	Evapo-transpiration	Snowmelt	No. of soil zones	Runoff components	Routing	Members
PRMS	Hamon Jensen-Haise	energy balance method	2	surface flow subsurface flow groundwater	None	PR-HA PR-JH
SWAT	Penman-Monteith Priestley-Tayor Hargreaves	degree-day method	2	surface flow Interflow groundwater	Muskingum	SW-PM SW-PT SW-HG
SLURP	Penman-Monteith* Granger * Spittlehouse/ Black *	modified degree-day method	1-6	surface flow subsurface flow groundwater	Muskingum	SL-PM SL-GR SL-SB

Study Area

- **Area : 6,661.0 km2**
- **Major multi - purpose dam**
- **Annual precipitation ranges from 800 to 1800 mm**
- **Annual mean runoff coefficient is approximately 60%**
- **Snowmelt will be one of main sources in the early spring discharge regime of the area.**



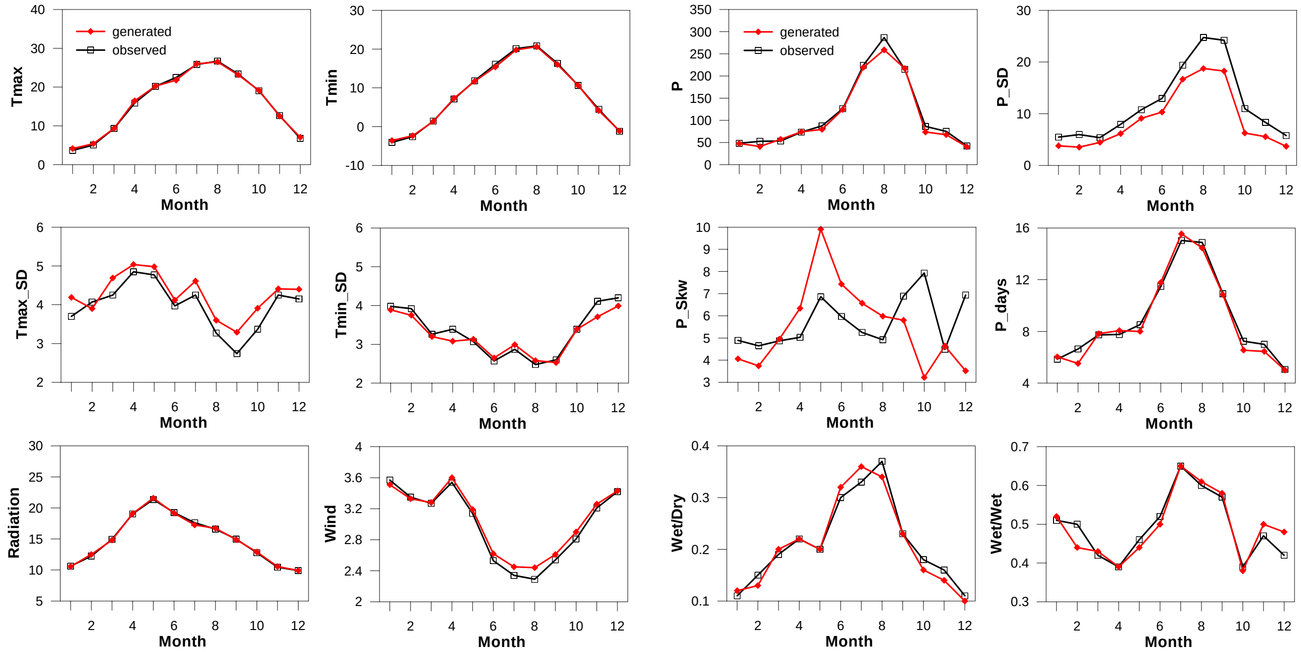
Hydrological Model Performance

- **Calibration period : 1996 – 2005**
- **Verification period : 1986 – 1995**
- **Before the selected hydrological models are used for hydrological uncertainty analysis of climate change impact assessment, they are calibrated and verified their performances**

Model	Calibration period				Verification period				Total period			
	r	RMS	NSE	VE	r	RMS	NSE	VE	r	RMS	NSE	VE
PRMS-HA	0.90	2.29	0.80	4,28	0.85	3.70	0.72	-2.79	0.87	2.91	0.76	2.20
PRMS-JH	0.91	2.31	0.80	3.01	0.87	3.15	0.74	-1.70	0.88	2.76	0.77	1.04
SWAT-PM	0.93	2.44	0.86	-0.39	0.87	3.40	0.76	5.52	0.90	2.96	0.81	2.53
SWAT-PT	0.93	2.47	0.85	-1.46	0.87	3.45	0.76	5.02	0.90	3.01	0.80	2.50
SWAT-HG	0.92	2.50	0.84	-2.50	0.86	3.51	0.74	4.89	0.88	3.22	0.79	2.15
SLUR_PM	0.92	2.74	0.83	-1.96	0.86	3.49	0.75	3.14	0.89	3.14	0.78	0.55
SLUR_MC	0.90	2.81	0.81	-2.40	0.85	3.66	0.74	1.79	0.87	3.27	0.77	-0.49
SLUR_GR	0.90	2.90	0.80	-3.50	0.84	3.70	0.73	0.60	0.87	3.34	0.76	-1.15

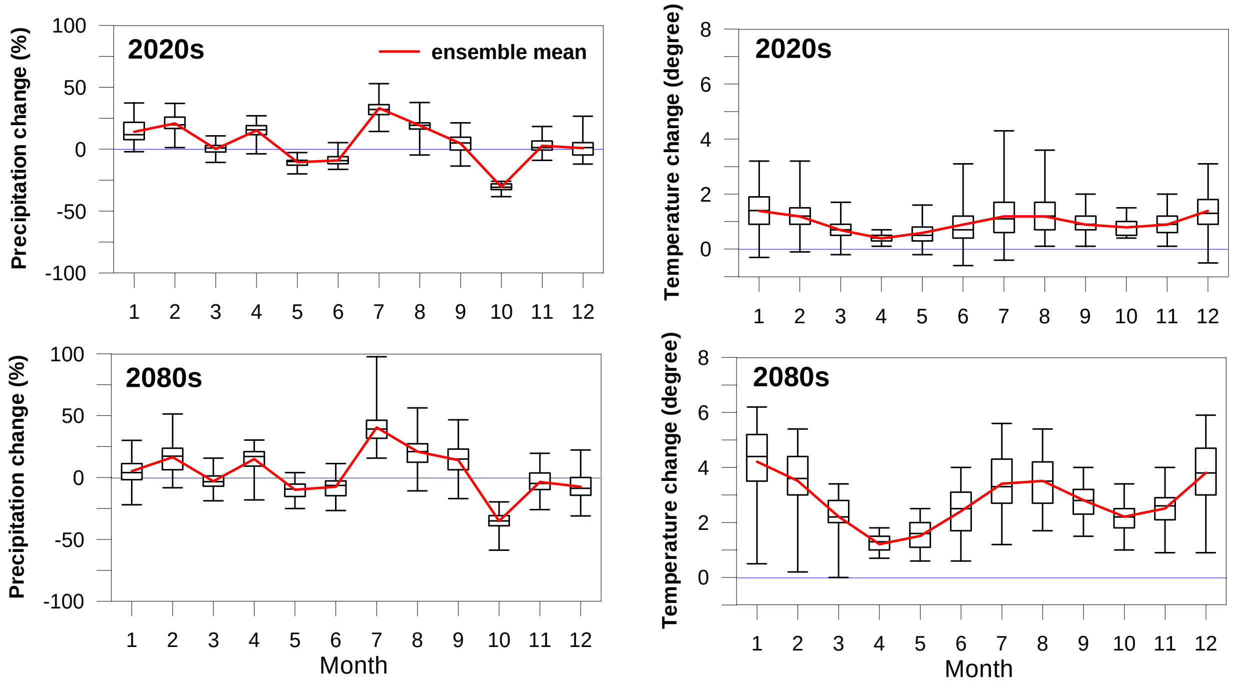
Verification of WXGEN for Bias Correction & Disaggregation

- Comparison of observed and generated climate
- Accepted at the 90% confidence level for t-test & F-test



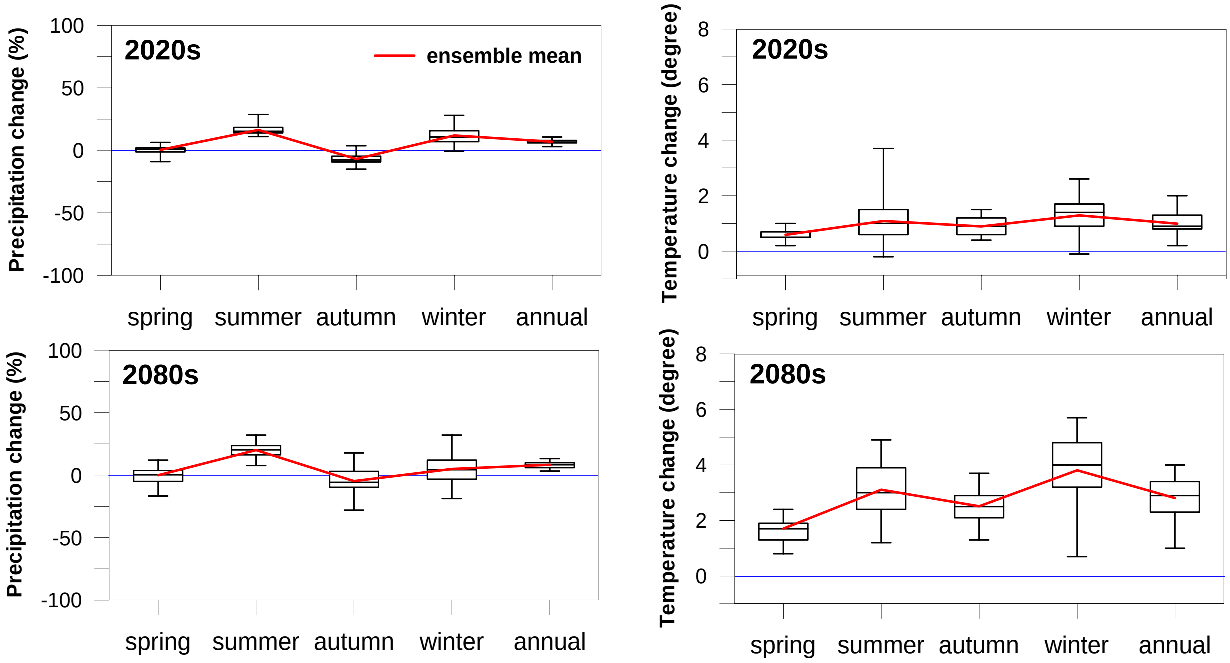
Relative variations of monthly Precipitation & Temperature

- **Variations for the 2080s are much higher than those for the 2020s**
- **The reason is that the CO_2 Concentration as time spans are increased for 2080s**



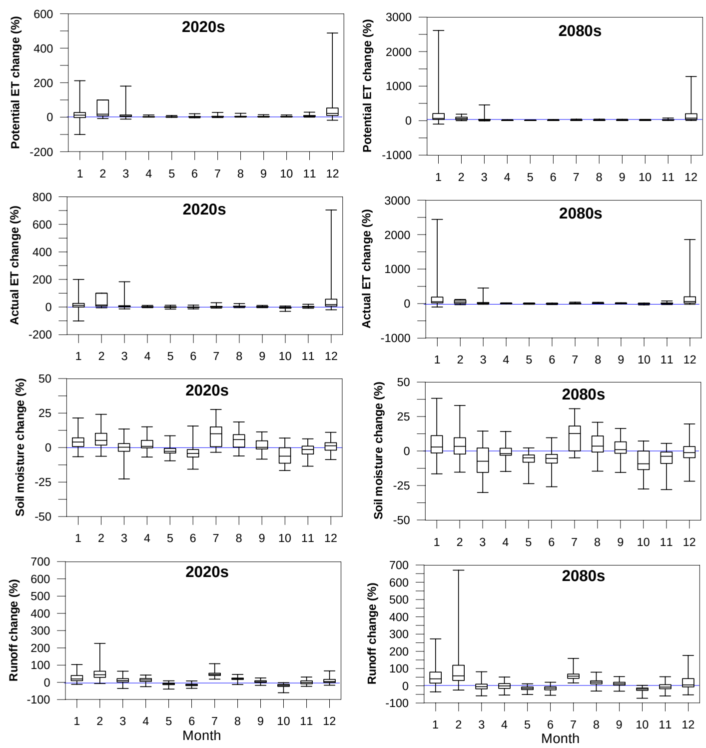
Relative Variations of Seasonal and Annual P and T

- **The annual average increase of precipitation is expected to be +6.8%, +8.2% and the temperature is expected to be +1.0℃, +2.8℃ on 2020s, 2080s**



Monthly Mean Variations of PET,AET, SM, Runoff

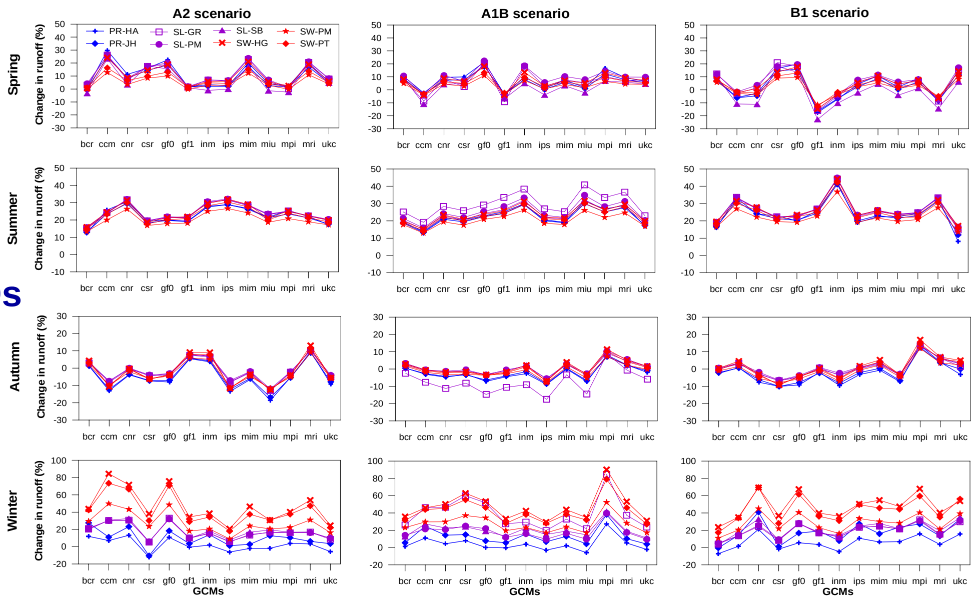
- The changes of Evapo-transpirations and runoff during December to February are significant
- The hydrological model effect on the simulations of soil moisture and runoff is higher to the 2080s rather than 2020 simulation



Relative Variations of Seasonal Runoff 2020s

- The runoff changes on all the seasons except winter during the 2020s by GCMs output rather than hydrological model type

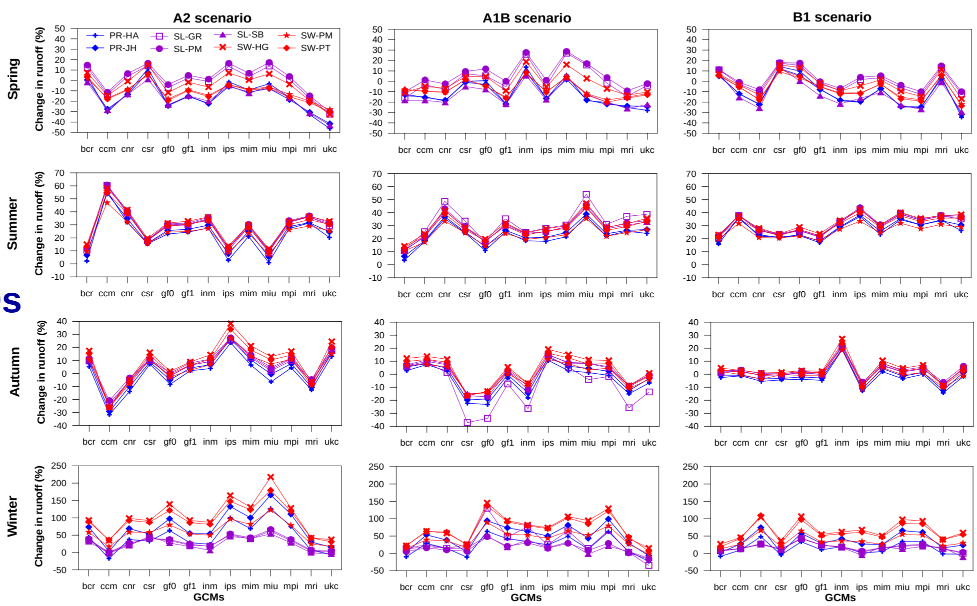
2020s



Relative Variations of Seasonal Runoff for 2080s

- The range of runoff changes due to the selection of hydrological model, GCMs and emission scenarios is higher than that for the 2020s.

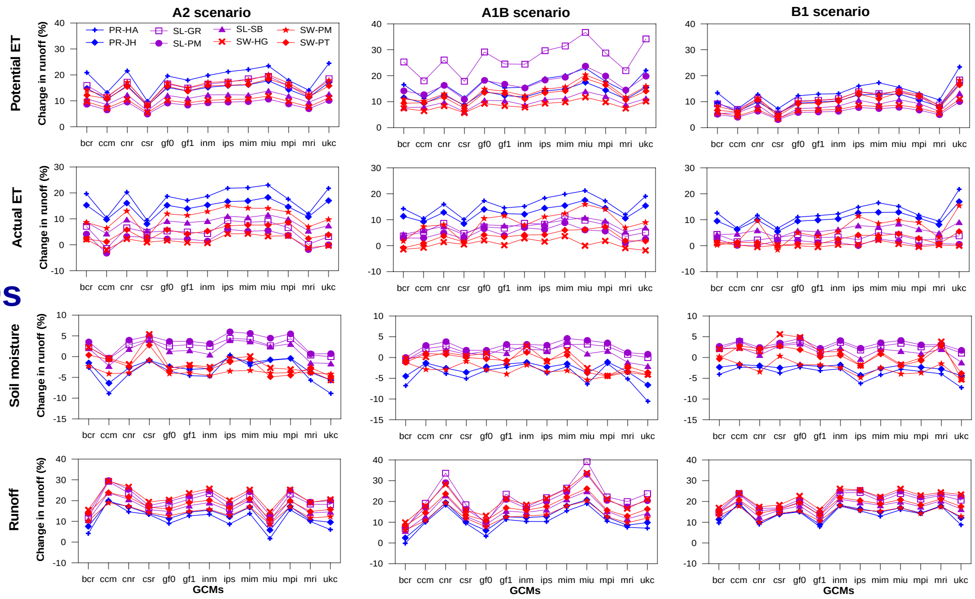
2080s



Relative variations of Annual Mean of PET & AET, SM, Runoff for 2080s

- The annual mean changes evapotranspiration according to hydrological models for the 2080s are much higher that those for the 2020s.

2080s

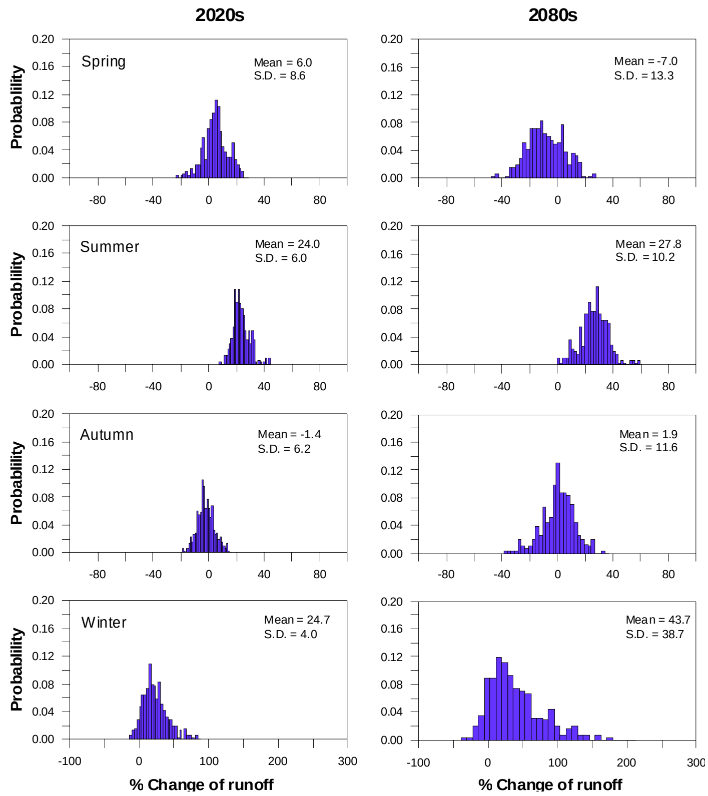


Ensemble Mean Values of Runoff Changes for Hydrological Models and 39 GCMs Outputs for 2020s

- It show that the runoff change from a hydrological model is not much different form that of all ensemble hydrological model except winter season

Time	Hydrologic models								
	PR-HA	PR-JH	SL-GR	SL-PM	SL-SB	SW-HG	SW-PM	SW-PT	Total
1	2	12	18	16	17	55	35	55	26
2	37	66	61	49	44	53	33	48	49
3	25	22	5	10	-4	12	8	13	12
4	10	7	21	21	16	17	8	8	13
5	-10	-10	-13	-8	-8	-10	-9	-9	-10
6	-21	-19	-15	-14	-14	-12	-11	-12	-15
7	47	46	54	50	49	48	41	46	48
8	19	20	22	21	21	21	18	20	20
9	2	3	4	6	6	5	3	4	4
10	-15	-16	-23	-11	-11	-25	-22	-24	-19
11	-10	-9	-6	-3	-6	15	8	11	0
12	-4	0	1	2	2	35	14	25	9
Spring	7	6	7	9	3	7	3	5	6
Summer	23	23	27	25	25	25	21	23	24
Autumn	-3	-3	-3	0	0	0	-2	-1	-1
Winter	4	14	25	18	20	47	28	42	25
Annual	14	14	18	17	16	17	13	16	16

Empirical PDF of Seasonal Runoff



- **The dispersion of seasonal runoff changes for the 2080s is larger than that for the 2020s**
- **The Uncertainty of summer projection of runoff variation is smaller than that of winter season**

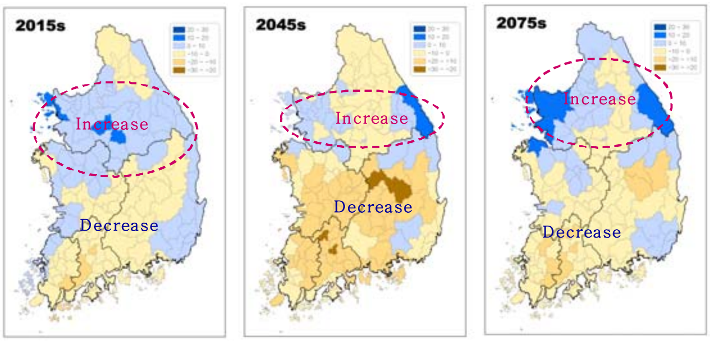
Summary

- **The 8 hydrological models having similar performance of runoff simulations during the past observation periods show different results when the future GCMs outputs are used as an input of the model.**
- **The differences among hydrological models are demonstrated differently for each monthly evaluation. In particular, the differences are significant for the winter season (December-February) in this study area.**
- **As a comparison result of the mean runoff from each hydrological model and ensemble mean of all hydrological model runoffs obtained from 13 GCM outputs, the differences are within ±10% for both 2020s and 2080s periods. It represents that except for winter season the uncertainties from the selection of hydrological models are smaller than those of GCM outputs in this area.**

MME Based Climate change impact assessment

Backgrounds of this Study

- Several studies have assessed the climate change impact on Korean water resources (Bae et al. 2008, Climate Research 35, 213-226)

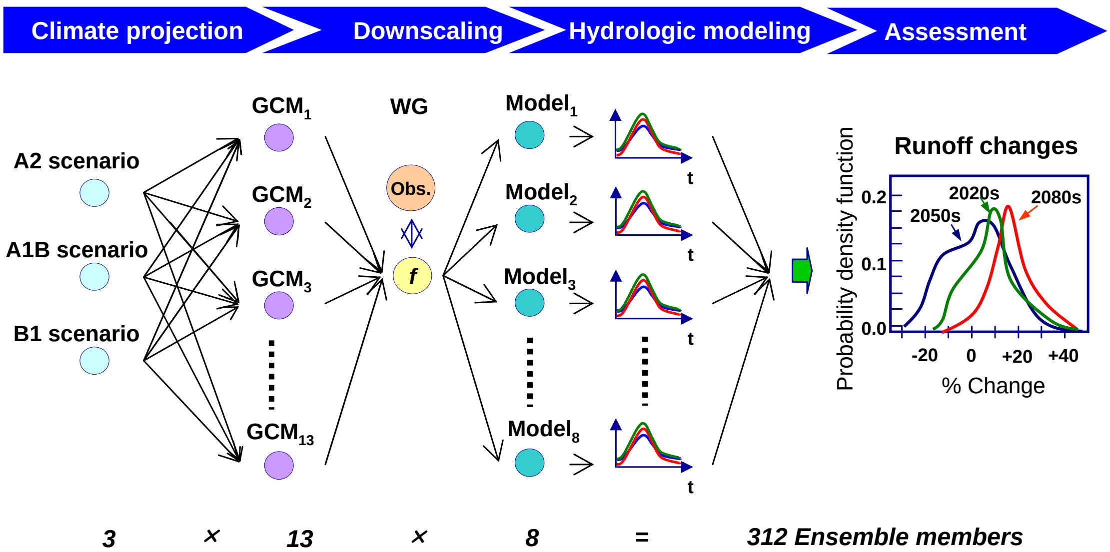


The objectives of this Study

- Analyze the spatial and temporal variations in Korean water resources using multi-model ensemble scheme
- Quantify the uncertainty of the climate change impact assessment on water resources

Methodology

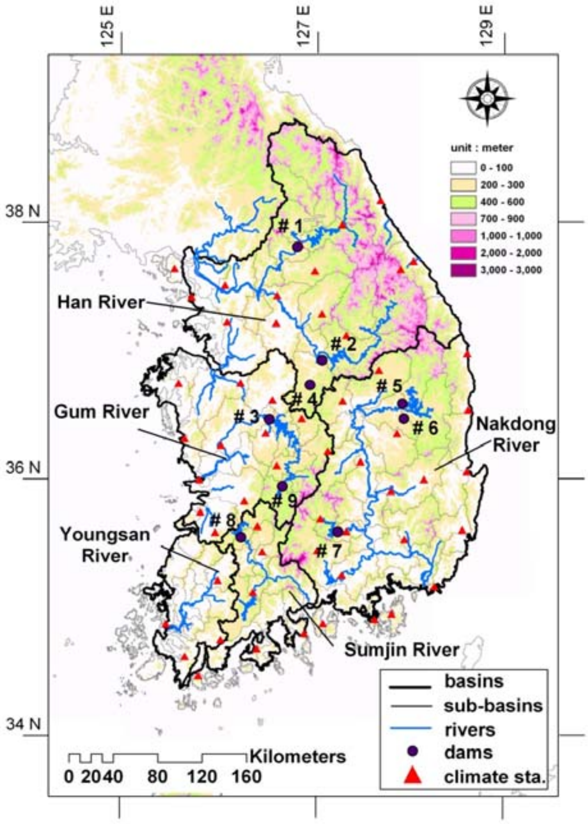
- Multi-Model Ensemble (MME)



- In this part, Reference(Scenario, GCM, Downscaling method, Hydrologic model) of used data & method will be skiped because they are used in previuos part

Study Area

- **The 109 sub-basins with 5 major river basins for climate change impact assessments on water resources**
- **The 56 climate stations in South Korea for statistical downscaling**
- **6 dam sites for calibration and verification of hydrological models**
- **3 dam sites for verification of regionalization method**



Methodology for Regionalization of Model Parameters

Selection of physical characteristics of catchments

↓

Principle Component Analysis

↓

Cluster analysis using principle components

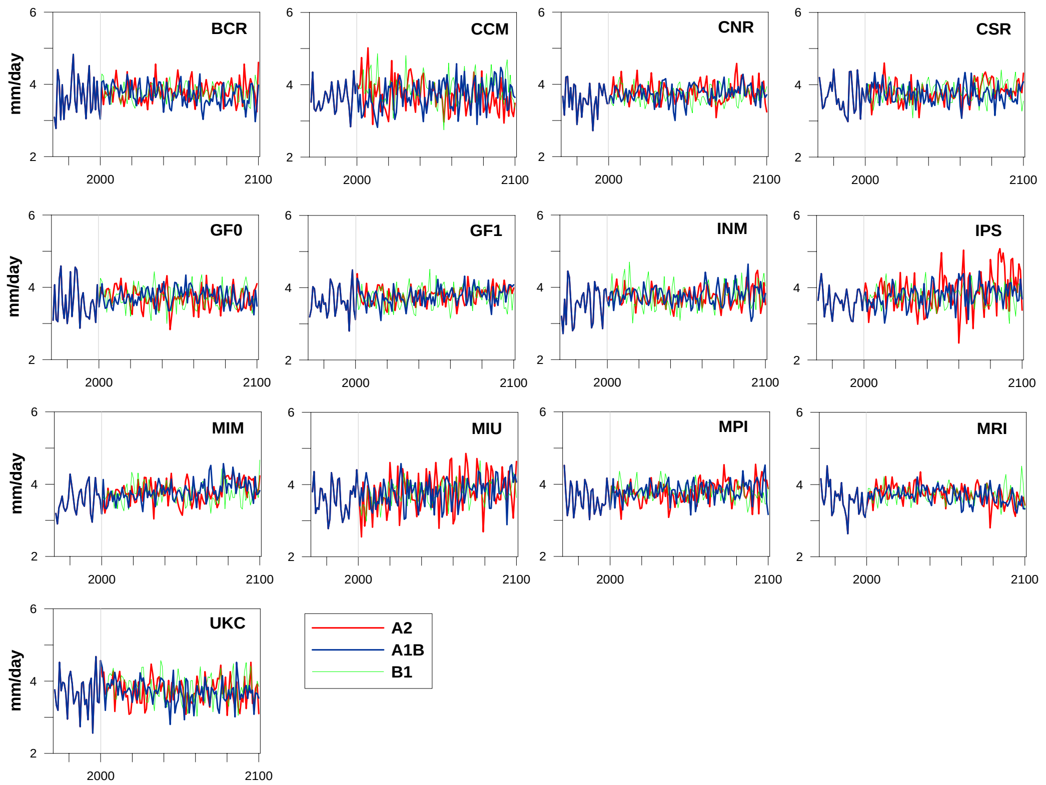
↓

Regionalization of model parameters

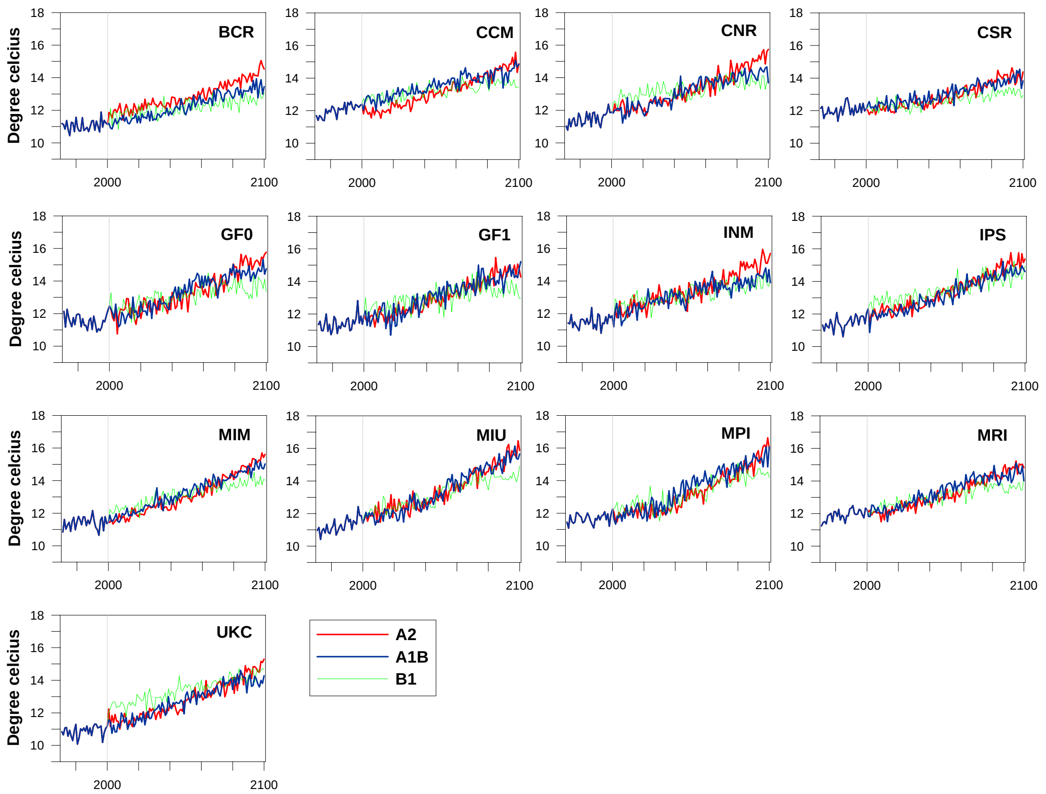
↓

Performance verification of regionalized model parameters

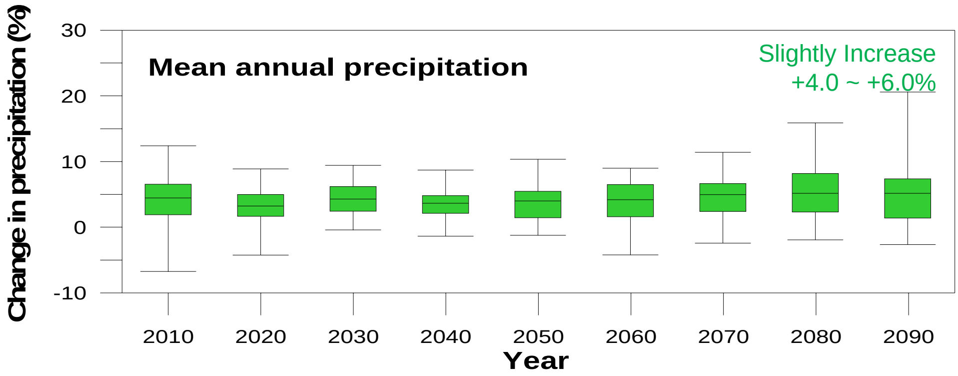
Projection of Mean Annual Temperature of 13 GCMs

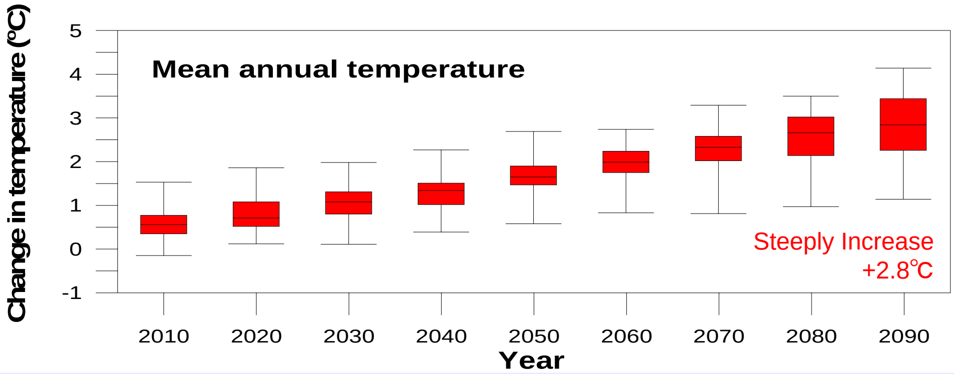


Projection of Mean Annual Precipitation of 13 GCMs

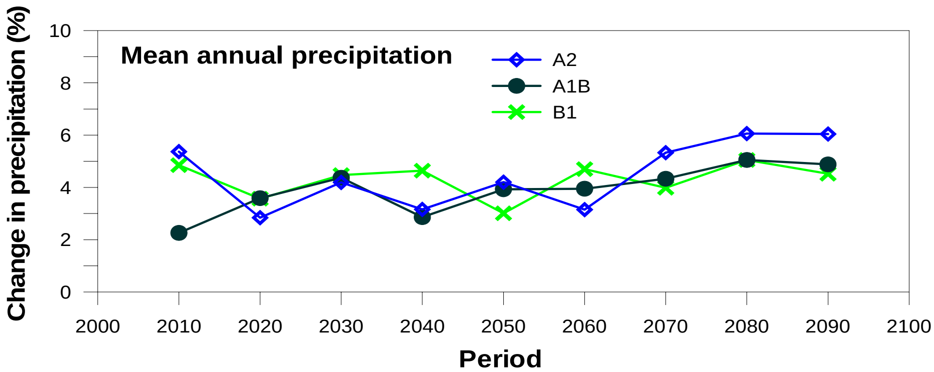


Variations of Mean Annual Precipitation and Temperature under 39 Scenarios





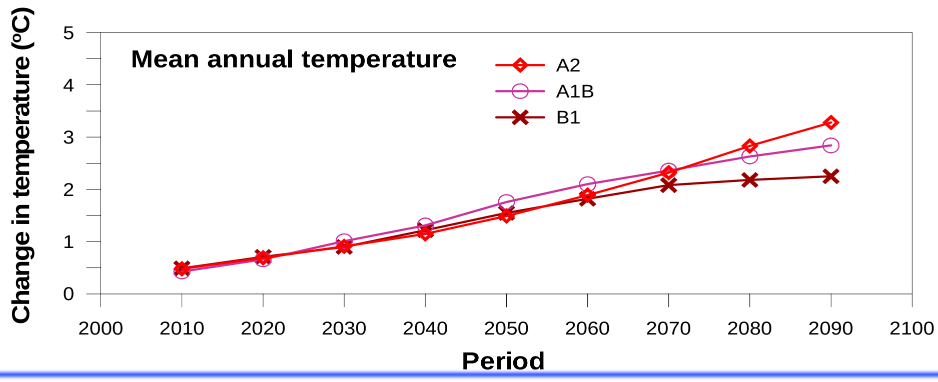
Variations of Mean Annual Precipitation and Temperature according to Emission Scenarios



+6.0% for A2

+4.9% for A1B

+4.5% for B1



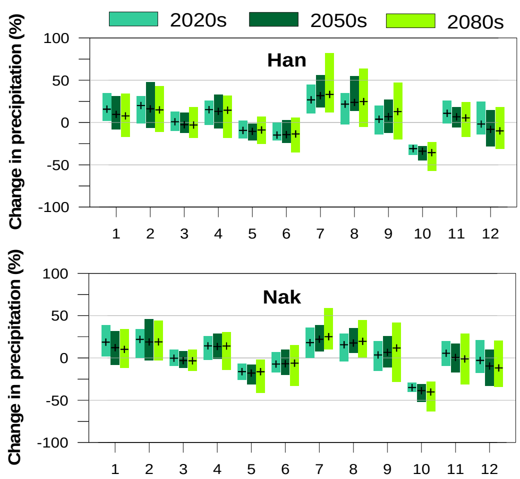
+3.3℃ for A2

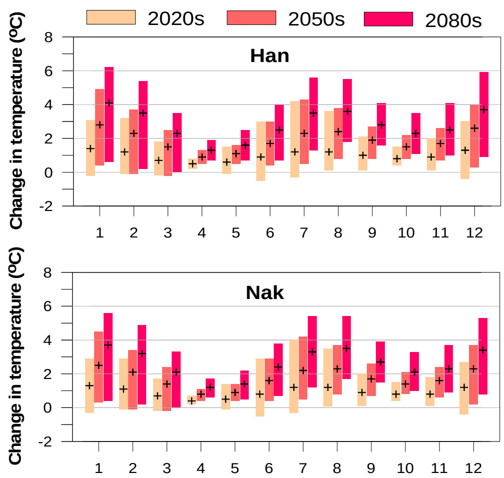
+2.8℃ for A1B

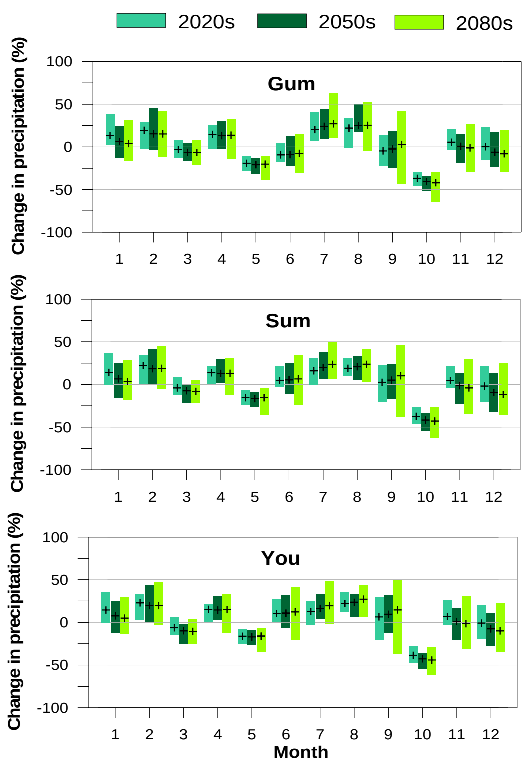
+2.3℃ for B1

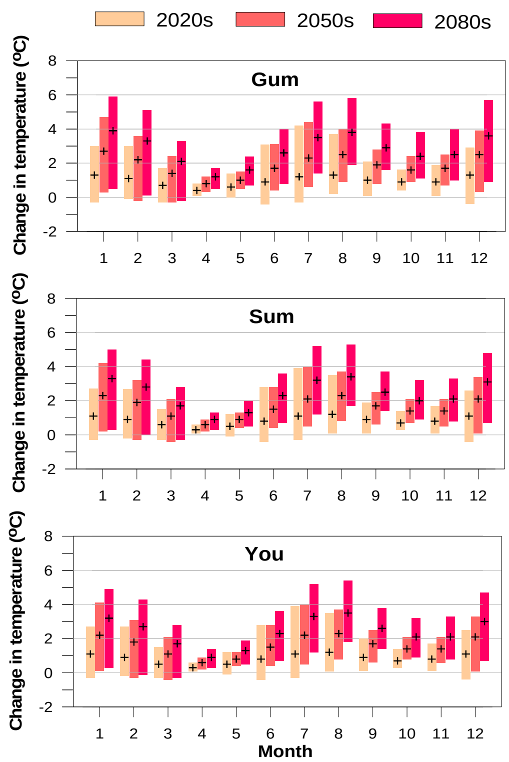
Variations of Mean Monthly Precipitation & Temperature over 5 Basins

- **The precipitation was expected to increase on July & August and decrease on October in most basins.**
- **The temperature was expected to more increase in summer and winter than in fall and winter.**



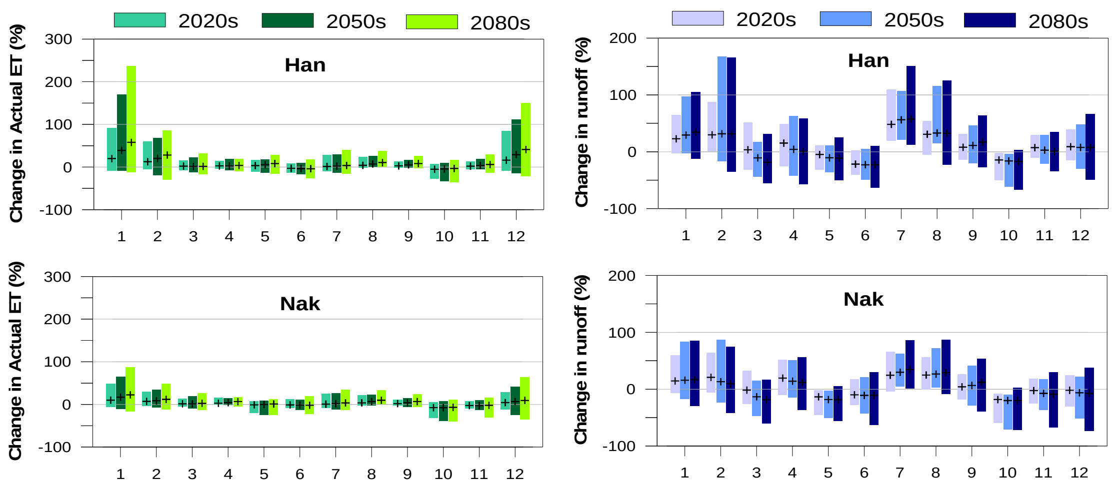


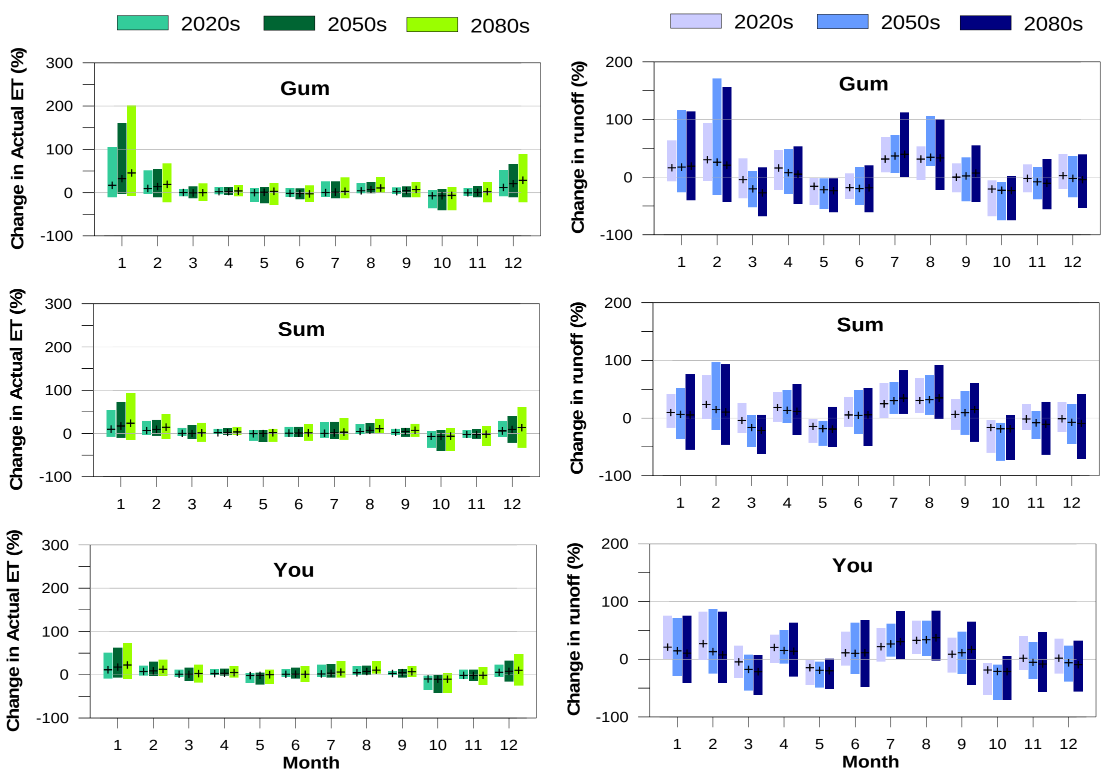




Variations of Mean Monthly AET & Runoff over 5 Basins

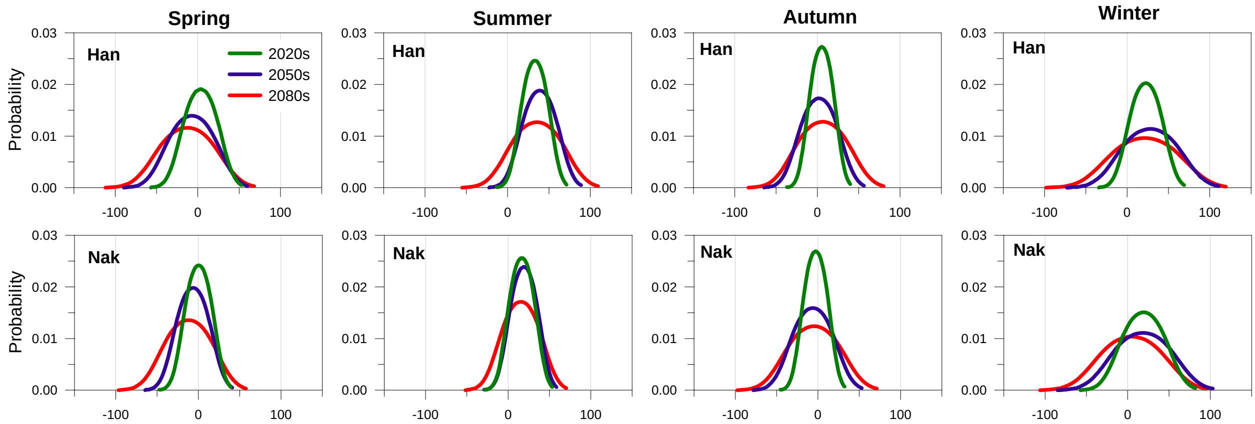
- **The AET was expected to high increase in winter**
- **The runoff was expected to increase on July & August and decrease on October in most basins.**
- **Uncertainty in runoff change was increased than in precipitation change**

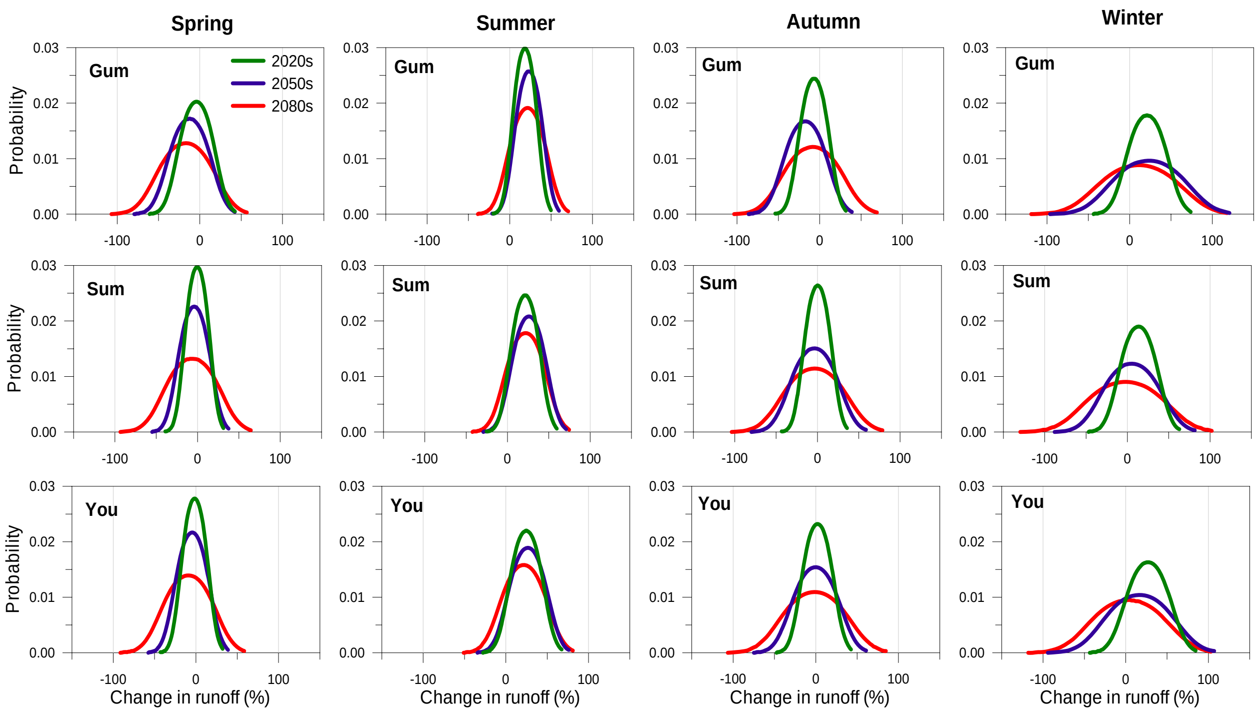




Kernel Density Function of Seasonal Runoff Changes

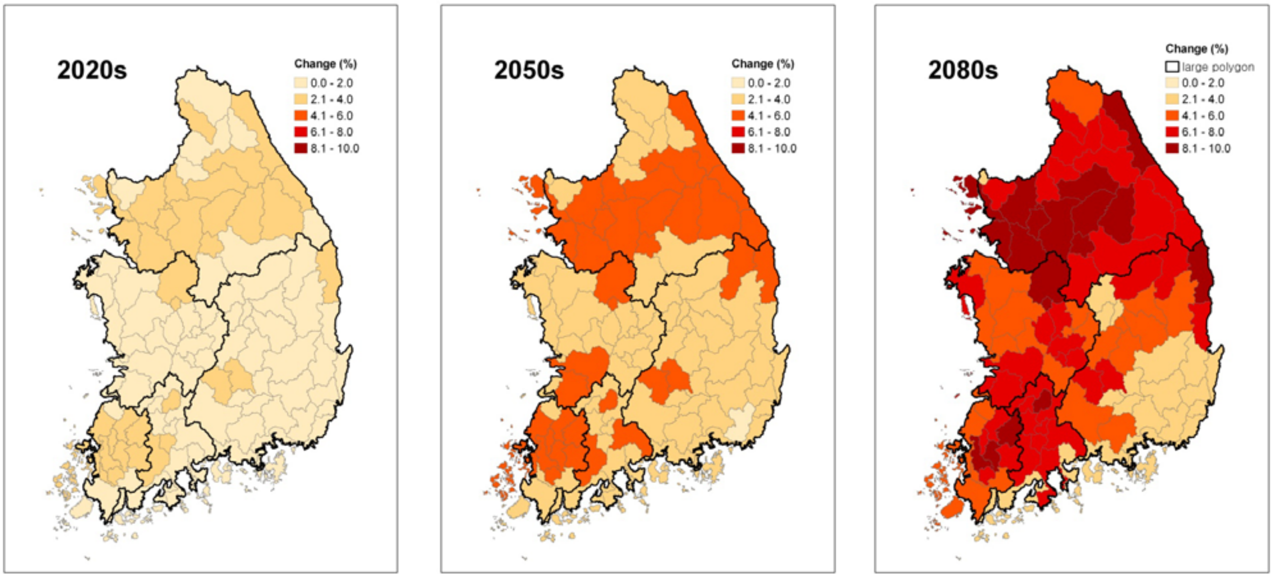
- **In most basins, the mean runoff in summer increases in 2020s, 2050s, 2080s.**
- **The runoff in spring decrease in 2050s, 2080s**
- **Uncertainty in runoff changes were the largest in winter and the lowest in summer**
- **The 2080s than 2020s and 2050s period shows higher uncertainty**





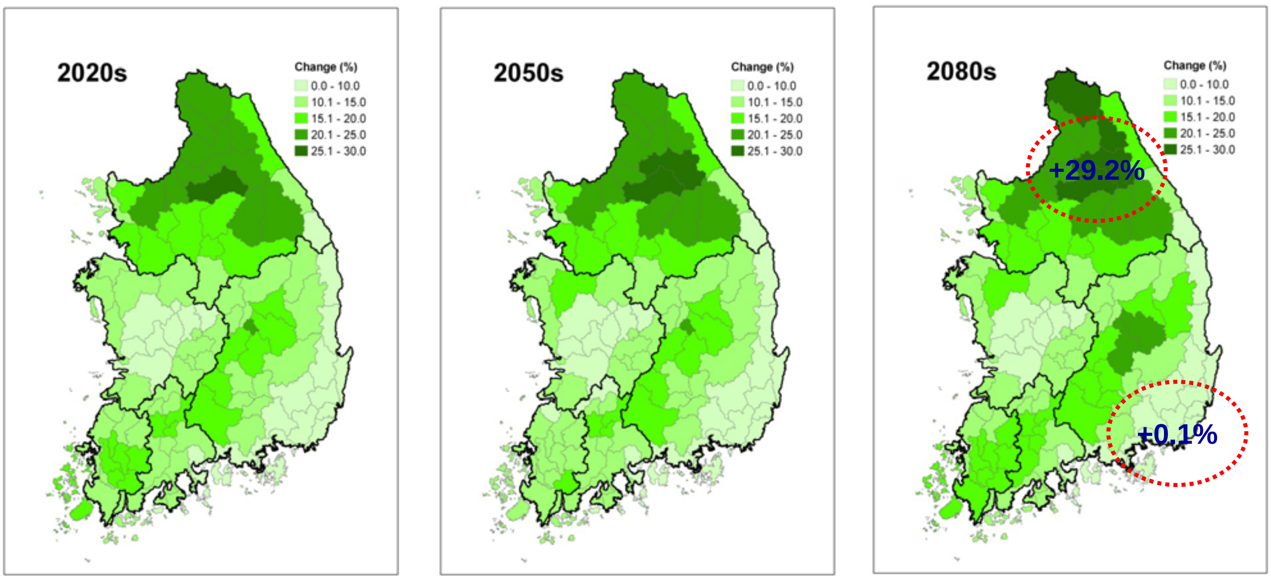
Change in Annual Mean Actual Evapotranspiration

- **Evapotranspiration substantially increases as the temperature rises**
- **More increase in northern regions than in the southern regions**
- **+1.7% (2020s), +3.7% (2050s), +6.2% (2080s)**



Change in Annual Mean Runoff

- **More increase in northern regions than in the southern regions**
- **+13.1% (2020s), +13.2% (2050s), +14.3% (2080s)**



Change in Mean Seasonal Runoff

Basin	Period	2020s			2050s			2080s		
		A2	A1B	B1	A2	A1B	B1	A2	A1B	B1
Han	Spring	+9	+5	+2	-4	-6	-3	-9	-8	-8
	Summer	+28	+30	+31	+34	+34	+34	+32	+35	+36
	Autumn	+2	+4	+5	+5	+4	+4	+11	+6	+6
	Winter	+17	+20	+20	+19	+22	+20	+28	+19	+18
Nak	Spring	+7	+3	+2	-3	-4	-1	-7	-4	-3
	Summer	+16	+16	+17	+19	+18	+20	+22	+21	+23
	Autumn	-3	-2	0	-2	-1	-1	+4	+2	+1
	Winter	+11	+12	+9	+7	+8	+6	+9	+4	+3
Gum	Spring	+5	+0	-2	-8	-11	-7	-15	-12	-10
	Summer	+20	+21	+22	+24	+24	+24	+24	+24	+27
	Autumn	-6	-5	-4	-6	-5	-5	-1	-5	-4
	Winter	+15	+17	+15	+12	+14	+11	+13	+9	+7
Sum	Spring	+5	+2	+1	-3	-5	-2	-8	-5	-4
	Summer	+20	+21	+22	+24	+23	+24	+27	+25	+28
	Autumn	-1	+1	+2	-1	+3	+1	+5	+5	+3
	Winter	+12	+12	+9	+5	+5	+4	+5	+1	0
You	Spring	+6	+3	+1	-3	-6	-2	-7	-5	-4
	Summer	+22	+23	+23	+26	+24	+26	+29	+27	+29
	Autumn	0	+3	+4	+1	+5	+3	+6	+7	+5
	Winter	+19	+19	+15	+8	+8	+7	+4	+3	+2

Summary

- This research investigated the potential changes in Korean water resources and associated uncertainties using multi-model simulations of 13 GCMs, three GHG emission scenarios, and eight hydrologic models.
- In the most catchments, spring runoff is projected to decrease and summer and winter runoff amounts are projected to increase.
- The uncertainties in runoff change for 2080s were larger than for 2020s and the uncertainties in summer runoff relatively smaller than in other season
- Water resources management and practices in South Korea is likely to be distressed by climate change, although there were high uncertainties associated with the future projection.

Concluding Remarks

❖ We discussed the theory and methods of climate change impact assessment on water resources

❖ We demonstrated the uncertainty sources for climate change impact assessment on water resources

❖ We also showed the results from MME approach that estimates variability of hydrometeorologic variables in the future

Thank you !