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고해상도 기후자료를 이용한 우리나라의 논 관개요구량 예측

Projecting Future Paddy Irrigation Demands in Korea Using High-resolution Climate Simulations

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Abstract

The impacts of climate change on paddy irrigation water demands in Korea have been analyzed. High-resolution (27 × 27 km) climate data for the SRES A2 scenario produced by the Korean Meteorological Research Institute (METRI) and the observed baseline climatology dataset were used. The outputs from the ECHO-G GCM model were dynamically downscaled using the MM5 regional model by the METRI. The Geographic information system (GIS) was used to produce maps showing the spatial changes in irrigation water requirements for rice paddies. The results showed that the growing season mean temperature for future scenarios was projected to increase by 1.5℃ (2020s), 3.3℃ (2050s) and 5.3℃ (2080s) as compared with the baseline value (1971 ~ 2000). The growing season rainfall for future scenarios was projected to increase by 0.1% (2020s), 4.9% (2050s) and 19.3% (2080s). Assuming cropping area and farming practices remain unchanged, the total volumetric irrigation demand was projected to increase by 2.8% (2020s), 4.9% (2050s) and 4.5% (2080s). These projections are contrary to the previous study that used HadCM3 outputs and projected decreasing irrigation demand. The main reason for this discrepancy is the difference with the projected climate of the GCMs used. The temporal and spatial variations were large and should be considered in the irrigation water resource planning and management in the future.

Keywords : climate change, GIS, irrigation, paddy, RCM

요 지

기후변화가 우리나라의 논 관개요구량에 미치는 영향을 분석하였다. 기상연구소의 SRES A2 시나리오에 대한 고해상도 (27 × 27 km) 기후 자료와 기준년도 (1971 ~ 2000)의 관측 기상자료를 이용하였다. 기상연구소가 전지구모형 ECHO-G 예측자료를 MM5 모형으로 역학적으로 상세화한 결과를 이용하였다. 논 관개요구량의 공간적인 변화를 분석하기 위하여 GIS 기법을 이용하였다. 연구결과는 벼 생육기간의 평균기온은 기준년도에 비해 1.5℃ (2020s), 3.3℃ (2050s) 및 5.3℃ (2080s) 상승할 것으로 예측되었다. 벼 생육기간의 강우량은 0.1% (2020s), 4.9% (2050s) 및 19.3% (2080s) 증가할 것으로 예측되었다. 영농 형태와 논 면적이 변하지 않는다고 가정하면 우리나라 논의 총 관개용수량은 2.8% (2020s), 4.9% (2050s) 및 4.5% (2080s) 증가할 것으로 예측되었다. 본 연구의 결과는 총 관개용수량이 다소 감소할 것으로 예측한 다른 연구결과와는 상반된 결과를 나타내었으며, 그 주원인은 사용된 GCM에 따른 기후 예측치의 차이에서 온 것으로 판단된다. 관개용수량의 시공간적 변동성이 큰 것으로 나타났으며 이는 앞으로 관개계획과 물 관리에서 고려되어야 할 것이다.

핵심용어 : 기후변화, GIS, 관개, 논, RCM

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1. INTRODUCTION

Climate change will affect temperature and rainfall patterns (IPCC, 2007), these will impact irrigation water requirements. Agricultural water use constitutes about 47% (61% excluding stream maintenance water requirement) of the total water usage in South Korea (MOCT, 2006). Most of the agricultural water expenditure in Korea is for irrigating paddy rice, thus efficient irrigation water management is very important.

Many studies have been performed on the climate change impacts on irrigation water requirements worldwide. Doll (2002) studied long-term average irrigation requirements worldwide using two GCM (ECHAM4 and HadCM3) outputs, and projected that two-thirds of the area equipped for irrigation in 1995 would possibly suffer from increased water requirements. De Silva et al. (2007) studied the impacts of climate change on paddy irrigation requirements in Sri Lanka and found that average rainfall would decrease and potential evapotranspiration (ETo) and average paddy irrigation requirements would increase in the future. Rodríguez Díaz et al. (2007) did a similar study for field crops in Spain and projected a significant increase in irrigation demand for 2050s. Thomas (2008) used a regression method to predict the irrigation demand in China for the year 2030 by using long-term observed monthly climate data. He found that irrigation demand showed considerable temporal and spatial variations during the period of 1951?1990, and that irrigation demand was projected to increase with a varied pattern and the subtropical cropping zone was projected to enlarge for the future scenarios. Matthews et al. (1997) predicted climate change impact on rice production in Asia using two crop models (ORYZA1 and SIMRIW), and found rice production would decrease on average by 3.8% in the next century. In general, the increased temperature will make the rice growing region move to higher. Tao et al. (2006, 2008) predicted that rice production would face challenges from global warming and water shortages. The impact of global warming on rice production has become a key concern, and many researchers have studied climate change impacts on rice production in Asia using crop models (e.g., Matthews et al., 1997; Yao et al., 2007, Hayashi and Jung, 2000). In Korea, concerning climate change modeling, several studies have been done using the MM5 and RegCM3 regional models along with ECHO-G GCM model outputs for Special Report on Emission Scenarios (SRES) A2 scenario (e.g., METRI, 2004; Oh et al., 2004; Im et al., 2007). Chang et al. (2007) studied the vulnerability of Korean water resources to climate change and Bae et al. (2008) studied potential changes in Korean water resources. Both researchers used high-resolution climate data produced by downscaling the ECHO-G outputs using the MM5 regional climate model (RCM) for the SRES A2 scenario (METRI, 2004). They found that runoff would increase in the northern part and decrease in the southern part of South Korea and that spatial and temporal variation would increase. Yoo and Kim (2007) studied impact of climate change on rice production in Korea using the CERES-rice model for the MM5 simulation results for the SRES A2 scenario and found that the rice production would decline about 16.5% on average in the 2080s. Chung (2009a,b) studied climate change impacts on paddy irrigation water requirement in the Nakdong river basin and Chung et al. (2010) studied the impacts of climate change on the irrigation water demand for paddy in Korea using downscaled HadCM3 outputs for the SRES A2 and B2 scenarios. They found that the projected irrigation water demand would vary between scenarios and decrease in general with large temporal and spatial variability. The objective of this research is to assess the impacts of climate change on paddy irrigation water demand in the Republic of Korea by using high-resolution climate simulations. The projected irrigation demands from this study were compared with the results of a previous study that used HadCM3 outputs.

2. MATERIALS AND METHODS

2.1 Study Area and Rice Culture

The Republic of Korea is located in the Far East between China and Japan (33° N, 125° E to 39° N, 131° E) with land area of 9.97×10^6 ha, of which 17.9% is farmland and 64.0% is forest (MFAFF, 2008a). Farmland comprises of 1.07×10^6 ha (10.8%) paddy and 0.71×10^6 ha (7.1%) upland field. It was reported that 0.95×10^6 ha was planted to japonica variety rice (*Oryza*

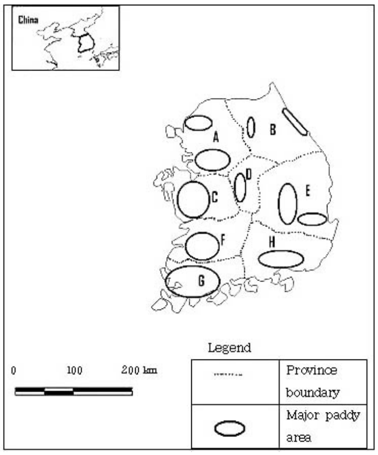

Fig. 1. Map of South Korea with 8 Provincial Major Rice Areas (after Chung et al., 2010)

sativa L.) and 4.41 million metric tons of rice were produced in Korea in 2007 (MFAFF, 2008b). Rice is the main staple crop in Korea. The climate of Korea is Asian monsoon with an annual mean temperature 12.2℃ and a 1,274 mm mean precipitation. Two thirds of the annual precipitation falls in summer months, June to September. The rice growing period is from May to September and monoculture is the general practice. May is the nursery period and seedlings are transplanted in late May. Irrigation water is supplied from May to September to keep the water depth at 5～10 cm and rice is harvested in late October. Fig. 1 shows major paddy growing regions within the 8 provinces. About 70% of the total paddy fields lie in the west and south lowlands and the rest in valleys between mountains (Chung et al., 2010).

2.2 Climate Scenarios

Despite rapid advances in the GCM models, their outputs generally show some biases in climate prediction. Temperature is generally well represented, but precipitation less so (Bae et al., 2007). In this study, the climate data produced by METRI (2004) and the observed baseline (1971～2000) monthly mean values were used. METRI used the MM5 model developed by the Pennsylvania State University/National Center for Atmospheric Research to downscale the ECHO-G outputs for the A2 scenario. ECHO-G was developed by the Max-Planck Institute for Meteorology and is one of the 23 atmosphere-ocean general circulation models (AOGCMs) used for the IPCC 4th assessment report (IPCC, 2007). The downscaled climate data have 27 × 27 km of high-resolution over Korea. Since high-resolution data of mean monthly precipitation and temperature were available, these two climate parameters were used in this study. The A2 scenario represents strong economic values under increasing regionalization (IPCC-TGICA, 2007). The projections are monthly for 2001～2100 year periods. We used mean monthly data centered on the decades of 2020s (2010～2039), 2050s (2040～2069) and 2080s (2070～2099) by averaging each 30 year monthly values.

The projected changes in climate need to be considered relative to observed baseline values. A baseline climate dataset observed at 58 weather stations for 1971～2000 was used. The observed climate parameters are averaged monthly values of the mean, maximum, minimum temperatures, precipitation, sunshine, wind speed and humidity.

As the resolutions of the MM5 outputs and observed climate data are not the same, an interpolation technique was applied to generate baseline climate data at MM5 grid pixels. Then, the relative changes of the MM5 simulated average monthly temperature and precipitation for the future scenarios as compared with those of baseline (1971～2000) were computed. Finally, the relative changes were applied to the generated baseline data to obtain projected future climate data. These climate data were used in ETo calculations for each month from May to September at each pixel.

2.3 Estimating Volumetric Irrigation Demand

The paddy irrigation requirement is defined as the depth of water required for the rice growing per unit area, and paddy irrigation demand is volume of water obtained by multiplying the irrigation requirement and paddy area. The former includes crop ET, deep percolation and land preparation water minus effective rainfall, and it does not include other water losses. The effective rainfall is the portion of total rainfall that is used directly in the paddy field, i.e. total rainfall minus losses due to surface runoff and deep percolation. To estimate monthly effective rainfall, the USDA-SCS method was used:

$$P_{eff} = P_{tot} * (125 - 0.2 * P_{tot}) / 125 \quad \text{for } P_{tot} < 250\,mm \tag{1}$$

$$P_{eff} = 125 + 0.1 * P_{tot} \quad \text{for } P_{tot} > 250\,mm \qquad (2)$$

where P_{eff} is monthly effective rainfall (mm) and P_{tot} is monthly total rainfall (mm).

The paddy irrigation requirement can be estimated using a water balance model such as CROPWAT developed by the Food and Agriculture Organization (Smith, 1992). The model requires data such as rainfall, reference crop evapotranspiration (ETo), crop coefficients, and water allowances for land preparation and seepage losses. The ETo was calculated for each pixel using the baseline and projected temperature dataset for 2020s, 2050s and 2080s. Since only temperature data were available, the Hargreaves ETo equation is used as recommended by Allen et al. (1998):

$$ETo = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} * R_a \qquad (3)$$

where ETo is reference evapotranspiration (mm day-1), T_{mean}, T_{max}, T_{min} are monthly mean, maximum, and minimum temperatures (°C), and R_a is extraterrestrial radiation (mm day^{-1}). For the irrigation requirement calculation, there are many grid points rather than one point, therefore, we used a spreadsheet model to replicate the CROPWAT methodology following De Silva et al. (2007). The mean monthly values of rainfall, ETo, percolation, land preparation allowance and crop coefficient were input into the spreadsheet model and the paddy water requirements were calculated across Korea. Land preparation water of 140 mm and nursery area of 5% of the total paddy area and deep percolation value of 2 mm/d assuming clay or loam soil were used following the design standards (MOAF, 1998). Monthly crop coefficients of 1.05, 1.13, 1.2, 1.2 and 0.9 for May to September were obtained by interpolating those for growth stages from the FAO (Allen et al., 1998).

The volumetric irrigation demands for 8 provinces were computed. The irrigation demand is for the average year and water losses are not included. The computed irrigation requirements were average values in the major paddy regions in each province. Then, they were multiplied by the paddy area of each province to get the provincial volumetric irrigation demand. Then, changes of paddy irrigation demand for the future scenarios in each province and whole country were analyzed.

2.4 Mapping Irrigation Water Requirements

The precipitation and paddy irrigation requirement gridded data for the baseline and future scenarios were imported into a GIS. Then, a series of raster maps showing the spatial variation in precipitation and paddy irrigation requirements for the baseline and future scenarios were produced.

3. RESULTS AND DISCUSSION

3.1 Climate Change Projection

The spatial variations of rainfall in Korea during the growing season (May to September) for the baseline and 2020s, 2050s and 2080s for A2 scenario are shown in Fig. 2. Tables 1 and 2 show the total and effective rainfall amounts during the growing season for the

Table 1. Comparison of Predicted Rainfall During the Growing Season (May to Sept.) for the Future Scenarios in the 8 Provincial Paddy Areas

Symbol in Fig. 1	Province	Baseline (mm)	2020s (mm, %)	2050s (mm, %)	2080s (mm, %)
A	Gyeonggi	973	1,040 (6.8)	1,129 (16.0)	1,181 (21.3)
B	Gangwon	947	979 (3.3)	1,032 (9.0)	1,018 (7.5)
C	Chungnam	926	956 (3.2)	1,003 (8.3)	1,124 (21.3)
D	Chungbuk	908	902 (-0.6)	964 (6.2)	1,042 (14.7)
E	Gyeongbuk	754	743 (-1.4)	755 (0.1)	970 (28.6)
F	Jeonbuk	940	921 (-2.0)	942 (0.3)	1,209 (28.7)
G	Jeonnam	988	944 (-4.4)	977 (-1.1)	1,185 (19.9)
H	Gyeongnam	1,008	968 (-4.0)	1,003 (-0.5)	1,155 (14.5)
	Mean	931	932 (0.1)	976 (4.9)	1,110 (19.3)

Table 2. Comparison of Predicted Effective Rainfall for the Future Scenarios in the 8 Provincial Paddy Areas

Symbol in Fig. 1	Province	Baseline (mm)	2020s (mm, %)	2050s (mm, %)	2080s (mm, %)
A	Gyeonggi	338	363 (7.3)	396 (17.2)	402 (18.7)
B	Gangwon	413	428 (3.7)	446 (7.9)	455 (10.0)
C	Chungnam	348	365 (4.8)	382 (9.6)	429 (23.0)
D	Chungbuk	380	386 (1.4)	410 (7.7)	425 (11.9)
E	Gyeongbuk	398	396 (-0.4)	405 (1.8)	456 (14.6)
F	Jeonbuk	393	394 (0.2)	406 (3.4)	459 (16.8)
G	Jeonnam	457	447 (-2.1)	466 (1.9)	520 (13.8)
H	Gyeongnam	475	465 (-2.1)	484 (1.7)	523 (10.0)
	Mean	400	406 (1.3)	424 (6.0)	459 (14.5)

baseline and future scenarios in the 8 provincial rice areas. Average growing season rainfall amounts were projected to increase by 0.1% (2020s), 4.9% (2050s) and 19.3% (2080s) as compared with the baseline (1971~2000). However, the effective rainfall amounts were projected to increase by 1.3% (2020s), 6.0% (2050s) and 14.5% (2080s) since the larger the rainfall amounts are, the smaller the effective rainfall ratios are. The 2080s scenario showed the largest increase in rainfall volume. The rainfall amounts in southern provinces were projected to either increase little or decrease for 2020s and 2050s and to increase significantly in the 2080s.

Rainfall variations are strongly influenced by vertical movement of air due to atmospheric instabilities of various kinds and by the flow of air over orographic features. For models to accurately simulate the seasonally varying pattern of precipitation, they must correctly simulate a number of processes that are difficult to evaluate at a global scale. Many models therefore individually display substantial precipitation biases. Biases can be attributed to errors in the sea surface temperature field of the ocean-atmosphere coupled model, and failure of models to capture the regional rainfall patterns. The inaccuracy of predicted rainfall by the GCM is carried over to the downscaled rainfall predictions. Therefore, the irregular trend among the scenarios can be attributed to the lower confidence in rainfall predictions of the GCM (Nkomozepi and Chung, 2011).

The growing season mean temperature for the baseline was 21.3℃ and it was projected to increase by 1.5℃ (2020s), 3.3℃ (2050s) and 5.3℃ (2080s).

3.2 Paddy Irrigation Demand

Average baseline ETo was 509.0 mm and the future ETo was projected to increase by 3.8% (2020s), 8.6% (2050s) and 13.8% (2080s). Since the ETo was projected to increase more than the effective rainfall the irrigation requirements increased for the future scenarios. In addition, the spatial variation of paddy irrigation requirements was large as shown in Fig. 3. The southern and northeastern parts of the country have the smallest irrigation requirements, while the east central region has the largest. Table 3 shows the irrigation requirements and volumetric irrigation demands for the baseline and future scenarios in the 8 provincial rice regions. The projected provincial irrigation demands vary from -4.1% to 8.1% from the baseline values excluding 2080s Gangwon province that showed 18.4% increase. However, the paddy area in Gangwon province is only 4.4% of the total paddy area in Korea, the influence of Gangwon province will be minimal to the national irrigation water demand. Total volumetric paddy irrigation demand for the baseline was $4{,}283 \times 10^6\ m^3$ and future demands were projected to increase by 2.8% (2020s), 4.9% (2050s) and 4.5% (2080s). These projections are contrary to the previous study (Chung et al., 2010) that had used the HadCM3 outputs and projected decreasing irrigation demand. The main reason for this discrepancy is the difference in the projected rainfalls of

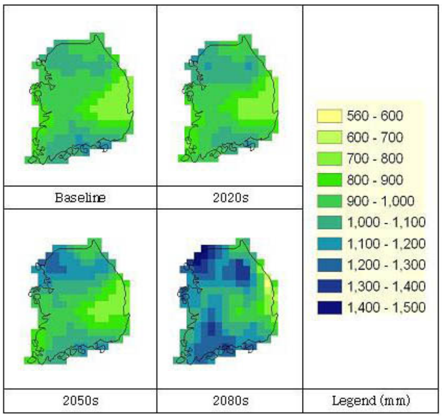

Fig. 2. Spatial Variation in Mean Growing Season Rainfall for the Baseline (1971-2000) and Future A2 Scenario

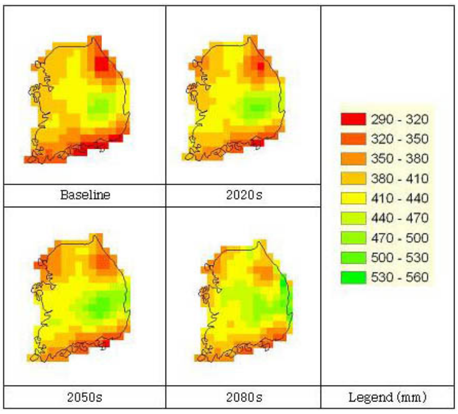

Fig. 3. Spatial Variation in Seasonal Paddy Irrigation Requirements for the Baseline and Future A2 Scenario

Table 3. Comparison of Predicted Paddy Irrigation Requirement and Volumetric Irrigation Demand for the Future Scenarios in the 8 Provincial Paddy Areas

Symbol in Fig. 1	Province	Paddy area (ha)*	Paddy irrigation requirement (mm) Volumetric irrigation demand (10^6 m^3) Change from baseline (%)			
			Baseline	2020s	2050s	2080s
A	Gyeonggi	124,626	409	402	392	421
			510	501	489	525
				(-1.7)	(-4.1)	(2.9)
B	Gangwon	46,889	367	382	381	434
			172	179	179	203
				(4.1)	(3.8)	(18.4)
C	Chungnam	183,582	407	405	417	421
			747	745	767	774
				(-0.6)	(2.5)	(3.4)
D	Chungbuk	57,098	427	433	438	456
			244	247	250	260
				(1.4)	(2.7)	(6.7)
E	Gyeongbuk	156,174	467	487	505	462
			729	761	789	722
				(4.5)	(8.1)	(-1.0)
F	Jeonbuk	157,719	409	419	437	421
			645	661	689	664
				(2.6)	(6.9)	(3.1)
G	Jeonnam	218,477	369	390	398	397
			806	852	870	867
				(5.9)	(7.9)	(7.8)
H	Gyeongnam	125,266	343	366	370	369
			430	458	463	462
				(6.7)	(8.0)	(7.6)
	Total/Mean	1,069,831	400	411	417	423
			4,283	4,403	4,495	4,476
				(2.8)	(4.9)	(4.5)

*Source: MFAFF, 2008

the GCMs used. The temporal and spatial variations were great as shown in Table 3 and Fig. 3 and should be considered in the irrigation water resources planning and management.

3.3 Monthly Variations

Not only total seasonal values but also monthly values are important. Fig. 4 compares the projected average monthly values of temperature, rainfall, ETo and paddy irrigation requirement for the baseline and future scenarios. The average growing season temperature will increase consistently from baseline to future scenarios. The growing season mean temperature for the baseline was 21.3℃ and it was projected to increase by 1.5℃ (2020s), 3.3℃ (2050s) and 5.3℃ (2080s). The ETo was projected to increase in response to the mean temperature increase for the future scenarios. The rainfall amount was projected to increase significantly during June through August in the 2080s. Some variations in paddy irrigation requirements during July through September were projected among the scenarios. In May, most of the irrigation requirement is for land preparation prior to transplanting and therefore all the scenarios show similar values. In July, August and September irrigation requirements varied inconsistently due to the varying monthly rainfall amounts as shown in Fig. 4(b).

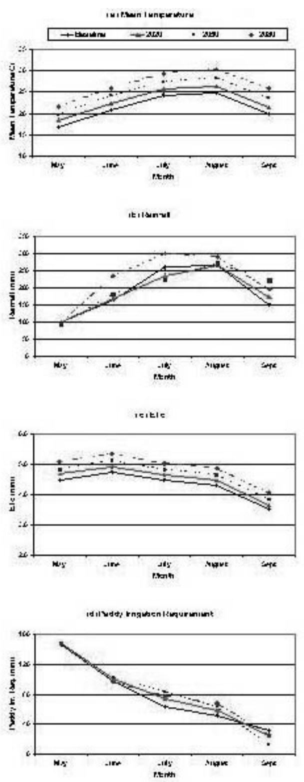

Fig. 4. Comparison of Monthly Mean Temperature, Rainfall, ETo and Paddy Irrigation Requirement for the Baseline and Future Scenario for the Entire Country

Fig. 4(d) shows that most of the irrigation requirements occur in May and June, whereas the extra rainfalls mainly occur in July and August. This coincides with the results of previous study that the rainfall and runoff increases will tend to come during the wet season and the extra water may not be available during the dry season in eastern Asia (Arnell, 2004).

Since the rainfalls in May would not increase in the future, it is most likely that farmers will face water shortage during rice transplanting period, as they often did in the past. An adaptation strategy for paddy irrigation might be postponing the rice-growing period about a month to utilize excess rainfalls in July and August. However, this might not a good strategy with respect to the increased temperature impact on crop growth. Another one may be construction of more irrigation reservoirs to store excess rainfalls in July and August for the following year's irrigation supply.

3.4 Methodological Limitations

This study depends on many assumptions as mentioned in Chung et al. (2010). The rice area, location and cultural practice were assumed to be unchanged. The impacts of higher temperatures and elevated atmospheric CO_2 level on the growth rates and yields for rice were not included. The projected irrigation demands are for an average year, not for a design dry year. More importantly, only one GCM outputs were used, thus the results are a small subset of large possible outcomes. Even though we compared the results of this study with the previous study using a different GCM, further research should include ensemble simulations produced by a number of different GCMs for the different SRES scenarios. The uncertainties of the SRES scenarios and GCM and RCM were not analyzed. Uncertainty analyses should be the priority for future studies.

Despite these caveats, we feel that this study marks significant progress in how climate changes might affect paddy irrigation demands in South Korea. Even if the absolute values of the irrigation demands may not be highly reliable, the comparison of the results from this study and the previous study shows the uncertainty between GCMs used and the likely impacts of spatial variation and different changes across the country have been highlighted.

4. CONCLUSIONS

The impacts of climate change on paddy irrigation demands in the Republic of Korea have been analyzed. Across the Korean peninsula, the growing season mean temperature for the baseline was 21.3℃ and was projected to increase by 1.5℃ (2020s), 3.3℃ (2050s) and 5.3℃ (2080s). The ETo for the future scenarios was projected to increase in accordance with the temperature changes. The growing season rainfall for the future scenarios was projected to increase by 0.1% (2020s), 4.9% (2050s) and 19.3% (2080s). Assuming cropping area and farming practices remain unchanged, the total volumetric paddy irrigation demand for the future were projected to increase by 2.8% (2020s), 4.9% (2050s) and 4.5% (2080s) as compared with the baseline value. These projections are contrary to the previous study that used the HadCM3 outputs and projected irrigation demand to decrease. The main reason for this discrepancy is the difference in the projected rainfalls of the GCMs used. The temporal and spatial variations were large and should be considered in the irrigation water resources planning and management.

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