

Article

Changes in Future Drought with HadGEM2-AO Projections

Minsung Kwon ¹ and Jang Hyun Sung ^{2,*}

¹ K-water Research Institute, Water Resources Research Center, Daejeon 34045, Korea; minsung8151@gmail.com

² Ministry of Environment, Han River Flood Control Office, Seoul 06501, Korea

* Correspondence: jhsung1@korea.kr; Tel.: +82-2-590-9983

Received: 6 January 2019; Accepted: 10 February 2019; Published: 12 February 2019



Abstract: The standardized precipitation index (SPI)—a meteorological drought index—uses various reference precipitation periods. Generally, drought projections using future climate change scenarios compare reference SPIs between baseline and future climates. Here, future drought was projected based on reference precipitation under the baseline climate to quantitatively compare changes in the frequency and severity of future drought. High-resolution climate change scenarios were produced using HadGEM2-AO General Circulation Model (GCM) scenarios for Korean weather stations. Baseline and future 3-month cumulative precipitation data were fitted to gamma distribution; results showed that precipitation of future climate is more than the precipitation of the baseline climate. When future precipitation was set as that of the baseline climate instead of the future climate, results indicated that drought intensity and frequency will decrease because the non-exceedance probability for the same precipitation is larger in the baseline climate than in future climate. However, due to increases in regional precipitation variability over time, some regions with opposite trends were also identified. Therefore, it is necessary to understand baseline and future climates in a region to better design resilience strategies and mechanisms that can help cope with future drought.

Keywords: SPI; reference precipitation; reference period; climate change

1. Introduction

Drought is a natural disaster that causes widespread damage incurring severe economic, social, and environmental costs [1]. Climate change is expected to increase drought frequency and severity in the near future [2]. Studies by the Pew Research Center have shown that drought is one of the most concerning aspects of climate change [3]. Drought can be difficult to define. As such, several indexes have been used to monitor drought, and the phenomenon is often classified as either meteorological or socio-economic [4,5]. Meteorological drought typically occurs first, and is analyzed using drought indexes that calculate precipitation surpluses and deficits [6]. The Standardized Precipitation Index (SPI) suggested by McKee et al. [7] is a representative meteorological drought index used to analyze meteorological and hydrological drought; its primary advantage is its ability to consider multiple time scales [8,9]. Experts of ‘The Inter-Regional Workshop on Indices and Early Warning Systems for Drought’, held at the University of Nebraska-Lincoln, in the United States, agreed to use SPI as a global meteorological drought index [2]. Combining high-resolution climate change scenarios with drought indexes are a common method for producing drought projections in the context of climate change. To produce a high-resolution scenario, spatial downscaling has been performed statistically and dynamically. Statistical downscaling cannot consider non-stationarity of the climate because of its assumption that the relationship between the observations and the simulation baseline period will continue in the future. However, there is an advantage to statistical

downscaling in that it can be directly compared with the baseline climate through bias corrections between observations and the model. Recently, statistical downscaling techniques have been developed to consider long-term trends of the projected data, which minimized the limitations of earlier statistical downscaling techniques [10]. Eum and Cannon [10] applied Spatial Disaggregation/Quantile Delta Mapping (SDQDM) that combined daily Bias-Correction/Spatial Disaggregation (BCSD) and Quantile Delta Mapping (QDM) to produce downscaled climate projections over South Korea. Most of the previous studies for future drought projected both drought severity and duration for each period.

SPI represents drought as a shortage relative to normal, meaning that long-term precipitation data are essential to calculate it. Furthermore, SPI is the random variable of the standard normal distribution corresponding to the non-exceedance probability of a gamma distribution. Therefore, depending on the data used to estimate the probability distribution, the non-exceedance probability of cumulative precipitation can change, which in turn alters SPI. Studies of future extreme precipitation changes have primarily used comparisons of non-exceedance probabilities and return periods based on identical precipitation normals for both the baseline and future climates [11–14]. Unlike projections of extreme precipitation changes, studies of future drought projections have been largely based on non-exceedance probabilities as opposed to a comparison of cumulative precipitation. Kim et al. [15] calculated the baseline and future Standardized Precipitation Evapotranspiration Index (SPEI) using the Representative Concentration Pathway (RCP) 8.5 scenario [16]. They projected that drought frequency will increase in the future. SPEI follows the same progression as SPI except for the input variable. SPEI uses the difference between precipitation and potential evapotranspiration ($D = P - PET$) instead of precipitation alone [17,18]. They also projected a change in the drought magnitude of SPEI -1 . Lee et al. [19] evaluated future changes in the spatial distribution of drought frequency and severity using Intergovernmental Panel on Climate Change (IPCC) GCM simulations. Kyung et al. [20] assessed future droughts in Seoul using the Special Report on Emissions Scenarios (SRES) A2 scenario and predicted that future long-term droughts would increase in severity. Park et al. [21] projected future droughts in Korea using SRES A2 and RCP8.5 scenarios and projected that drought frequency will increase in the future. Kim et al. [22] analyzed the future drought of the Han River Basin using the RCP8.5 scenario and showed that drought frequency will increase in that location. Park et al. [23] projected the future drought in Korea using the RCP8.5 scenario and found projected increases in both drought duration and severity. In these studies, drought was compared based on each non-exceedance probability in the baseline and future climates. In other words, to compare baseline and future periods, these studies employed the same non-exceedance probabilities. The same non-exceedance probability means that a different surplus and deficit for cumulative precipitation will occur with the same frequency in baseline and future. However, the sustainability of the present drought mitigation plan for the future cannot be fully evaluated because these studies did not make a quantitative comparison.

Most studies have calculated the SPI for the future and baseline period, which it evaluated the future compared to the baseline using the future climate change scenarios as shown in references [1,3] of Figure 1. The frequency and magnitude of drought were expected to increase, because of increasing of evapotranspiration due to an increase in temperature and the decreasing number of rainy days. However, climate change scenarios generally projected an increase in precipitation in the future. We assume that the criteria classifying the average state are different from future and baseline. The definition of drought is based on the criteria (or threshold) levels. Non-parametric methods using criteria precipitation can be analyzed using the same criteria as baseline and future. The SPI known as the representative parametric methods have defined the drought as excess probability, and the baseline and the future period (that is, the sample) are different, resulting in a difference of the criteria precipitation defining the drought. Therefore, we projected future droughts based on baseline precipitation called as criteria defining drought in the baseline period (Figure 1). The excess probabilities of future precipitation were calculated from the Cumulative Distribution Functions (CDF) of the gamma in the baseline climate as shown in reference [2] of Figure 1, which the

frequencies of future drought were calculated as the baseline. Section 2 introduces the methodology and data, and Section 3 compares future precipitation with baseline and future climate standards. Finally, conclusions and a discussion of results are presented in Section 4.

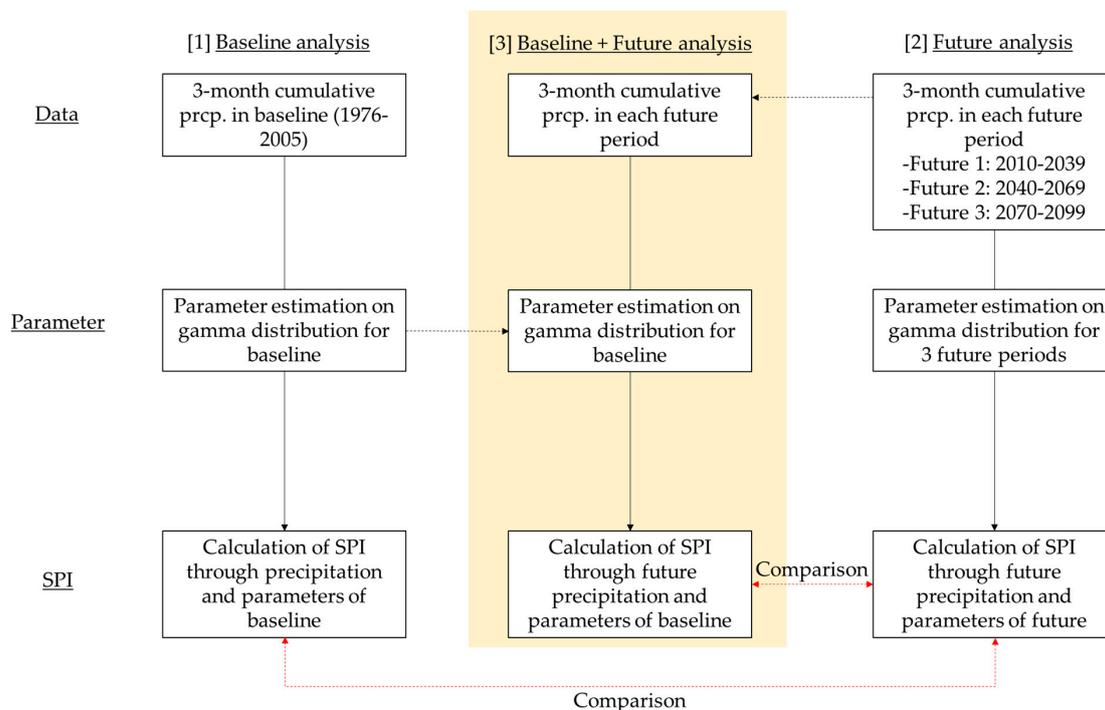


Figure 1. Concept of this Study.

2. Data and Method

2.1. Downscaling and Study Area

Evaluation periods were divided into four 30-year periods: The baseline ones (1976–2005) and three future ones (2010–2039, 2040–2069, 2070–2099). The change in Probability Density Function (PDF) of the gamma distribution was based on future climate change using baseline and future cumulative precipitation. The change in precipitation corresponding to one-month SPI (SPI–1) was projected by each of these gamma CDFs. Finally, we projected the SPI of future drought from the baseline drought criteria.

As greater than 70% of South Korea is mountainous, downscaling of climate change scenarios is essential because of large topographic impacts. Therefore, HadGEM2-AO (Hadley Centre Global Environment Model version 2 Atmosphere Ocean; [24]), a GCM based on RCP scenarios was downscaled for 57 weather stations in South Korea (Figure 2), preserving the long-term trend of the climate simulations (Figure 2). HadGEM2-AO, within the framework of CMIP5, has played an important role in assessing future climate at the national level in South Korea.

RCP 8.5 reflects the current trend of greenhouse gas (GHG) emissions, and RCP2.6 is the maximum limit at which the Earth can still have resilience. RCP4.5 and RCP6.0 are cases where a GHG reduction policy is realized to some extent. The radiative forcings of 8.5, 6.0, 4.5, and 2.6 correspond to approximately 3.6%, 2.5%, 1.9%, and 1.1% of solar radiation, respectively [25]. This study used the RCP8.5 scenario, in which the GHG emissions are relatively unchecked in the future.

Asia Pacific economic cooperation Climate Center (APCC) Integrated Modeling (AIMS) produced high-resolution data with two downscaling methods ([26]); the Simple Quantile Method (SQM) and SDQDM [10]. SDQDM preserves the long-term temporal trends and is essentially BCSD with QDM. QDM [27] (Cannon et al., 2015) is compared to synthetic data with Detrended Quantile Mapping (DQM), Burger et al. [28], which is designed to preserve any trends in the mean and with standard quantile

mapping (QM). In this study, SDQDM was used as a downscaling method, and high-resolution historical simulations and future projections of daily precipitation over 30-year intervals were produced using AIMS.

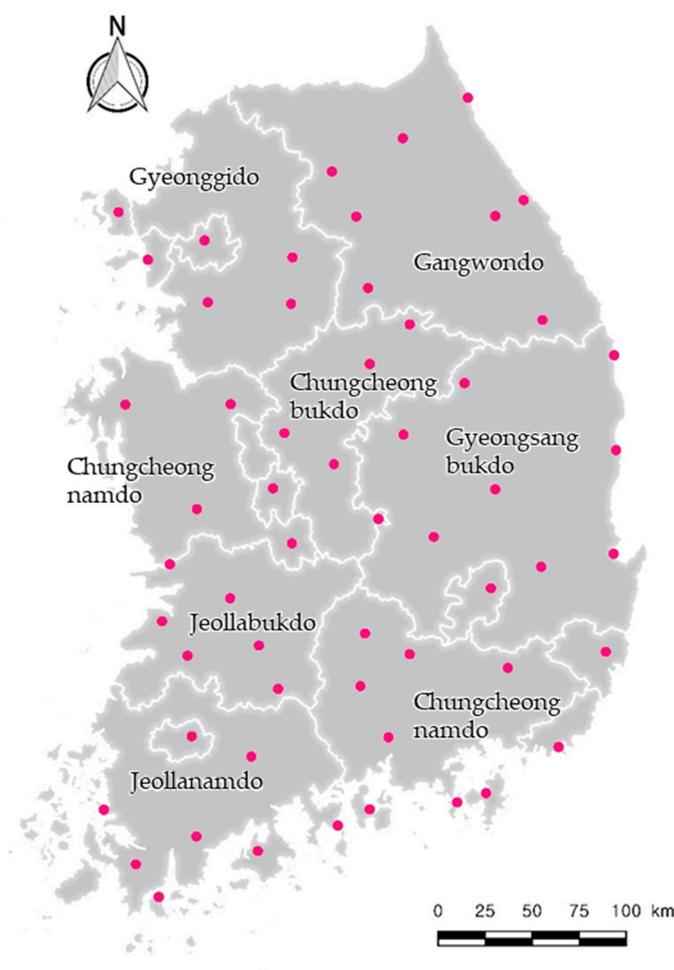


Figure 2. 57 weather stations over South Korea.

The HadGEM2-AO simulations were conducted by the National Institute of Meteorological Research/Korea Meteorological Administration (NIMR/KMA). The horizontal resolution of HadGEM2-AO was 1.875×1.250 . HadGEM2-AO showed good performance in simulating the temperature and precipitation over Northeast Asia, particularly the Korean Peninsula, in terms of annual cycle, precipitation pattern, and timing of the rainy season ([29–31]). The HadGEM2-AO climate model became a standard scenario officially certified by the central government. Before drought projection using simulated precipitation from HadGEM2-AO, we confirmed that the simulated precipitation properly reproduced the observed precipitation to identify spatial distribution. Figure 3a shows the spatial distributions of the observed and simulated precipitation during January–March. The eastern coast and the south region had large precipitation. From April to March, the amount of precipitation in the central region was smaller than other regions in the both precipitations (Figure 3b). The simulated precipitation similar to observation in the southeast region was small during July–September (Figure 3c), but there was a difference between precipitations. From October to December, the precipitation in the eastern inland region was smaller than other regions in both precipitation (Figure 3d). We confirmed that spatial distributions and magnitude captured by the models are in good agreement with the observations.

Figure 4 shows monthly observed and simulated precipitation, which HadGEM2-AO was underestimated during the rainy season. However, we focused on employing same criteria

precipitation regardless of the current and the future. Though differences were confirmed, the model projected precipitation in the current and future has been valid, therefore simulated precipitation was applied.

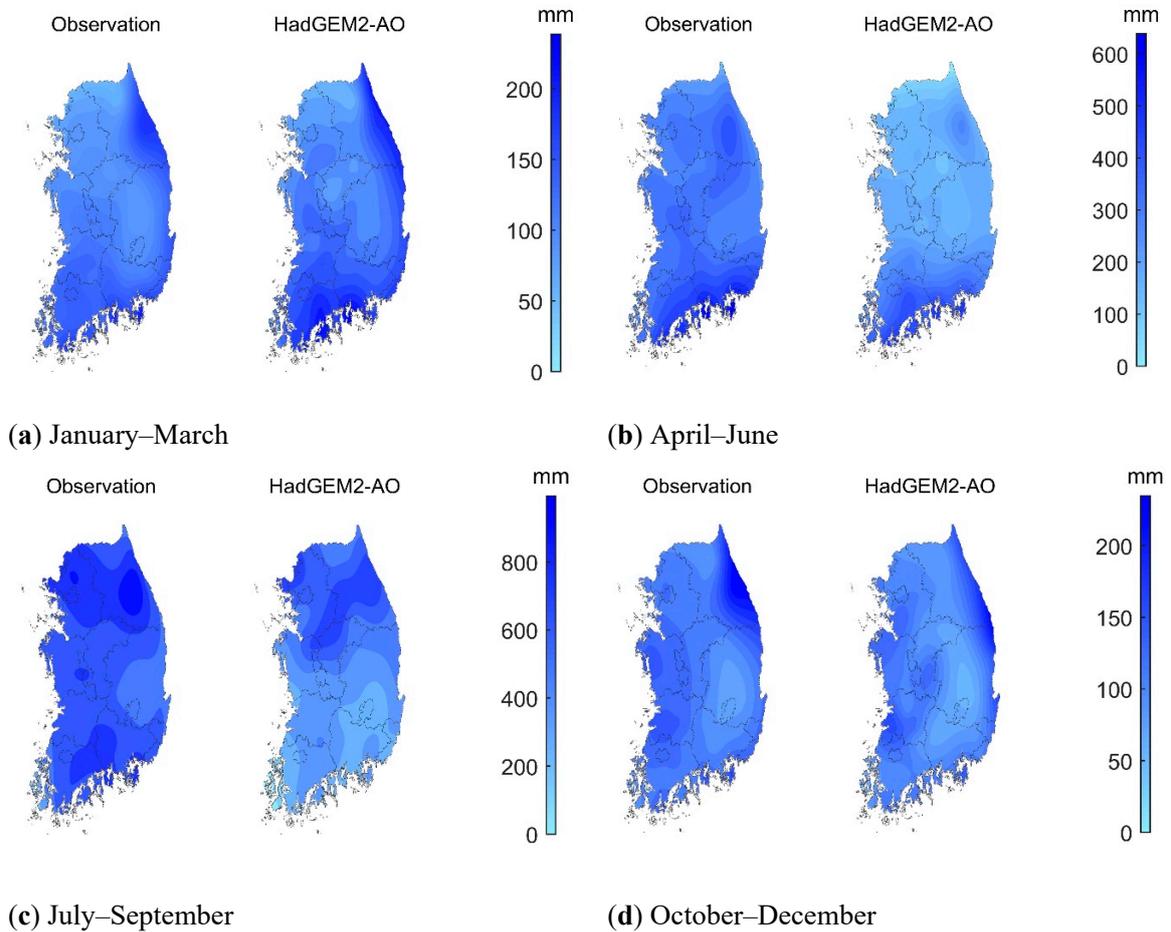


Figure 3. Spatial distribution observed and simulated 3-month cumulative precipitation.

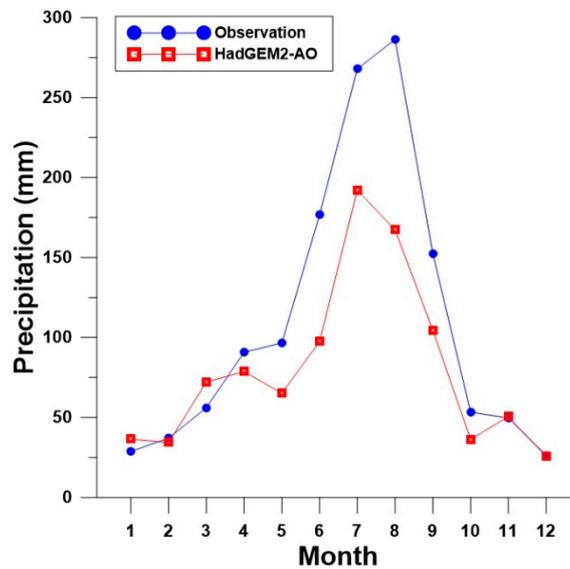


Figure 4. Monthly observed and simulated precipitation (1980–2005).

2.2. SPI

In this study, the drought was assessed using SPI and the change in precipitation corresponding to SPI of -1 , which is the drought criteria in SPI that was examined. And the future drought was evaluated by applying gamma parameters of the baseline to the future precipitation. The SPI proposed by McKee et al. [7] is one of the most widely used drought indexes with the advantage of simple calculation using only precipitation. In addition, the SPI was agreed to be used by drought experts as a global meteorological drought index at the 'Inter-Regional Workshop on Indices and Early Warning Systems for Drought' held at the University of Nebraska-Lincoln in 2009 [2].

The SPI is calculated by applying a gamma distribution to the cumulative precipitation over a period, and standardizing it. The gamma distribution was not defined at zero, thus the parameters of gamma probability distribution (Equation (1)) were estimated except for the zero of the cumulative precipitation.

$$G(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \quad (1)$$

$$H(x) = (1 - q)G(x) + q \quad (2)$$

where $G(x)$ is the CDF of the gamma distribution, α and β are the shape and scale parameters, q is the probability that cumulative rainfall is zero. The SPI is calculated by substituting the probability and applying the probability (Equation (2)) to Equation (3). In Equation (3), F^{-1} is the inverse of the standard normal distribution ($F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-x^2/2}$). That is, as shown in Figure 5, SPI is the random variable (②) of the standard normal distribution for $H(x)$ (①).

$$SPI = F^{-1}(H(x)) \quad (3)$$

To calculate the cumulative precipitation, which in turn determines drought, the precipitation when SPI is -1 can be calculated as Equation (4).

$$x = G^{-1}\left(\frac{F(-1) - q}{1 - q}\right) \quad (4)$$

where G^{-1} is the inverse CDF of the gamma distribution. To calculate the SPI for baseline and future climates, the non-exceedance probability of the gamma distribution for the 3-month cumulative precipitation during the future period was calculated, and the random variable of standard normal distribution with the same non-exceedance probability was obtained.

Figure 5 shows a method for calculating SPI and the meaning of change in the drought criteria by climate change. SPI is the random variable of the standard normal distribution corresponding to gamma CDF of specific precipitation. Even at the same precipitation, SPI varies according to change in the sample. In addition, criteria precipitation classifying the drought corresponding to SPI -1 also changes according to the sample. Therefore, magnitude and frequency of future drought can be changed depending on whether they are considering current (baseline) or future climate.

Ⓐ and Ⓑ in the figure represent criteria precipitation classifying drought. The left panel in Figure 5 shows CDF changes resulting in increasing precipitation of future compared to current (baseline). In this case, because the criteria precipitation corresponding to -1 increases, SPI values for the future is decreased (increased) on the basis of future or baseline (in case of employing gamma CDF of future or baseline) (Figure 5).

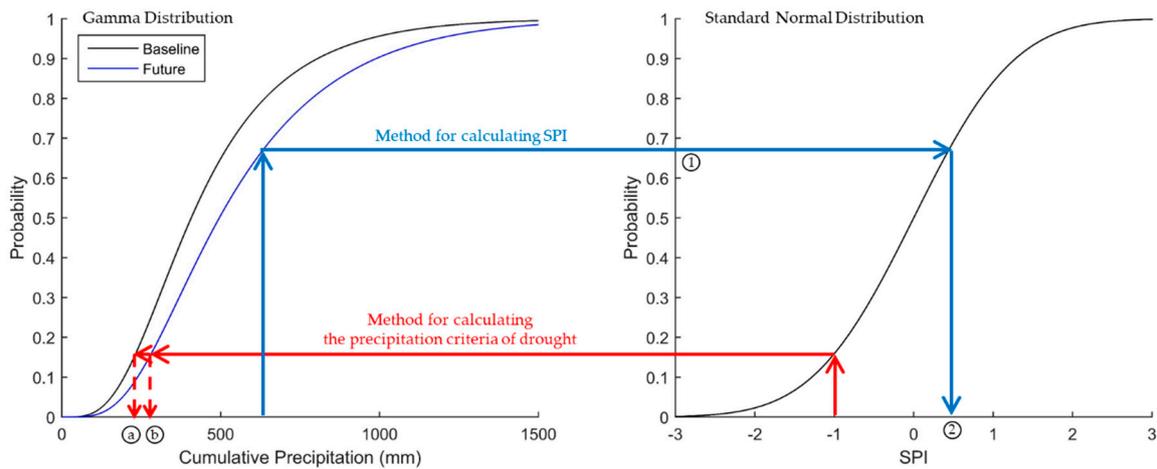


Figure 5. Concept of standardized precipitation index (SPI) and change in cumulative precipitation corresponding to SPI -1. As precipitation increases, the criteria of drought increase from (a) to (b).

3. Results

3.1. PDF Changes

This section analyzed the 3-month cumulative precipitation corresponding to SPI -1 during March, June, September, and December in the baseline and future climates. SPI values of ≤ -1 define drought. The non-exceedance probability of the random variable of -1 is 0.1587, and the 3-month cumulative precipitation corresponding to 0.1587 was obtained using the inverse function of the gamma distribution. Figure 6 shows results for the mean cumulative precipitation of all stations in each period. Future 1 (2010–2039) is expected to decrease in March and September compared to the baseline climate, and increase in June and December. Although Future 2 (2040–2069) increased overall compared to Future 1, it is expected to decrease in June. Finally, Future 3 (2070–2099) decreased more in March and December than Future 2 did but increased in June and September (Figure 6 and Table 1).

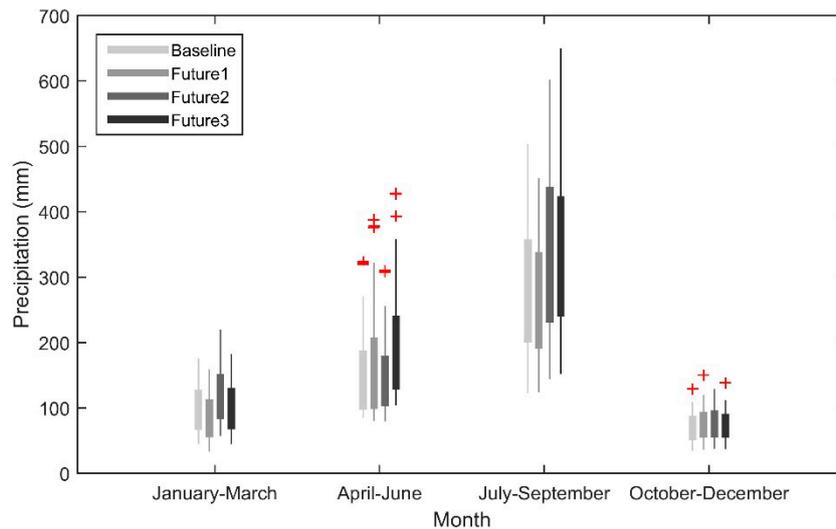


Figure 6. Box plot of 3-month cumulative precipitation corresponding to SPI of -1 .

Table 1. Mean precipitation amounts (mm/3-months) corresponding to an SPI of -1 .

Month	Baseline	Future		
		Future 1	Future 2	Future 3
March	97.3	86.8	120.1	100.7
June	152.7	169.0	150.6	197.8
September	270.3	257.3	326.1	328.8
December	70.3	75.6	78.1	72.7

The change of the gamma PDFs relative to the 3-month cumulative precipitation was analyzed for March, June, September, and December for the baseline and all future periods (Figure 7). Here, the band of each PDF indicates the range of the 95% confidence interval for all weather stations. Figure 7 shows that Future 1 is very similar to the baseline period, and the PDF shifts farther to the right between Future 2 and Future 3. Large precipitation amounts occur particularly frequently in Future 3, and the PDF of the mode is expected to be much smaller than for prior periods. Overall, 3-month cumulative precipitation increased in the future and the PDF shifted to the right. The average change in PDF was shown in Figure 7, it was projected that precipitation would increase in the future. However, due to the decrease in precipitation during autumn and winter, drought criteria precipitation (the precipitation which determines drought) was expected to decrease.

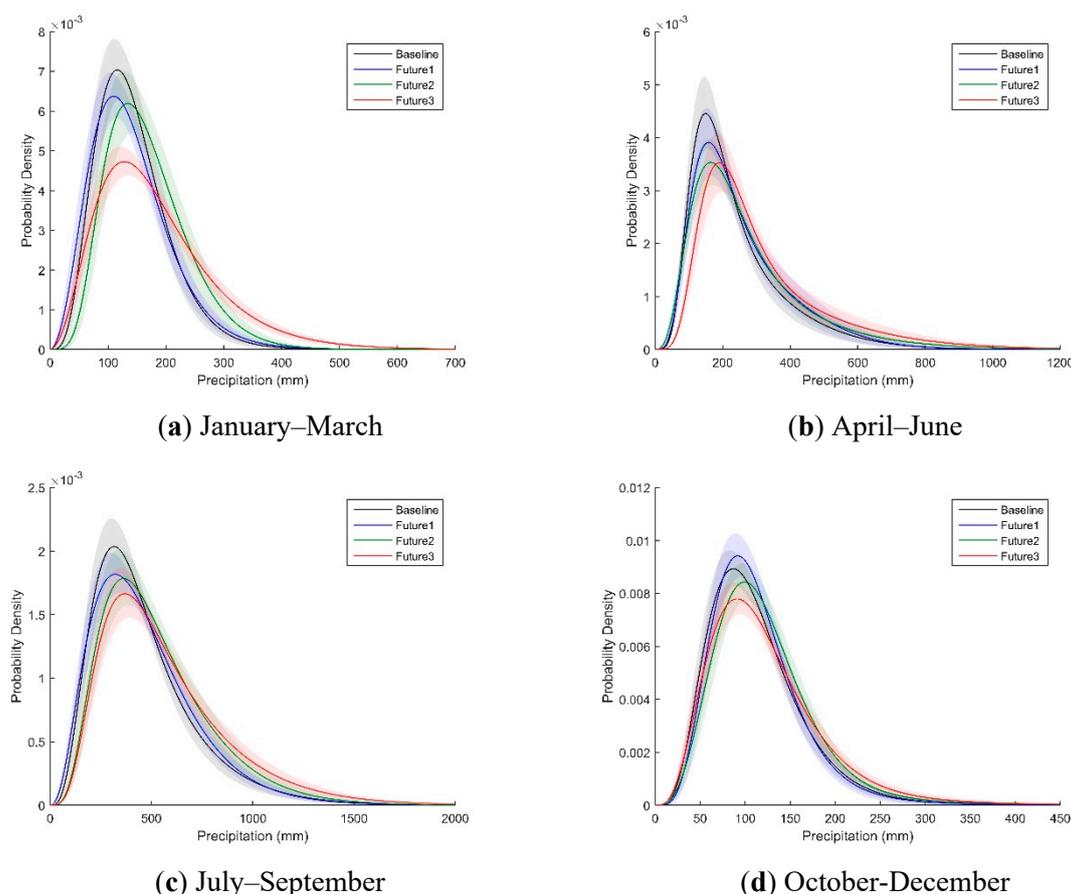


Figure 7. Probability density function (PDFs) of baseline and future 3-month precipitation.

Figure 8 shows the Coefficient of Variance (CV) for 3-month precipitation in baseline and future periods. The average CV values for the baseline and three future periods are 0.518, 0.517, 0.524, and 0.539, respectively; as such, CV was expected to increase in the future. Although larger CV means that the extreme climate is more likely to occur, it cannot be concluded that future drought is

more severe. Therefore, we analyzed the future drought assessed in the baseline climate criteria in Section 3.2.

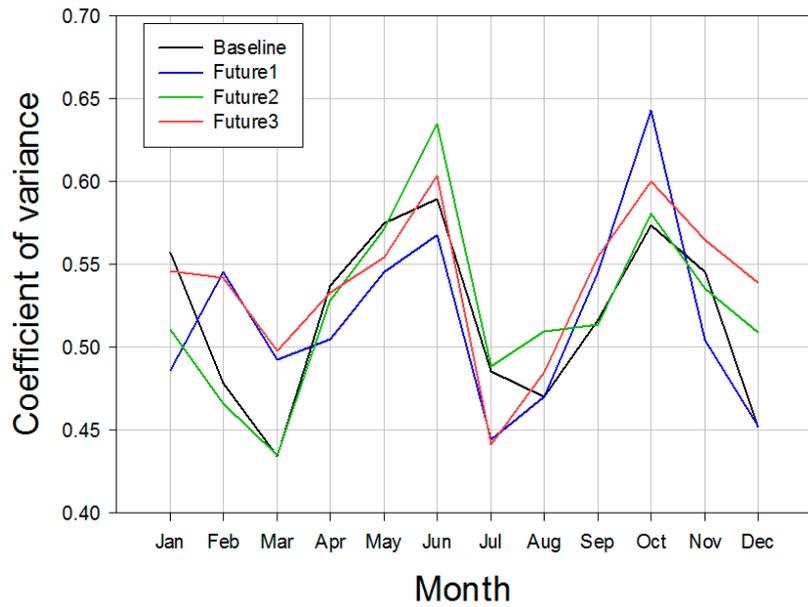
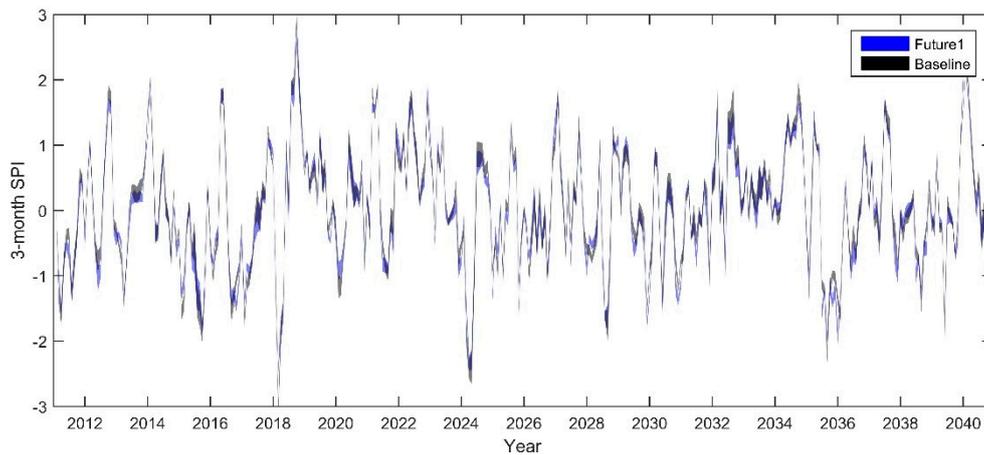


Figure 8. Coefficient of variance (CV) of baseline and future 3-month cumulative precipitation.

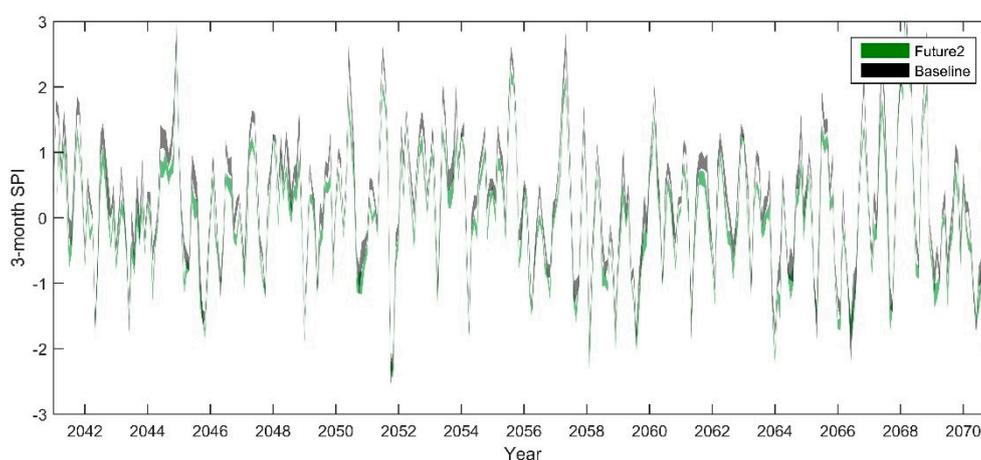
3.2. Changes in SPI

In Section 3.1, we identified changes in drought criteria precipitation for baseline and future climates. Results showed that drought criteria precipitation varied with each period due to changes in the PDFs, although overall precipitation increased over time. In this section, we compare a change in the drought index with the change in the reference period. To do so, the future SPI was calculated based on the baseline climate, and the severity and frequency of drought were compared (Figure 9).

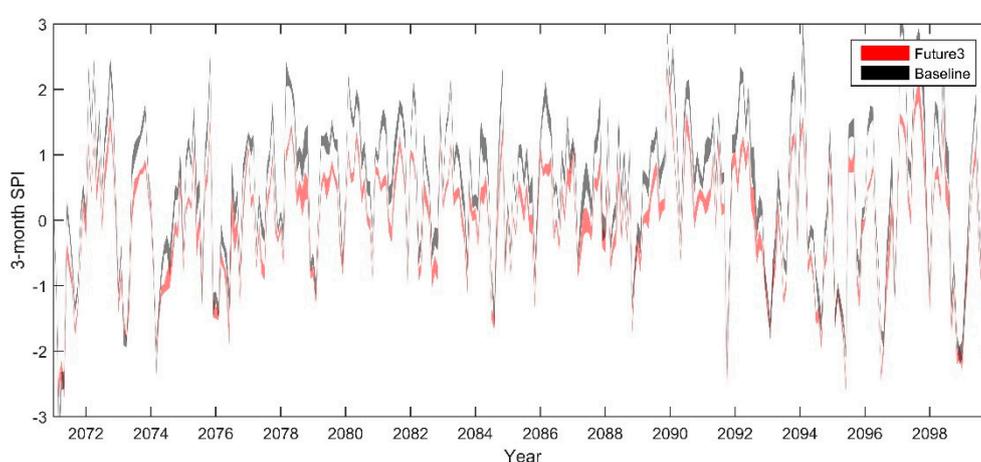


(a) Future 1

Figure 9. Cont.



(b) Future 2



(c) Future 3

Figure 9. Future SPIs changes due to changes in the statistical characteristics of baseline and future climates.

Figure 9 shows SPIs for future precipitation under the baseline and future climate, with the 95% confidence interval shown for all weather stations. For the future precipitation, the SPI based on the future climate is smaller than the SPI based on the baseline climate. This is because of the increase in future precipitation within the climate change scenarios; therefore, the drought criteria precipitation was generally larger than the baseline. In addition, the smaller SPI is caused by an increasing occurrence frequency of less precipitation than the drought criteria precipitation, which happens because the variability of precipitation is increasing (Figure 9).

However, the difference between SPIs of the baseline and future climates increased as the reference period changed, and the SPI difference obtained from the baseline and Future 3 was the largest (Figure 9c). Overall, SPIs in the future climate were more severely evaluating drought. That is, under the baseline climate criterion, future cumulative precipitation did not represent drought conditions, yet it did indicate drought using the future climate criterion. Using the criterion of the baseline climate, the mean future SPIs were 0.04, 0.30, and 0.52, respectively. We can therefore conclude that future drought would be weaker under the baseline climate.

Table 2 shows the number of months that SPI were less than -1 , -1.5 , and -2.0 during various periods. Because the future climate has more precipitation than the baseline, drought frequency estimated by the baseline climate criterion is less than that estimated by the future climate criterion. In addition,

moderate drought under the future climate criterion increased to 57.9, 57.4, and 59.4, respectively, but the frequency of drought under the baseline climate criterion decreased to 52.5, 42.5, and 41.4, respectively. From these results, we confirm that designs based on future climates may be exaggerated because of the higher frequency of drought under the future climate criterion than the baseline climate.

Table 2. Mean occurrence frequency of SPI less than or equal to -1.0 , -1.5 , and -2.0 .

Criteria	Future 1		Future 2		Future 3	
	Baseline	Future 1	Baseline	Future 2	Baseline	Future 3
<-1.0	52.5	57.9	42.5	57.4	41.4	59.4
<-1.5	21.1	22.6	18.4	24.9	20.9	28.8
<-2.0	8.9	7.4	6.2	7.5	9.3	10.1

3.3. Spatial Distribution of Change in Drought Frequency

In Section 3.2, we compared drought indexes of future precipitation according to each parameter of gamma distribution; one is the parameters of baseline and others are parameters of future. On average, future drought frequency evaluated using the baseline climate criterion decreased. However, because the spatial distribution of drought occurrences vary widely due to regional climate, this section examines the spatial distribution of changes in drought frequency. For this, future drought frequency obtained from the baseline and future climate criteria was examined for each of the 57 weather stations (Figures 10–13). Figures 10–13 show the difference in the number of occurrences of future drought ($SPI < -1$), which is calculated as the number of drought occurrences using the future climate criterion minus that using the baseline climate criterion. In Figures 10–13, progressively redder colors indicate a larger number of droughts estimated using the future climate criterion.

Comparing the cumulative precipitation between baseline and future climate criteria for March of Future 2, a large region exhibited positive differences (Figure 10). In other words, in the Future 2 climate there are a lot of areas where drought will be more frequent than in the baseline climate. In most regions of South Korea, precipitation is projected to increase after the middle of the 21st century, relative to baseline values. As such, the drought criteria precipitation and drought frequency also increased. However, drought frequency using the Future 2 climate criterion is much larger than if the baseline climate criterion is used (Figure 10), showing the dependence on drought criteria precipitation.

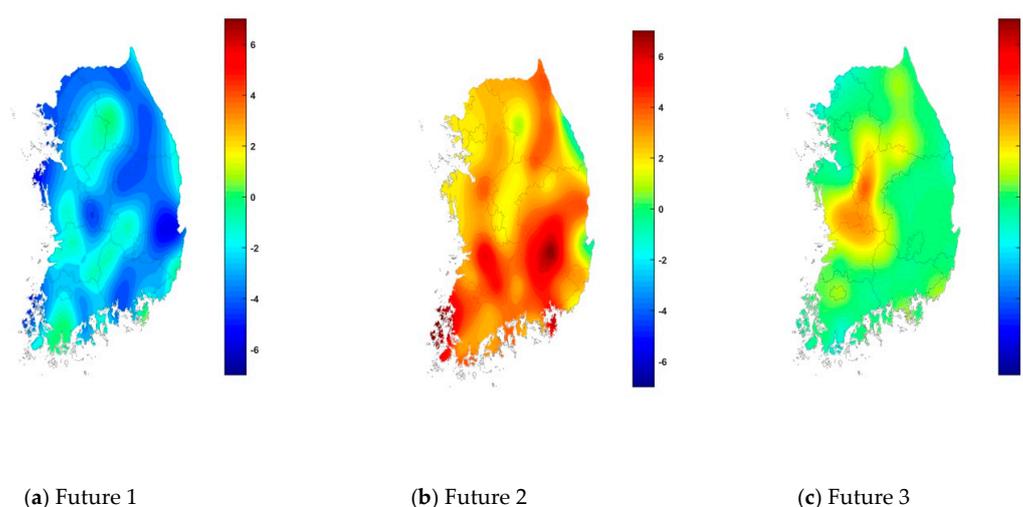


Figure 10. Future SPI changes in March due to changes in the statistical characteristics of the present and future climates.

In June, drought may be overestimated for all future periods, especially compared to March. In the case of Future 1, it was confirmed in Jeollanam-do and Chungcheongbuk-do, in Future

2, in Gyeonggi-do, and in Future 3, in Gyeonggi-do, Gangwon-do, and Gyeongsangnam-do. The difference was especially negative in the Gyeongsangnam-do of the Future 2 period. This is a region where frequent droughts occur relative to the baseline climate because the future precipitation in June is less than the baseline. This is because the gamma PDF of the future period is shifted to the left compared to the baseline due to less precipitation. As a result, these regions needed a strong drought response strategy to prepare for future droughts (Figure 11), which may be worse than projected.

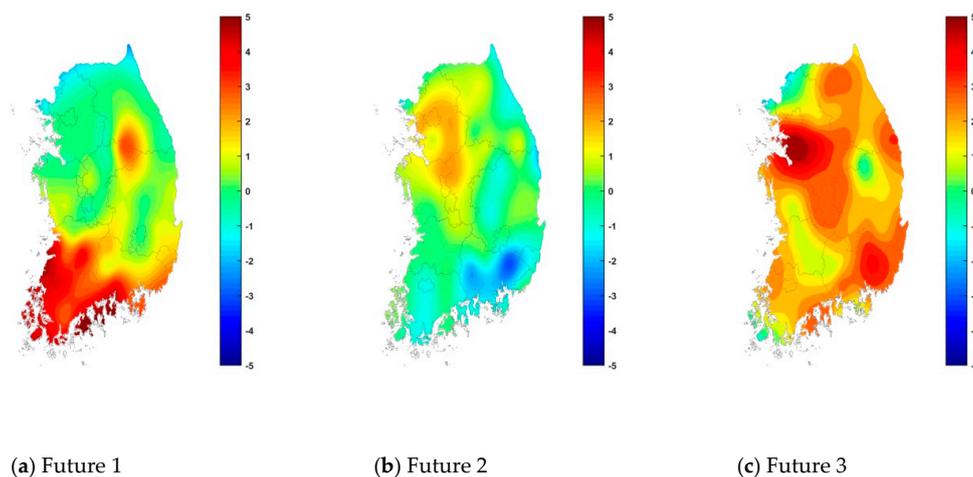


Figure 11. Future SPI changes in June due to changes in the statistical characteristics of the present and future climates.

In September in the Future 1 period, there was a broad area with a similar drought occurrence frequency between the baseline and future climate criteria, because there was no significant difference in drought criteria precipitation between the baseline and Future 1 climates. However, some regions such as Gangwon-do, exhibited negative differences. In Future 2, there was a wide region of positive differences due to the increase in criteria precipitation. On the west coast of Jeollanam-do and Jeollabuk-do, in some parts of Gangwon-do, Gyeongsangnam-do, and Gyeongsangbuk-do, positive difference regions were also observed in Future 3. Other areas are similar between future and baseline periods, and these regions are considered to be capable of coping with future droughts under a similar drought response strategy to that currently employed (Figure 12).

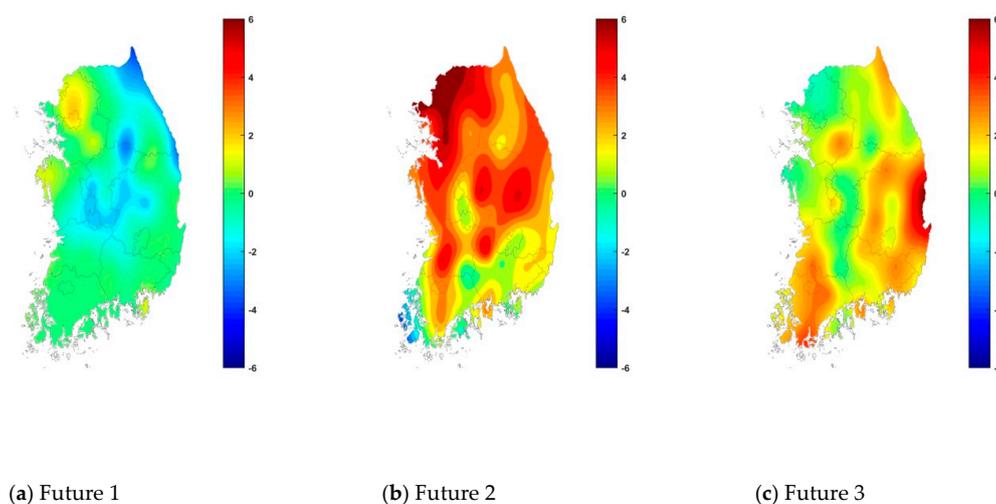


Figure 12. Future SPI changes in September due to changes in the statistical characteristics of the present and future climates.

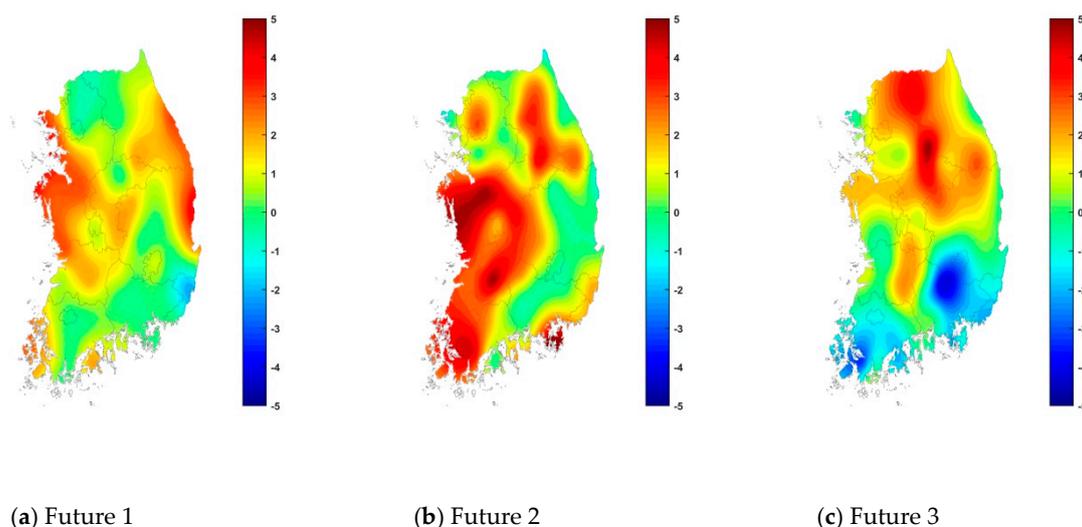


Figure 13. Future SPI changes in December due to changes in the statistical characteristics of the present and future climates.

In December, approximately half of South Korea experienced a larger drought frequency in Future 2 than the baseline period, due to the increase of precipitation in the future period. However, In Future 3, in most regions of Gyeongsangnam-do and Jeollanam-do, the opposite case was found. This is because future climate precipitation is less than the baseline, in most of the high-latitude regions in Future 3, drought has likely been overestimated due to the increase in future precipitation (Figure 13). Therefore, in these areas it may be sufficient to prepare for future drought using current mitigation strategies.

4. Conclusions

In general, studies that examined changes in future droughts calculated the frequency and severity of meteorological droughts as a criterion of a non-exceedance probability of precipitation over each period. Drought based on only future climates is difficult to quantitatively compare with the present since the drought criteria precipitation differs by period. Exceedance probability for the same quantitative value is required to prepare for extreme events, but drought studies to date have evaluated droughts based on the same non-exceedance probability for different criteria precipitation amounts. Therefore, this study predicted future drought changes based on the baseline climate.

Climate change scenarios were elucidated using statistical downscaling techniques representative of long-term climate change trends, and cumulative precipitation corresponding to drought criterion for each future period was calculated. Trends toward larger cumulative precipitation were generally confirmed, but some months in future period showed negative precipitation trends. Especially in September, when summer precipitation was included, variability was high. Moreover, results for the Future 1 period confirmed that it is important to prepare for drought due to lower expected precipitation compared to the baseline climate.

Kim et al. [15] projected that future droughts in South Korea will be more severe. They compared SPEI characteristics such as drought frequency and duration and found that mild drought frequency was projected to increase from the baseline 0.97/year to 3.72/year in the late of the 21st century, while severe drought was projected to increase from the baseline 0.20/year to 1.55/year in the late 21st century. Park et al. [21] predicted that drought would be severe in the Han River Basin in Korea under the RCP8.5 scenario. They indicated that drought severity will increase by approximately 45% in the Han River Basin as a result of the SDF (Severity-Duration-Frequency) curve. Kyoung et al. [20] projected that drought severity and frequency will increase in Seoul, while Park et al. [23] projected that drought duration and severity will increase in the central region of Korea, and Kim et al. [22] projected

that drought frequency will increase in the Han River Basin. However, our results are different. As precipitation increases in the future, the PDF shifts to the right, and therefore the non-exceedance probability increases. Therefore, if future precipitation is assessed based on the baseline climate, our results showed that drought was weaker and less frequent. Therefore, the occurrence frequency of moderate drought based on the future climate tended to increase, but drought frequency based on baseline climate decreased. In other words, designing drought responses based on a future climate may be excessive.

However, future drought is underestimated in some sub-regions because the variation of the regional climate increases in the future. In particular, March in the Future 1 climate, June of Future 2, September of Future 1, and December of Future 3 exhibited less precipitation than the baseline climate, meaning that drought frequency was higher for the baseline climate criterion than the future climate criterion. Areas with these characteristics will require preparation for future drought based on the baseline climate. Our results suggest that regional priority can be assessed when constructing facilities for drought response.

Other studies for future drought have defined drought by the same non-exceedance probability for each period, rather than a comparison of quantities. This is similar to quantile mapping among the simplest downscaling method, and it is not suitable for a quantitative comparison between the baseline and future. It is significant that this study suggests and applies a method to evaluate future droughts based on the current climate. The inherent limitations to our study are that only one GCM model and RCP were used. Especially, when there was a difference between HadGEM2-AO and observation during the rainy seasons, from this study, future water availability can be assessed realistically, and climate change scenario uncertainty can be quantified in the future by using additional models and RCPs.

Author Contributions: Conceptualization, J.H.S.; formal analysis, J.H.S. and M.K.; investigation, J.H.S. and M.K.; data curation, J.H.S.; writing—original draft preparation, J.H.S.; writing—review and editing, J.H.S. and M.K.

Funding: Funding: This research was funded by the Korea Environmental Industry & Technology Institute (KEITI) grant funded by the Ministry of Environment grant number Grant 18AWMP-B083066-05.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wilhite, D. Drought monitoring and early warning: Concepts, progress and future challenges. *World Meteorol. Organ.* **2006**, *1006*, 24.
2. WMO. Experts agree on a universal drought index to cope with climate risks. WMO Press Release 2009, No. 872. Available online: http://www.wmo.int/pages/prog/wcp/agm/meetings/wies09/documents/872_en.pdf (accessed on 17 July 2018).
3. Stokes, B.; Wike, R.; Carle, J. Global concern about climate change, broad support for limiting emissions. 2015. Available online: <http://www.pewglobal.org/2015/11/05/global-concern-about-climate-change-broad-support-for-limiting-emissions/> (accessed on 17 July 2018).
4. Wilhite, D.A.; Glantz, M.H. Understanding: The drought phenomenon: The role of definitions. *Water Int.* **1985**, *10*, 111–120. [CrossRef]
5. American Meteorological Society. Meteorological drought—Policy statement. *Bull. Am. Meteorol. Soc.* **1997**, *78*, 847–849. [CrossRef]
6. Heim, R.R., Jr. A review of twentieth-century drought indices used in the United States. *Bull. Am. Meteorol. Soc.* **2002**, *83*, 1149–1165. [CrossRef]
7. McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scales. In *Proceedings of the 8th Conference on Applied Climatology*; American Meteorological Society: Boston, MA, USA, 1993; pp. 179–183.
8. Zhai, J.; Su, B.; Krysanova, V.; Vetter, T.; Gao, C.; Jiang, T. Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in 10 large regions of china. *J. Clim.* **2010**, *23*, 649–663. [CrossRef]

9. Lorenzo-Lacruz, J.; Vicente-Serrano, S.M.; López-Moreno, J.I.; Beguería, S.; García-Ruiz, J.M.; Cuadrat, J.M. The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). *J. Hydrol.* **2010**, *386*, 13–26. [[CrossRef](#)]
10. Eum, H.I.; Cannon, A.J. Intercomparison of projected changes in climate extremes for South Korea: application of trend preserving statistical downscaling methods to the CMIP5 ensemble. *Int. J. Climatol.* **2017**, *37*, 3381–3397. [[CrossRef](#)]
11. Sung, J.H.; Kang, H.-S.; Park, S.; Cho, C.; Bae, D.H.; Kim, Y.-O. Projection of extreme precipitation at the end of 21st century over South Korea based on representative concentration pathways (RCP). *Atmosphere* **2012**, *22*, 221–231. [[CrossRef](#)]
12. Sung, J.H.; Kim, B.S.; Kang, H.-S.; Cho, C. Nonstationary frequency analysis for extreme precipitation based on Representative Concentration Pathways (RCP) climate change scenarios. *J. Korean Soc. Hazard Mitig.* **2012**, *12*, 231–244. [[CrossRef](#)]
13. Suh, M.S.; Oh, S.G.; Lee, D.K.; Cha, D.H.; Choi, S.J.; Jin, C.S.; Hong, S.Y. Development of new ensemble methods based on the performance skills of regional climate models over South Korea. *J. Clim.* **2012**, *25*, 7067–7082. [[CrossRef](#)]
14. Kwon, M.; Lee, G.; Jun, K.S. Analysis of Annual Maximum Daily Rainfall Using RCP Climate Change Scenario in Korean Peninsula. *J. Korean Soc. Hazard Mitig.* **2015**, *15*, 99–110. [[CrossRef](#)]
15. Kim, B.S.; Chang, I.G.; Sung, J.H.; Han, H.J. Projection in Future Drought Hazard of South Korea Based on RCP Climate Change Scenario 8.5 Using SPEI. *Adv. Meteorol.* **2016**. Available online: <https://www.hindawi.com/journals/amete/2016/4148710/abs/> (accessed on 11 February 2019).
16. Riahi, K.; Rao, S.; Krey, V.; Cho, C.; Chirkov, V.; Fischer, G.; Rafaj, P. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Clim. Chang.* **2011**, *109*, 33. [[CrossRef](#)]
17. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J. Clim.* **2010**, *23*, 1696–1718. [[CrossRef](#)]
18. Park, J.; Lim, Y.-J.; Kim, B.-J.; Sung, J.H. Appraisal of Drought Characteristics of Representative Drought Indices using Meteorological Variables. *KSCE J. Civ. Eng.* **2018**, *22*, 2002–2009. [[CrossRef](#)]
19. Lee, J.-H.; Kwon, H.-H.; Jang, H.-W.; Kim, T.-W. Future changes in drought characteristics under extreme climate change over South Korea. *Adv. Meteorol.* **2016**. Available online: <https://www.hindawi.com/journals/amete/2016/9164265/abs/> (accessed on 11 February 2019). [[CrossRef](#)]
20. Kyoung, M.; Lee, Y.; Kim, H.; Kim, B. Assessment of climate change effect on temperature and drought in Seoul: Based on the AR4 SRES A2 senario. *J. Korean Soc. Civ. Eng.* **2009**, *29*, 181–191.
21. Park, B.-S.; Lee, J.-H.; Kim, C.-J.; Jang, H.-W. Projection of future drought of Korea based on probabilistic approach using multi-model and multi climate change scenarios. *J. Korean Soc. Civ. Eng.* **2013**, *33*, 1871–1885. [[CrossRef](#)]
22. Kim, D.; Hong, S.J.; Han, D.; Choi, C.; Kim, H.S. Analysis of Future Meteorological Drought Index Considering Climate Change in Han-River Basin. *J. Wes. Res.* **2016**, *18*, 432–447.
23. Park, M.; Lee, O.; Park, Y.; Kim, S. Future drought projection In Korea under ar5 rcp climate change scenarios. *J. Korean Soc. Hazard Mitig.* **2015**, *15*, 423–433. [[CrossRef](#)]
24. Collins, W.J.; Bellouin, N.; Doutriaux-Boucher, M.; Gedney, N.; Halloran, P.; Hinton, T.; Hughes, J.; Jones, C.D.; Joshi, M.; Lid-dicoat, S.; et al. Development and evaluation of an Earth-system model – HadGEM2. *Geosci. Model Dev.* **2011**, *4*, 997–1062. [[CrossRef](#)]
25. IPCC. Climate change 2014: Synthesis report. In *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2014.
26. Cho, J.; Jung, I.; Cho, W.; Hwang, S. User-centered climate change scenarios technique development and application of Korean peninsula. *J. Clim. Chang. Res.* **2018**, *9*, 13–29. [[CrossRef](#)]
27. Cannon, A.J.; Sobie, S.R.; Murdock, T.Q. Bias correction of GCM precipitation by quantile mapping: How well do methods preserve changes in quantiles and extremes? *J. Clim.* **2015**, *28*, 6938–6959. [[CrossRef](#)]
28. Bürger, G.; Sobie, S.R.; Cannon, A.J.; Werner, A.T.; Murdock, T.Q. Downscaling extremes: An intercomparison of multiple methods for future climate. *J. Clim.* **2013**, *26*, 3429–3449. [[CrossRef](#)]
29. Hong, J.Y.; Ahn, J.B. Changes of early summer precipitation in the Korean Peninsula and nearby regions based on RCP simulations. *J. Clim.* **2015**, *28*, 3557–3578. [[CrossRef](#)]

30. Lee, H.S.; Gan, S.Y.; Byun, Y.H.; Kang, H.S.; Hyun, Y.K.; Haek, H.J.; Kwon, W.T. *Evaluation of HadGEM2-AO based on historical simulation of IPCC AR5*; Korean Meteorological Society: Daegu, South Korea, 2009.
31. Lee, H.S.; Gan, S.Y.; Baek, H.J.; Cho, C.H. *Evaluation of the pre-industrial simulation of HadGEM2-AO*; Korean Meteorological Society: Busan, Korea, 2010.



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).